BIOMECHANICAL EVALUATION & MITIGATION OF OCCUPATIONAL SAFETY HAZARDS RELATED TO MANUAL REBAR TYING

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CERTIFICATE OF ORIGINALITY

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ABSTRACT

Construction industry around the globe is distressed with unsatisfactory occupational health and safety records. The situation is similar in Hong Kong where the issue has become of utmost importance. While the matter is of great concern generally for all of the construction trades, some of them need special attention such as rebar work. Rebar work has been under spotlight because of projected local shortage of rebar workers for several years to come, highly physically demanding nature of their work, and poor health and safety records.

Published literature indicates that rebar workers are highly susceptible to work-related musculoskeletal disorders (MSDs) and fall accidents (FAs) as compared to other trade workers which could be partially attributed to prolonged rebar tying postures. Accordingly, this research endeavored to investigate the contribution of rebar tying postures to the development of MSDs and FAs among rebar workers. Advances in the health and safety informatics have provided us with the tools to identify and quantify risk factors arising from these rebar tying postures, and to evaluate appropriate mitigation schemes. To start with, owing to unknown prevalence of MSDs among construction workers, a systematic review and meta-analysis were conducted to comprehend the pervasiveness of musculoskeletal symptoms (MSS). The review highlighted that around one-half of the construction workforce face lower-back MSS every year and nearly one-third suffer from knee, shoulder and wrist MSS. The exorbitant prevalence rates necessitate further mechanistic studies to identify underlying associated risk factors of MSS and develop appropriate interventions.

Secondly, to better understand widely prevalent MSDs among rebar workers, specially of lower-back, an experimental study was conducted to examine the biomechanical demands of typical rebar tying postures namely stooping, one-legged kneeling and squatting posture. These postures were chosen because of their wide adoption by the rebar workers. Surface electromyography was used to study muscle activations and motion sensors were used to study trunk kinematics. The results revealed that multiple risk factors are involved in each posture which could lead to development of MSDs among rebar workers. Thirdly, to encounter the highlighted risk factors, a low-cost ergonomic intervention of stool-sitting was evaluated using biomechanical, physiological and subjective measures. The intervention was found to be simple yet effective, highlighting the need and efficacy of task-specific prevention measures.

Fourth, considering high rate of FAs in rebar workers, a study was conducted to investigate the temporal changes in standing balance after rebar tying in squatting, stooping and stool-sitting postures. To better understand the postural load during these postures, electromyography and oximeters were used. The study demonstrated that stool-sitting could significantly improve the standing balance owing to lesser postural load. Additionally, the results underscored the importance of individualized balance monitoring for proactive FAs` prevention. Fifth, to enable individualized standing balance monitoring, a wearable inertial measurement unit (WIMU) and smartphone-based tool was devised to monitor static balance of the construction workers. . The tool would enable proactive identification of fall prone workers and assist in informed decision making to prevent FAs. Overall this research work substantiates the use of health and safety informatics to improve the occupational well-being of the construction workers.

LIST OF PUBLICATIONS

Refereed Journal Papers: Published or Accepted

[1] **Umer, W.**, Antwi-Afari, M. F., Li, H., Szeto, G. P., and Wong, A. Y. (2018). "The prevalence of musculoskeletal symptoms in the construction industry: a systematic review and meta-analysis" *International Archives of Occupational and Environmental Health* 91(2), DOI: 10.1007/s00420-017-1273-4.

[2] **Umer, W.**, Li, H., Szeto, G. P. Y., and Wong, A. Y. L. (2017). "Identification of Biomechanical Risk Factors for the Development of Lower-Back Disorders during Manual Rebar Tying" *Journal of Construction Engineering and Management* 143(1), DOI: 10.1061/(ASCE)CO.1943-7862.0001208.

[3] **Umer, W.**, Li, H., Szeto, G. P. Y., and Wong, A. Y. L. (2017). "A Low-Cost Ergonomic Intervention for Mitigating Physical and Subjective Discomfort During Manual Rebar Tying" *Journal of Construction Engineering and Management* 143(10), DOI: 10.1061/(ASCE)CO.1943-7862.0001383.

[4] **Umer, W.**, Li, H., Szeto, G. P., and Wong, A. Y. (2018) "Proactive safety measures: Quantifying the upright standing stability after sustained rebar tying postures" *Journal of Construction Engineering and Management* 144(4), DOI: 10.1061/(ASCE)CO.1943-7862.0001458.

Refereed Journal Papers: Under Review

[5] **Umer, W.**, Li, H., Lu, Wei, Szeto, G. P., and Wong, A. Y. (2018) “Development of a tool to monitor balance of construction workers for proactive fall safety management” *Automation in Construction* (under review)

Refereed Conference Papers:

[1] **Umer, W.**, Li, H., Szeto, G. P., and Wong, A. Y. “Biomechanical testing of ergonomic interventions for rebar tying” 13th International Postgraduate Research Conference, 14-15 September 2017, University of Salford, Manchester. (honored with best presentation award)

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CHAPTER 1

INTRODUCTION

1.1 CONSTRUCTION INDUSTRY IN HONG KONG

Construction is a thriving industry in Hong Kong. The recent boom has been attributed to ten mega infrastructure projects announced by Hong Kong Government in 2007-08 Policy Address. Consequently, the contribution of the construction industry to the gross domestic product (GDP) has increased by 1.2% from 2011 to 2015 (Census and Statistics Department Hong Kong 2017). Similarly from 2013 to 2015, the gross value of construction works performed by main contractors have increased by 37% (The Hong Kong Trade Development Council 2016). The industry is expected to flourish further because of anticipated flagship projects such as Hospital Development Program, Railway Development Strategy (RDS), Climate Action Plan 2030 and Long-Term Housing Strategy (LTHS) (Timetric 2017). While the prospects look bright, a series of challenges need to be mitigated to meet the future demands of the construction industry.

1.2 LABOR ISSUES IN HONG KONG CONSTRUCTION INDUSTRY

Labor issues are one the most pressing challenge for the construction industry in the coming years. These issues include rising labor wages, ageing workforce and a shortage of manpower. From November 2012 to November 2015, labor wages index has increased by 44% for the construction labor (Cheung 2016). Beside, in 2013, the proportion of construction workforce over the age of 50 years was 44% whereas that of 60 years was 12% (Y.K. et al. 2015). Moreover, there is a consistent expected shortfall of 10,000 to 15,000 construction workers from 2017 to 2021 (Construction Industry Council 2016). While the government and industry are making efforts to solve these issues by attracting the younger generation, “4D” perception of “disorganized”, “dirty”, “demanding” and “dangerous” is inhibiting them to join the construction industry (Wong et al. 2015b).

To mitigate aforementioned labor issues, special attention should be given to sustain the current construction workforce. Unfortunately, unlike other industries, sustainable workforce seems to be a greater challenge to construction industry as it is still a labor-intensive and physically demanding industry (Albers and Hudock 2007; Hunting et al. 1999; Inyang and Al-Hussein 2011). As such, the accomplishment of the construction tasks exposes the workers to multiple risk factors of various occupational hazards (Forde and Buchholz 2004; Hanapi et al. 2013; Inyang and Al-Hussein 2011; Vi 2003). Consequently, health and safety of construction labor are being adversely affecting because of labor-intensive and physically demanding work tasks. (Seo 2016).

While it is paramount to pursue a goal of a sustainable workforce, statistics suggest that construction labor in Hong Kong faces greater occupational safety and health challenges than other local industries. For example, the accident rate and number of fatalities in construction workers are highest among all other industrial sectors with a trend of increasing number of accidents in the past decade (Labour Department 2017). Although a lot of strategies have been adopted to enhance occupational safety and health of Hong Kong construction workers such as awareness campaigns, safety trainings, guidelines brochures` publication and “pay for safety” scheme, additional measures are still required to further enhance the safety performance of construction workers and decrease the number of construction accidents (Wong et al. 2015b).

To better strategize against occupational hazards and make workforce more sustainable, trade-specific measures are highly recommended (Wang et al. 2015a; West et al. 2016). This recommendation is based on the fact that each construction trade involves specific sub-tasks which expose a worker to risk factor of a particular occupational hazard(s) (Choi 2012). As such, trade-specific mitigation of occupational hazards should be focused, first on high-risk trades that should be followed by the other ones.

1.3 REBAR WORK IN HONG KONG

The construction industry in Hong Kong is dominated by steel reinforced concrete construction. As such, it requires a large number of rebar workers for current and upcoming construction projects. To ensure a sustainable rebar workforce, special attention is required to encounter shortage of rebar workers in the local market, highly demanding nature of their work tasks and their heightened susceptibility to occupational hazards. According to an estimate, there is an expected shortage of rebar workers in the local market till the year 2020 (Construction Industry Council 2016). Besides, rebar work is considered as one of the most physically intensive construction trades (Silverstein and Kalat 1999; Umer et al. 2017b). The trade requires long working hours (Umer et al. 2017b), outdoor working in the scorching heat and under humid conditions (Yi and Chan 2013) and prolonged awkward postures such as squatting, stooping and combined trunk twisting, lateral bending and flexion for rebar tying (Umer et al. 2017a). Resultantly, the trade-specific exposures of rebar tying make them more prone to occupational hazards than other trades, specifically musculoskeletal disorders (MSDs) and fall accidents (FAs). Injury records and prevalence studies indicate that rebar workers have been perhaps the worst sufferers of spine injuries and back MSDs (Albers and Hudock 2007; Forde et al. 2005; Hunting et al. 1999). Likewise, rebar workers have been at substantially greater risk of FAs than other construction trades (Dong and Wang 2011; Huang and Hinze 2003; Hunting et al. 1999; Kang et al. 2017). Taken together, there is an urgent need to alleviate the risk factors of MSDs and FAs for rebar work in order to support the industry`s need of sustainable workforce.

1.4 REBAR WORK AND OCCUPATIONAL RISKS

Rebar tying is an important construction trade entailing repetitive work pattern. In particular, manual rebar tying require the workers to bend forward in stooping or squatting posture in order to tie reinforcement bars with metal tie-wires usually at the floor level (Dababneh et al. 2000). The task content of rebar work entails many risk factors for occupational health hazards (Forde et al. 2005; Hunting et al. 1999). In particular, various observational studies have reported that rebar workers hold non-neutral trunk postures for up to 48% of their work time such as stooping, squatting and one-legged kneeling (Buchholz et al. 2003; Forde and Buchholz 2004; Saari et al. 1978; Umer et al. 2017b). This working practice contrasts the recommendation of keeping the working duration in awkward postures less than 10% of the work shift, otherwise which may cause work-related MSDs (Punnett et al. 1991). In addition, rebar tying work requires the workers to frequent transition between work postures and walk on rebar mesh (Burdorf et al. 1991; Hunting et al. 1999). Both of them are known to be risk factors for loss of balance which might result in FAs (DiDomenico et al. 2010b; Hunting et al. 1999). Accordingly, this research work has focused on how rebar tying in these nonneutral trunk postures is related to likely development of MSDs and a risk factor for FAs, and how these hazards could be potentially mitigated.

Given that rebar work is labor excessive, physically demanding and involves prolonged working in awkward postures, it could be one of the greatest beneficiaries of the ergonomics (Bernold and AbouRizk 2010). Ergonomics is a science which deals with matching a job to a worker considering anatomical, biomechanical, physiological and psychological aspects such that worker`s efficiency and occupational health and safety can be optimized (Gupta 2011). Applying ergonomics principles to rebar tying could allow comprehending the underlying root causes of MSDs and FAs and can support in deriving and evaluating ergonomic interventions.

1.5 PROBLEM-SOLVING APPROACH

Generally, occupational safety hazard research and practice have been limited to general guidelines without considering the task-specific requirements and risk factors (Seo et al. 2014). On the contrary, it is a fact that some of the construction activities pose more occupational risk than the others (Hallowell and Gambatese 2009). Since the task content of a construction activity itself is one of the major causation factors for MSDs and FAs (Nadhim et al. 2016; Wang et al. 2015a), task-specific strategies are highly recommended to alleviate occupational hazards in high-risk trades. Therefore, it was planned to limit the scope of research work to a specific trade. Since, previous research has indicated that rebar workers to be one of the worst sufferers of lower-back MSDs (Forde et al. 2005) and FAs compared to other construction trades (Dong and Wang 2011; Hunting et al. 1999; Kang et al. 2017), it was decided to limit the target population of this research work to rebar workers.

Among various task-specific strategies, prevention through design (PtD) approach has been considered as a potential avenue for preventing hazards (Gambatese et al. 2005). It focusses on intervening the potential risk factors earlier in the process that might result in occupational safety hazards (Earnest and Branche 2016). Importantly, this could lead to better practices, procedures, work environment that could mitigate the propensity of MSDs and FAs (Dekker et al. 2011; Hsiao et al. 2008) among the rebar workers.

1.6 SCOPE OF THE RESEARCH

The commonly recognized risk factors of work-related MSDs include forceful executions (e.g. hammering), prolonged, repetitive and awkward postures, contact stresses and vibrations, operating heavy tools and manual material handling (Inyang and Al-Hussein 2011; Wang et al. 2015a). On the other hand, risk factors of FAs could be generally divided into three domains, (1) environmental factors (2) personal factors and (3) task-related factors (Hsiao and Simeonov 2001). To mitigate the risk factors of MSDs and FAs, concerted effort is needed against multiple causation factors at (1) individual workers and teams level, (2) work environment and site level, (3) task, material, methods and equipment level, and (4) design, policy and safety-culture level (Haslam et al. 2005). For this research endeavor, the scope has been limited to task-related risk factors contributing to MSDs development and FAs.

For rebar tying, there could be numerous task-related risk factors for MSDs and FAs. One of the most dominant risk factors that has been highlighted in published research, is related to the issue of awkward postures (non-neutral working position of back and lower limbs). The posture opted for a task is dependent on the environmental conditions, work station characteristics, the nature of work task, workers` experience, methods and psychosocial factors (Armstrong et al. 1993; Seo 2016). It is observed that most common postures for manual rebar tying include squatting, stooping and one-legged kneeling (Dababneh et al. 2000; Forde and Buchholz 2004; Umer et al. 2017b). This research explored how rebar tying in these postures could affect MSDs development and cause loss of balance. Furthers the research explored means and methods to encounter the risks posed by these postures, and evaluated their efficacy using experimental studies.

1.7 AIMS AND OBJECTIVES

With aforementioned background and scope, this research work aimed to explore the use of contemporary health and safety informatics to identify and mitigate the risk factors of the two most widely prevalent occupational hazards faced by rebar workers i.e. lower back MSDs and FAs. The specific objectives established for this research work are as follow:

1. Given the widespread prevalence of work-related MSDs, there existed no systematic review which had summarized the precise prevalence of MSS (musculoskeletal symptoms of MSDs) in the construction industry and among different trades. In order to effectively manage MSDs, it was crucial 1) to understand the extent and scope of the problem, 2) to inform all stakeholders (e.g. policy makers, medical professionals and construction managers) and 3) to guide the development of prevention and treatment strategies for MSDs in the construction industry. **Accordingly, an objective was set to systematically review and meta-analyze the MSS prevalence data in the global construction industry.**

2. Rebar workers are at a greater risk of work-related MSDs, specifically of lower-back. It might be linked to their task contents that involve prolonged work at ground level while adopting awkward postures (Albers and Hudock 2007; Buchholz et al. 2003; Forde et al. 2005). However, prior to this research work, no previous study had quantified the biomechanical risk factors of lower-back disorders (i.e. muscle activity and trunk kinematics) for rebar workers. Such information could help in better understanding of the rebar work, identifying distinct risk factors for lower-back problems and help in suggesting/deriving appropriate ergonomic alternatives. **Hence, it was aimed to investigate the temporal changes in muscle activity and spinal kinematics during simulated rebar tying work in different postures.**

3. It is known that rebar workers are sufferers of MSDs and ergonomic interventions are one of the effective ways to mitigate risk factors of work-related MSDs (Lehtola et al. 2008; Rinder et al. 2008). Although there are some ergonomic interventions available that could be used for rebar work, experts have pointed out several issues impeding their wide industrial adoption. **Therefore, it was intended to derive a simple and pragmatic ergonomic intervention, and evaluate it using biomechanical, physiological and subjective parameters.**

4. Rebar workers spend a considerable amount of their work-shift in rebar tying with periodic postural transitions. Such postural transition could possibly result in loss of balance upon standing and may cause a FA (DiDomenico et al. 2016).Prior to this research, it was unknown how rebar tying in various postures could affect standing

balance and could an ergonomic intervention make a difference? **Therefore, it was aimed to explore how ensuing standing balance is affected by rebar tying in commonly opted postures and using an ergonomic intervention?**

5. Fatal and non-fatal FAs are one of the most prevalent occupational safety hazard faced by the construction workers around the globe (Cameron et al. 2007; BLS 2016b; Yung 2009). Despite exorbitant occurrence, there was no readily available onsite tool which could identify workers with poor postural controls who are associated with a higher risk of a FA. **Accordingly, an objective was set to develop a wearable inertial measurement sensor (WIMU) and smartphone-based tool that could assess the static balance of construction workers.** Ultimately, the tool could enable proactive identification of FA prone workers and strategize safety measures before a FA happens.

CHAPTER 2

THE PREVALENCE OF MUSCULOSKELETAL SYMPTOMS IN THE CONSTRUCTION INDUSTRY: A SYSTEMATIC REVIEW AND META-ANALYSIS[1]

2.1 INTRODUCTION

Musculoskeletal symptoms (MSS) are one of the most prevalent occupational health problems among construction workers (Inyang et al. 2012). Given the high physical work demand, prolonged awkward static/repetitive postures, whole-body vibration, long working hours, and unfavorable work environment (Buchholz et al. 1996; Forde and Buchholz 2004; Antwi-Afari et al. 2017; Umer et al. 2017a, b), construction workers are constantly exposed to multiple ergonomic risk factors. Consequently, work-related musculoskeletal symptoms are the main contributing factor to non-fatal injuries in the construction industry (Wang et al. 2015a).

The high prevalence of work-related MSS not only causes work absenteeism, schedule delays and compensation claims but also heightens the recruitment/training costs of the construction industry (Inyang et al. 2012). Approximately 33.0% of the total absenteeism in the US construction industry in 2012 were attributed to MSS (BLS 2013). Similarly, The Alberta Construction Safety Association reported that 41.9% of all accepted lost time claims in 2008

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Umer, W., Antwi-Afari, M. F., Li, H., Szeto, G. P., and Wong, A. Y. (2018). "The prevalence of musculoskeletal symptoms in the construction industry: a systematic review and meta-analysis" International Archives of Occupational and Environmental Health, 91(2)

were related to MSS (Inyang et al. 2012). In Germany, MSS is the major cause of occupational disabilities among construction workers (Arndt et al. 2005).

Although individual studies have reported prevalence rates of various MSS in numerous construction trades, no systematic review has summarized these findings. Without such information, it is difficult for relevant stakeholders (e.g. policymakers, project managers, and healthcare providers) to comprehend the scope of the problem and to allocate resources to develop/evaluate prevention or treatment strategies for musculoskeletal symptoms in various trades of the construction industry. Importantly, given the increased employments of females (Kinoshita and Guo 2015) and older workers (Samorodov 1999; Schwatka et al. 2012) in the construction industry, it is essential to critically appraise the evidence regarding the prevalence of MSS in construction workers of different genders or ages. This information can help develop specific management strategies (e.g. job modification) to reduce the risk of work-related MSS in vulnerable subgroups.

Given the above, the primary objective of this systematic review was to synthesize the prevalence of various MSS in the construction industry. The secondary objectives were to compare the prevalence of MSS: (1) among different construction trades (2) between male and female workers, and (3) among different age groups in the industry.

2.2 METHODS

This systematic review protocol was registered with the International Prospective Register of Systematic Reviews (PROSPERO, registration ID: CRD42016036051). The current review was reported according to the Preferred Reporting Items for Systematic Reviews and Meta-analyses guidelines (Moher et al. 2009).

2.2.1 Literature search and study selection

Candidate publications were searched from nine databases from their inception to August 2016: Academic Premier (1990+), CINAHL (1937+), Health and Safety Science Abstract (1981+), Medline (1965+), PsycINFO (1806+), Science Direct (1823+), Scopus (1996+), SportDiscus (1830+) and Web of Science (1970+). The search string included keywords, MeSH terms, and free-text words and consisted of three parts. The first part was related to prevalence or incidence. The second part encompassed the topic of MSS, while the third-one covered construction trades. Since there were no universal list/definitions of the construction trades around the globe, the search string utilized both distinct trade names and general terms to amass all potential articles. Appendix A illustrates the exact search strategy employed. The corresponding authors of the included articles were contacted via email to identify additional articles.

Articles were included if they were primary studies published in peer-reviewed journals regarding the prevalence rates of MSS in one or more construction trades. There was no language restriction. Studies were excluded had they solely reported MSS related to infections, or accidents occurred at or outside worksites. Additionally, publications that did not directly or indirectly provide the prevalence rate of MSS (e.g. proportion of affected workers) were excluded. For multiple articles presenting the same data from a single cohort, only the one with the largest relevant data set was included.

Citations identified from the systematic searches were stored in EndNote X7 (Thomson Reuters, New York, USA) and duplicated citations were removed. Two reviewers (WU and MA) independently screened the titles and abstracts and selected the potential citations based on the selection criteria. Any disagreement was resolved by consensus. Those potential citations were then retrieved for full-text reading. The same screening procedures were adopted for full-text screening. Disagreements between the two reviewers were discussed to achieve consensus. Persistent disagreements were resolved by the third reviewer (AW). The reference lists of the included articles were searched for relevant citations. Forward citation tracking of the included articles was conducted using Scopus to identify relevant articles that were missed at the initial database searches.

2.2.2 Data extraction

The two reviewers independently extracted relevant data from the included articles. The extracted data included year of the publication, duration and location(s) of data collection, study design, involved trade(s), sample size, response rate, age and gender of the participants, case definition, types of period prevalence (e.g. point or 1-week), and data pertaining to the prevalence or frequencies of different MSS in the sample. Consensus meetings were held to resolve any discrepancies arising from data extraction.

2.2.3 Quality assessment

Both reviewers independently evaluated the quality of each included study using a tool developed by *Loney et al.* (1998). The tool (Appendix B) has been used in many systematic reviews to evaluate the quality of primary incidence/prevalence studies (Fejer et al. 2006;

Graham et al. 2003; King et al. 2011; Kok et al. 2015; Peppas et al. 2008). The tool consists of eight questions in three domains. The first six questions appraised the study methodology (i.e. study design and method, sampling frame, adequacy of the sample size, validity of the measurement tools, potential biases of the outcome measurement, and response rate and descriptions of non-respondents). The last two questions evaluated domains related to the results reporting quality and sociodemographic description of participants. Six of the eight questions in the tool score either 0 or 1 point each, while another two questions comprise two sub-questions. Each sub-question may score a maximum of 0.5 points. Accordingly, each study might score between 0 and 8. Studies with scores $\leq$ 4 were labeled as low-quality whereas studies with scores > 4 were considered as high-quality (Kok et al. 2015; Wong et al. 2013). Discrepancies between reviewers were resolved by discussion.

2.2.4 Data synthesis

The 95% confidence interval of the prevalence rate in a given included study was estimated using Wald's formula had it not been reported (Agresti and Coull 1998), which is explained as follow:

$$p \pm z_{\alpha}\sqrt{p\,(1-p)/n} \quad \text{(eq 2.1)}$$

Where p refers to prevalence, z_{α} is statistic for 95% confidence interval for normal distribution and n is the population of the study. Meta-analysis was planned for each type of period prevalence rate of a given MSS if the studies had an identical case definition. I-squared (I^2) statistic was used to quantify the extent of statistical heterogeneity among the prevalence estimates. A large I^2 value indicates greater heterogeneity among the prevalence estimates of different studies. A random-effect model was used to estimate the period prevalence. Outliers were subjectively identified through scatterplots and were discarded from meta-analysis if the study quality was low (Hoy et al. 2012). RevMan 5.3 software (The Cochrane Collaboration, Oxford, UK) was used for the meta-analysis. To minimize publication bias, comprehensive literature searches were conducted to ensure that relevant studies were included (Hoy et al. 2012).

2.3 RESULTS

The searches identified 1,130 citations (Figure 2.1). Five hundred and twenty-eight citations were screened for titles and abstracts after duplicates` removal. Among them, 484 were excluded as the titles and abstracts were unrelated to construction or MSS. Fifty-two articles were selected for full-text screening (including eight articles identified from forward citation tracking and reference lists of the included studies). Seventeen articles were excluded after reviewing the full text because they did not report prevalence data or had insufficient data for the prevalence estimation (e.g. injury/claim data without healthy workers’ statistics, or hospital reports). Therefore, 35 articles were included in this review (Table 2.1).

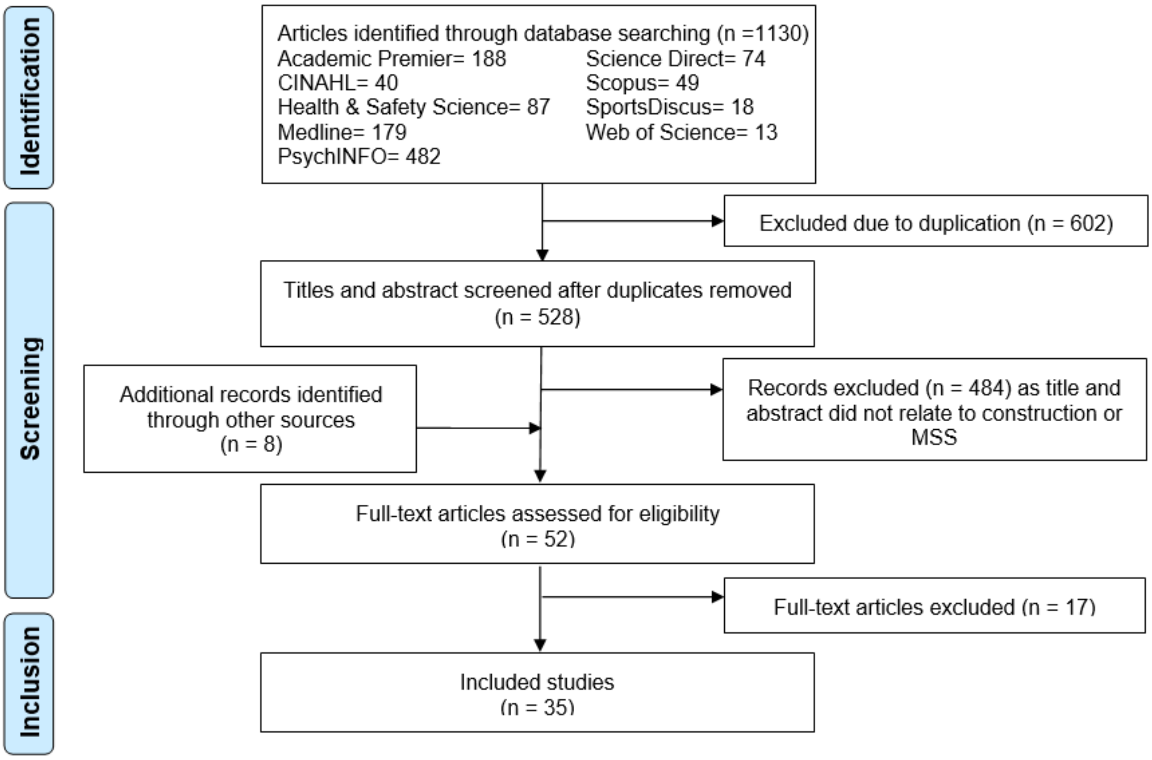


Figure 2.1 A flowchart depicting the systematic search

Table 2.1 Characteristics of the included studies (arranged according to the year of publication)

Study name	Country	Study population	Mode of data collection	Sample size, response rate	Age (years)	Gender	Case definition	Types of MSS	Type of period prevalence	Quality score
Arndt et al. (1996)	Germany	Architects, Carpenters, Engineers, Laborers, Office employees, Painters, Plasterers, Plumbers	Physical examination	N= 4,958 R= 78.0%	Range: 40.0 to 64.0	100.0% male	Pain, tenderness or symptoms at the spine, arms and legs	Spine, arms and legs	Point	7.5
Rothenbacher et al. (1997)	Germany	Carpenters, Laborers, Painters, Plasterers, Plumbers	Q	N= 4,958 R= 78.0%	Mean= 50.0, SD= 5.4	Unknown	Any type of back pain or sciatica experienced	Spinal	Point	6
Lemasters et al. (1998)	USA	Carpenters	Phone interview	N= 489 R= 83.0%	Mean= 42.3, SD= 10.6	97.8% male	Any recurring symptoms such as pain, aching, numbness	8 anatomical parts	1-year	8

de Zwart et al. (1999)	The Netherlands	Bricklayers, Carpenters, Laborers, Painters	Q	N= 3,827 R= unknown	Young workers: mean= 25.9 Older workers: mean= 50.1	100.0% male	Complaints	Neck, spinal, upper and lower extremities MSS	Point	5
Ueno et al. (1999)	Japan	Carpenters, Electricians, Interior finish workers, Iron-workers, Laborers, Painters, Plasterers, Plumbers	Q	N= 2,205 R= 81.0%	Mean= 44.7, SD= 12.0	100.0% male	Have hand and arm pain, shoulder pain, or low back pain	Shoulders, hand and arm, and low back	Point	5
Jensen et al. (2000)	Denmark	Carpenters, Floor layers	Q	Floor layers: N= 133, R= 85.0%	Floor layers: mean= 47.0	Unknown	Ache, pain, or discomfort (for 1-week and 1-year)	Knee	1-week, 1-year	6.5
				Carpenters: N= 506, R= 79.0%	Carpenters: mean= 45.0		Knee complaints >30 days (1-year)			
Molano et al. (2001)	The Netherlands	Scaffolders	Q	N=323, R= 86.0%	Mean= 37.0, SD= 9.1	Unknown	Pain, which had continued for at least a few hours	Neck, shoulder, back and knee	1-year	5

Rosecrance et al. (2001)	Hungary	Apprentices (Electricians, Plumbers, Sheet metal workers)	Q	N= 193, R= 96.0%	Mean= 17.0, SD= 1.2	100.0% male	Job-related ache, pain, discomfort	As per NMQ	1-year	4
Goldsheyder et al. (2002)	USA	Demolition workers, Laborers, Masons	Q	N= 312, R= 70.2%	Mean= 39.9, SD= 9.2	85.0% mason male, 94.0% labor male	Musculoskeletal symptoms experienced	As per NMQ	Point, 1-year	5
Merlino et al. (2003)	USA	Electricians, Plumbers, Sheet metal workers	Q	N= 996, R= 84.8%	Mean= 27.7, SD= 6.2	93.9% male	Job-related ache, pain, discomfort	As per NMQ	1-year	5.5
Elders et al. (2004)	The Netherlands	Scaffolders	Q	At baseline: N= 288 R= 85.0% At 1-year FU: N= 209 R= 73.0%	Range: 35.0 to 44.0	Unknown	One episode of low back pain, stiffness or discomfort	Lower back	1-year	4.5

				At 2-year FU: N= 182 R= 78.0% At 3-year FU: N= 144 R= 78.0%						
Guo et al. (2004)	Taiwan	Nation-wide study stratified for construction industry	Q	N= 588* R= unknown	unknown	Unknown	Soreness or pain in any body part	As per NMQ	1-year	6.5
Engholm and Holmström (2005)	Sweden	Construction workers from multiple trades	Q	N= 85,191 R= unknown	Range: 25.0 to 60.0+	Unknown	Pain, ache	As per NMQ	1-year	7.5
Forde et al. (2005)	USA	Iron-workers	Phone interview	N= 981 R= 72.0%	Mean= 48.8, SD= 13.7	97.9% male	Chronic or recurring musculoskeletal symptoms (pain, aching, discomfort, or numbness)	As per NMQ	Over the entire working career	6.5

Lee et al. (2005)	Taiwan	Nation-wide study stratified for construction industry	I	N= 2021 R= 85.0%	unknown	90.0% male	Soreness or pain	Neck, shoulder, upper back, elbow, wrist and hand	1-year	5.5
Gilkey et al. (2007)	USA	Carpenters	Q	N= 91 R= unknown	Mean= 37.0	Unknown	Low back pain which resulted in lost time from work and/or altered some aspects of the normal activities of daily living and/or caused the sufferer to seek medical care	Lower back	2-week, 1-year, lifetime	2.5
Welch et al. (2008)	USA	Roofers	Phone interview	N= 979 R= 62.0%	Range: 40.0 to 59.0	Unknown	In the past 2 years, did you take medication for or need to regularly see a doctor for musculoskeletal problems?	8 anatomical parts	2-year	4.5

Gheibi et al. (2009)	Iran	Laborers, Machine operators, Truck drivers	Q	N= 110 R= unknown	Mean= 34.9, SD= 9.4	100.0% male	Ache, pain, or discomfort	As per NMQ	1-year	3
van der Molen et al. (2009)	The Netherlands	Carpenters, Pavers	Q	Carpenters At baseline: N= 401 R= 61.0%, At 5-year FU N= 361 carpenters, R= 78.0%, Pavers: At baseline: N= 177 R= 53.0% At 5-year FU N= 163 R= 64.0%	Carpenters: At baseline, mean= 42.0, SD= 10.0 At 5-year FU, mean= 47.0, SD= 10.0 Pavers At baseline, mean= 39.0, SD= 9.7 At 5-year FU, mean= 43.0, SD= 9.6	Unknown	Musculoskeletal lower back or shoulder complaints	Shoulders, lower back	1-year	5
Caban-Martinez et al. (2010)	USA	Hispanic construction workers in the US	Q	N=49 R= 98.0%	Mean= 41.9, SE=1.8	100.0% male	Any symptoms of pain, aching, or stiffness in or around a joint. During the past 3 months, did you have low back	7 anatomical parts	1-month for other parts, 3-month for LBP	3.5

							pain that lasted a whole day?			
Hoonakker and van Duivenbooden (2010)	The Netherlands	Carpenters, Concrete workers, Masons and others	Q	From 1993 to 94: N= 53,500 R= unknown From 1995 to 96: N= 50,300 R= unknown From 1997 to 98: N= 58,340 R= unknown From 1999-2000: N= 50,500	unknown	Unknown	Regular pain or stiffness	Spinal, upper and lower extremities MSS	Point	5

				R= unknown From 2002 to 03: N= 75,500 R= unknown						
Bodhare et al. (2011)	India	Bricklayers, Carpenters, Electricians, Laborers, Painters, Plumbers, Welders	Q	N= 211 R= unknown	Range: 15.0 to 65.0	85.0% male	Pain, numbness, tingling, aching, stiffness or burning in the past year that lasted at least a week or more or occurred at least monthly with a pain scale rating of moderate on a 5-point scale.	As per NMQ	1-week, 1-year	3
Boschman et al. (2012)	The Netherlands	Bricklayers	Postal questionnaire	At baseline: N= 292 R= 39.0%	At baseline: Median age 50	100.0% male	Regular or long-lasting complaints during the last six months	11 anatomical parts	6-month	6
				At 1-year FU:	At 1-year FU: Median age 51					

				N= 256 R= 34.0%						
Dong et al. (2012)	USA	Unknown	Q	At baseline: N= 616 R= unknown At 16-year FU: N= 364 R= unknown	Mean= 55.46, SE= 0.15 Mean= 70.91, SE= 0.18	90.3% male 90.4% male	Back pain	Back	Point	4.5
Pandey et al. (2012)	India	Managers	Q	N= 22, R= unknown	Mean= 34.4, SD= 9.5	Unknown	Musculoskeletal problem	As per NMQ	1-year	3
Burstrom et al. (2013)	Sweden	Construction workers from multiple trades	I	N= 118,258 R= 80.0%	Mean= 40.6, SD= 13.5	100.0% male	Pain in the upper back and neck that hindered your work	Neck, lower back	1-year	4.5
Meo et al. (2013)	Saudi Arabia	Concrete workers, Electricians, Iron-workers, Laborers, Machine operators, Masons,	Q	N= 389 R= 72.0%	Mean= 34.6, SD= 8.3	100.0% male	Complaints of the musculoskeletal system	Neck, shoulder, upper back, lower back, leg, ankle	Point	6.5

		Plumbers, Supervisors								
Telaprolu et al. (2013)	India	Laborers	I	N= 118 R= 94.4%	Mean= 36.4, SD= 7.8	100.0% female	Musculoskeletal symptoms	As per NMQ	1-year	4
Visser et al. (2013)	The Netherlands	Floor-layers	Postal questionnaire	N= 409 R= 53.0%	Mean= 41.0, SD= 12.0 and mean= 42.0, SD= 13.0 for two types of floor layers	Unknown	Regular/recurring musculoskeletal complaints	As per NMQ	6-month	5
Deros et al. (2014)	Malaysia	Bricklayers, Housekeepers, Plasterers, Skimcoaters	Q	N= 60 R= unknown	Range: 17.0 to 50.0	Unknown	Trouble (ache, pain, discomfort, numbness)	As per NMQ	1-year	3
Ekpenyong et al. (2014)	Nigeria	Bricklayers, Carpenters, Earth-movement laborers, Electricians, Iron-workers	Q+I	N= 1,200 R= 56.0%	Mean= 26.4, SD= 0.4	100.0% male	Musculoskeletal problems that could have prevented their normal activities	Spinal, upper and lower extremities MSS	1-year	6
Hanklang et al. (2014)	Thailand	Iron-workers	Q	N= 272	Mean= 48.2, SD= 9.7	100.0% female	Musculoskeletal pain/symptoms	Neck, shoulders,	1-year	3.5

				R= unknown				wrist/hand, back and knee		
Kim et al. (2014)	USA	Bricklayers, Electricians, Iron-workers, Painters, Pipefitters, Plumbers	Q	N= 1,817 R= 93.6%	Range: 18.0 to 45.0+	95.2% male	Pain, aching, burning, stiffness, cramping, or soreness in your neck more than 3 times or that lasted more than 1 week	Neck, shoulder, hand and back	Over the entire working career	5
Alghadir and Anwer (2015)	Saudi Arabia	Bricklayers, Carpenters, Crane operators, Electricians, Interior finish workers, Laborers, Painters, Plumbers, Scaffolders	I	N= 165 R= unknown	Mean= 34.8, SD= 8.3	100.0% male	Musculoskeletal pain	As per NMQ	1-year	2
Eaves et al. (2016)	UK	Bricklayers, Carpenters, Electricians, Iron-workers,	Q+I	N= 74 R = unknown	Range= under 25.0 to 50.0+	Unknown	Aches and pains in body areas	As per NMQ	1-year	3.5

Joiners,
Laborers,
Painters,
Plasterers,
Plumbers,
Scaffolders,
Welders

Note: FU, follow-up; I, face-to-face interview; MSS, musculoskeletal symptoms; N, number of participants; NMQ, Nordic musculoskeletal questionnaire; Q, questionnaire; R, response rate; SD, standard deviation; SE, standard error; *, it indicates data was calculated from the data provided in the included study; Type of period prevalence refers to the time duration during which the workers suffered from MSS e.g. Point prevalence indicate the prevalence of MSS among workers at the time of data collection for that specific study.

2.3.1 Study characteristics

Four types of study designs were observed in the included studies. Twenty-six studies were cross-sectional studies. One study was a repeated cross-sectional cohort study (Hoonakker and van Duivenbooden 2010). Four studies were case-control studies (Arndt et al. 1996; Burström et al. 2013; Rothenbacher et al. 1997; Ueno et al. 1999), and four were prospective cohort studies (Boschman et al. 2012; Dong et al. 2012; Elders and Burdorf 2004; van der Molen et al. 2009). The included studies comprised 303,384 construction workers in at least 19 different construction trades/specialties from 15 countries. Two cohorts were reported in four distinct included articles (Arndt et al. 1996; Elders and Burdorf 2004; Molano et al. 2001; Rothenbacher et al. 1997). Since none of them reported duplicate data from the same cohort, all four studies were included for review. Most of the included studies were conducted in the USA (n = 9) followed by the Netherlands (n = 7) and India (n = 3) (Table 2.1). Other data were collected from Denmark, Hungary, Iran, Japan, Malaysia, Nigeria, Saudi Arabia, Sweden, Taiwan, Thailand, and the UK (Table 2.1).

The included studies had variable sample sizes, data collection methods, and response rates. The sample size of the included studies ranged from 22 to 118,258 (Burström et al. 2013; Pandey et al. 2012). Of them, 23 (66%) had a sample size of more than 300 participants. Twenty-three included studies used self- or researcher-administered questionnaires to collect prevalence data (Table 2.1). Four studies used face-to-face interviews, three used phone interviews, two used postal questionnaires, and two adopted semi-structured questionnaires for data collection (Table 2.1). Further, one study estimated the prevalence of MSS solely based on physical examination findings (Arndt et al. 1996). Thirteen studies did not report the response rate (Table 2.1). Five studies had a response rate of less than 70%, while 17 studies reported response rates ranging from 70.2% (Kim et al. 2014) to 98% (Caban-Martinez et al. 2010).

The included studies reported divergent types of period prevalence for work-related MSS (Table 2.1). Seven studies exclusively reported point prevalence, two described 6-month, 18 reported 1-year, and one described 2-year prevalence. Two studies revealed prevalence over the entire working career. Only five studies reported two to three types of period prevalence. The case definitions employed by the included studies also varied markedly from subjective pain perception to symptoms that caused the sufferer to seek medical care (Table 2.1).

2.3.2 Study quality

The quality assessment scores varied from a minimum of two (Alghadir and Anwer 2015) to a maximum of eight (Lemasters et al. 1998) with a mean value of 4.9 (1.5) (Table 2.2). Eleven out of 35 included studies (31%) were rated as low-quality (Table 2.2). Overall, the included studies scored well on items related to demographics and work setting description (86%), and the use of a validated questionnaire for data collection (77%). Only five included studies adopted physician examinations of sub-samples to validate the results of self-reported prevalence or used physical examinations as a primary tool for data collection (Arndt et al. 1996; Engholm and Holmström 2005; Lemasters et al. 1998; Meo et al. 2013; Rothenbacher et al.

1997). However, the included studies scored poorly on the description of non-respondents' characteristics (refusers, n= 29) and on the confidence interval of prevalence rate (n= 22) (Table 2.2, Appendix B).

Table 2.2 The quality assessment results of the included studies.

Included studies/ Quality assessment criteria	Study design	Sampling frame	Sample size	Suitable and standard criteria used	Biases possibility in outcome reporting	Adequate response rate & refusers described	95% CI given & sub-group analysis done	Participants demographics and work setting described	Total score
Low-quality studies									
Alghadir and Anwer (2015)	1	0	0	0	0	0	0	1	2
Gilkey et al. (2007)	1	1	0	0	0	0	0.5	0	2.5
Bodhare et al. (2011)	1	0	0	1	0	0	0	1	3
Deros et al. (2014)	1	1	0	1	0	0	0	0	3
Pandey et al. (2012)	1	0	0	1	0	0	0	1	3
Gheibi et al. (2009)	1	0	0	1	0	0	0	1	3
Hanklang et al. (2014)	1	1	0	0	0	0	0	1	3
Caban-Martinez et al. (2010)	1	0	0	1	0	0.5	0	1	3.5
Eaves et al. (2016)	1	0	0	1	0	0	0.5	1	3.5
Telaprolu et al. (2013)	1	0	0	1	0	0.5	0.5	1	4
Rosecrance et al. (2001)	1	0	0	1	0	1	0	1	4
High-quality studies									
Elders et al. (2004)	1	0	0	1	0	0.5	1	1	4.5
Welch et al. (2008)	1	1	1	1	0	0.5	0	0	4.5
Burstrom et al. (2013)	1	1	1	0	0	0.5	0	1	4.5
de Zwart et al. (1999)	1	1	1	1	0	0	1	0	5
Dong et al. (2012)	1	1	1	0	0	0	1	1	5
Goldsheyder et al. (2002)	1	0	1	1	0	0.5	0.5	1	5
Hoonakker and van Duivenbooden (2010)	1	1	1	1	0	0	0	1	5

Kim et al. (2014)	1	1	1	0	0	0.5	0.5	1	5
Molano et al. (2001)	1	0	1	1	0	0.5	0.5	1	5
Ueno et al. (1999)	1	1	1	0	0	0.5	0.5	1	5
van der Molen et al. (2000)	1	1	1	0	0	0.5	0.5	1	5
Visser et al. (2013)	1	1	1	1	0	0	0	1	5
Lee et al. (2005)	1	1	1	1	0	0.5	0	1	5.5
Merlino et al. (2003)	1	1	1	1	0	0.5	0	1	5.5
Ekpenyong et al. (2014)	1	1	1	1	0	0	1	1	6
Rothenbacher et al. (1997)	1	1	1	1	1	0.5	0.5	0	6
Boschman et al. (2012)	1	1	1	1	0	0	1	1	6
Guo et al. (2004)	1	1	1	1	0	0.5	1	1	6.5
Jensen et al. (2000)	1	1	1	1	0	1	0.5	1	6.5
Forde et al. (2005)	1	1	1	1	0	1	0.5	1	6.5
Meo et al. (2013)	1	0	1	1	1	0.5	1	1	6.5
Arndt et al. (1996)	1	1	1	1	1	0.5	1	1	7.5
Engholm and Holmström (2005)	1	1	1	1	1	1	0.5	1	7.5
Lemasters et al. (1998)	1	1	1	1	1	1	1	1	8

Note: CI, confidence interval

2.3.3 Different types of estimated period prevalence of MSS

The included studies reported diverse types of period prevalence and case definitions of MSS (Table 2.2 and 2.3). Since, most studies reported 1-year prevalence using the case definition of having at least one episode of pain/MSS in the last 12 months, only 1-year prevalence of MSS at nine body regions (as described in the Nordic Musculoskeletal Questionnaire) were pooled to calculate the respective mean prevalence. The following section summarizes the most common MSS (two to three body regions) for each period prevalence. The detailed period prevalence rates of MSS in different body regions are presented in Table 2.3.

Table 2.3 Summary of various types of prevalence of musculoskeletal symptoms in the construction industry

	Prevalence (%)								
Region/case	**Point**	**1-week**	**2-week**	**1-month**	**6-month**	**1-year**	**2-year**	**Over the entire career**	**Lifetime**
Neck	5.5 to 22.0[1,2,3]	--	--	--	--	24.4* (10.0 to 38.9)	--	--	--
Chronic	--	17.0[7]	--	--	7.0 to 50.0[11,12]	9.2 to 48.0[7,13]	14.1[17]	30.3 to 39.5[18,19]	--
Activity-	--	--	--	--	--	8.6 to 48.2[7,14,15,16]	--	--	--
Shoulder	10.5 to 28.7[1,3,4]	--	--	6.0 to 7.7[10]	--	32.4* (17.2 to 47.7)	--	--	--
Chronic	--	13.0[7]	--	--	13.0 to 54.0[11,12]	18.4 to 40.0[7,13]	10.7[17]	35.6 to 40.7[18,19]	--
Activity-	--	--	--	--	--	18.0 to 34.0[7,15]	--	--	--
Elbow	12.0[1]	--	--	1.5[10]	--	20.3* (7.7 to 32.9)	--	--	--
Chronic	--	6.0[7]	--	--	9.0 to 28.0[11,12]	18.8 to 24.0[7,13]	9.7[17]	21.2[19]	--
Activity-	--	--	--	--	--	11.0[7]	--	--	--
Wrist/hand	21 to 28.4[1,4]	--	--	1.5[10]	--	30.4* (19.1 to 41.7)	--	--	--
Chronic	--	6.0[7]	--	--	13.0 to 35.0[11,12]	18.8 to 28.0[7,13]	8.3[17]	28.5 to 40.4[18,19]	--
Activity-	--	--	--	--	--	9.0[7]	--	--	--
Upper back	6.2 to 14.0[1,3]	--	--	--	--	19.8* (5.8 to 33.8)	--	--	--
Chronic	--	6.0[7]	--	--	10.0 to 14.0[12]	19.0[7]	14.1[17]	18.1[19]	--
Activity-	--	--	--	--	--	9.0[7]	--	--	--

Lumbar	16.5 to 60.3[1,3,4,5,6,20]	--	--	--	--	51.1* (40.9 to 61.3)	--	--	--
Chronic	--	34.0[7]	--	--	26.0 to 53.0[11,12]	15.7 to 92.0[7,13]	28.7[17]	50.5 to 56.0[18,19]	--
Activity-	--	--	14.0[9]	--	--	24.3 to 42.0[7,9,14]	--	--	54.0[9]
Hip/thigh	11.0[1]	--	--	1.5[10]	--	15.1* (0.5 to 29.7)	--	--	--
Chronic	--	9.0[7]	--	--	6.0 to 53.0[11,12]	7.0 to 23.0[7,13]	3.9[17]	19.6[19]	--
Activity-	--	--	--	--	--	12.0[7]	--	--	--
Knee	22.0[1]	27.0 to 39.0[8]	--	33.8[10]	--	37.2* (22.4 to 52.0)	--	--	--
Chronic	--	15.0[7]	--	--	18.0 to 56.0[11,12]	15.3 to 68.0[7,8,13]	15.0[17]	39.4[19]	--
Activity-	--	--	--	--	--	19.0 to 37.0[7,15]	--	--	--
Ankle/foot	13.4 to 19.0[1,3]	--	--	3.1 to 4.6[10]	--	24.0* (15.2 to 32.8)	--	--	--
Chronic	--	4.0[7]	--	--	0.0 to 48.0[11,12]	4.3 to 17.0[7,13]	8.9[17]	29.4[19]	--
Activity-	--	--	--	--	--	8.0[7]	--	--	--

Note: In each cell, the range of prevalence rate is presented, if possible. * represents the estimated mean 1-year prevalence from meta-analysis. The numbers in the parenthesis represent the 95% confidence interval.

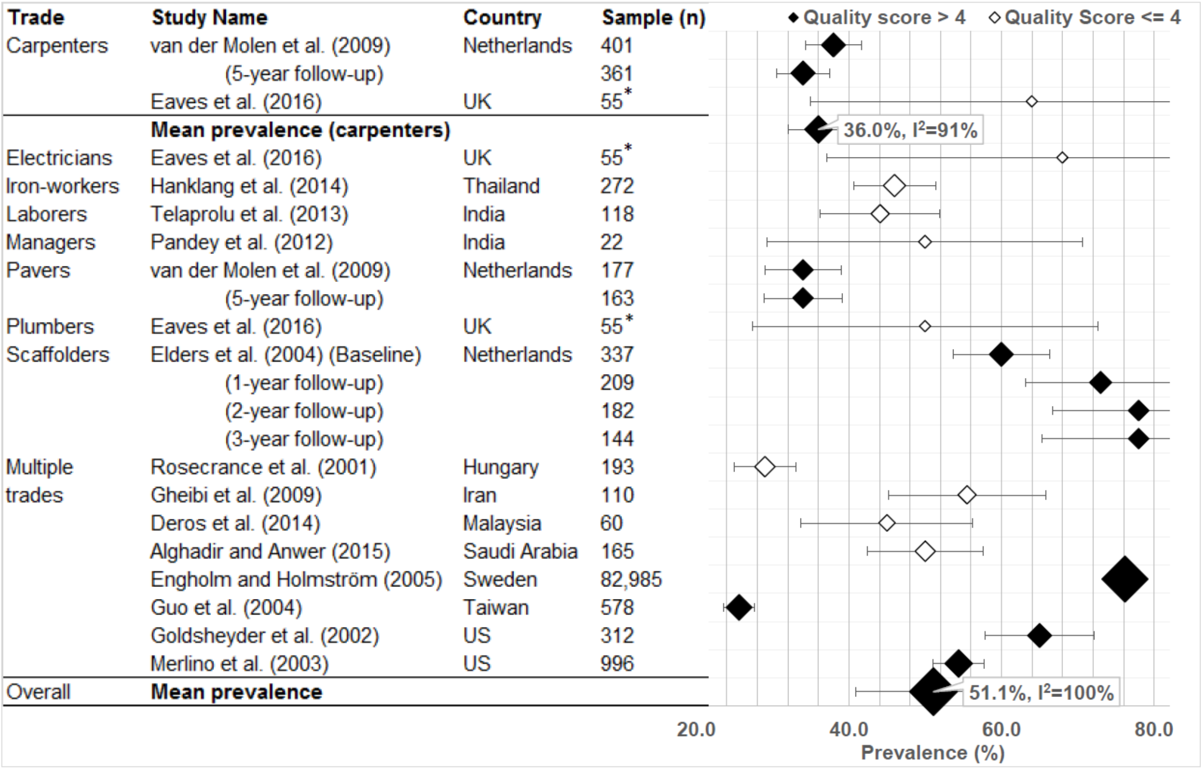
1= (Goldsheyder et al. 2002); 2= (de Zwart et al. 1999); 3= (Meo et al. 2013); 4= (Ueno et al. 1999); 5= (Arndt et al. 1996); 6= (Dong et al. 2012); 7= (Bodhare et al. 2011); 8= (Telaprolu et al. 2013); 9= (Gilkey et al. 2007); 10= (Caban-Martinez et al. 2010); 11= (Boschman et al. 2012); 12= (Visser et al. 2013); 13= (Lemasters et al. 1998); 14= (Burström et al. 2013); 15= (Molano et al. 2001); 16= (Ekpenyong and Inyang 2014); 17= (Welch et al. 2008); 18= (Kim et al. 2014); 19= (Forde et al. 2005); 20= (Rothenbacher et al. 1997)

Seven studies reported point prevalence of MSS among construction workers (Table 2 and 3) with lumbar, neck and lower limb MSS being the most common ones. In the USA, the point prevalence of lumbar pain/MSS ranged from 33% to 39%, while neck and knee MSS were also common with a prevalence rate of 22% each (Dong et al. 2012; Goldsheyder et al. 2002). In Saudi Arabia, the most common MSS were legs, lumbar and foot with the estimated point prevalence rates of 23.9%, 16.5% and 13.4%, respectively (Meo et al. 2013). A Japanese study involving multiple construction trades reported that the point prevalence rates of lumbar and shoulder MSS were substantial with the respective estimated rates of 53.2% and 28.7% (Ueno et al. 1999). Likewise, the point prevalence of self-reported back pain ranged from 47.8% to 60.3% among German construction workers whereas another German study entailing physical examination/diagnosis revealed a slightly lower prevalence of back MSS (32.5%) (Arndt et al. 1996; Rothenbacher et al. 1997). Similarly, back MSS is the most noteworthy MSS among Dutch construction workers. The point prevalence rates of back MSS among young and older workers were 25.0% and 43.8%, respectively (de Zwart et al. 1999).

Two studies reported 1-week prevalence of MSS while one reported the 2-week prevalence (Table 2.3). Two most prevalent recurring MSS were found at lumbar and neck regions among Indian construction workers with estimated 1-week prevalence rates of 34% and 17%, respectively (Bodhare et al. 2011). Conversely,.MSS in the knee region was the most common type among Danish floorlayers and carpenters in the last 7 days, with prevalence rates of 39% and 27%, respectively (Jensen et al. 2000). Additionally, the 2-week prevalence of activity-limiting lumbar MSS was 14% among American carpenters (Gilkey et al. 2007).

Only one study reported the 1-month and 3-month MSS prevalence while two reported 6-month MSS prevalence rates of different body regions (Table 2.3). Caban-Martinez et al. (2010) estimated the 1-month pain/MSS prevalence of knee (33.8%), shoulder (6.2% to 7.7%), and ankle (3.1% to 4.6%) among Hispanic-American construction workers. Additionally, their reported 3-month prevalence of all day lasting lumbar pain was 63%. The two most prominent regular/recurring MSS in sand-cement-bound and anhydrite-bound screed Dutch floorlayers were lumbar and shoulder MSS with 6-month prevalence rates of 39% and 27%; and 26% and 13%, respectively (Visser et al. 2013). A prospective Dutch survey on bricklayers also revealed that the 6-month prevalence rates of recurring MSS were 42% for back and 27% for the knee at baseline, while the respective rates at 1-year follow-up were 53% and 56% (Boschman et al. 2012).

The pooled mean 1-year prevalence rates of MSS (defined as at least one episode of pain/MSS in the last 12 months) are shown in Figure 2.2 and Appendix C. The estimated mean 1-year prevalence rates were 51.1% for the lumbar region (95% confidence interval (CI): 40.9% to 61.3%, from 19 estimates, Figure 2.2), 37.2% for knee (95% CI: 22.4% to 52.0%, from 13 estimates), 32.4% for shoulder (95% CI: 17.2% to 47.7%, from 10 estimates), 30.4% for wrist (95% CI: 19.1% to 41.7%, from 9 estimates), 24.4% for neck (95% CI: 10.0% to 38.9%, from 12 estimates), 24.0% for ankle/foot (95% CI: 15.2% to 32.8%, from 7 estimates), 20.3% for elbow (95% CI: 7.7% to 32.9%, from 6 estimates), 19.8% for upper back MSS (95% CI: 5.8% to 33.8%, from 6 estimates) and 15.1% for hip/thigh (95% CI: 0.5% to 29.7%, from 5 estimates) (Table 2.3, Appendix C).



Trade	Study Name	Country	Sample (n)
Carpenters	van der Molen et al. (2009)	Netherlands	401
	(5-year follow-up)		361
	Eaves et al. (2016)	UK	55*
	Mean prevalence (carpenters)		
Electricians	Eaves et al. (2016)	UK	55*
Iron-workers	Hanklang et al. (2014)	Thailand	272
Laborers	Telaprolu et al. (2013)	India	118
Managers	Pandey et al. (2012)	India	22
Pavers	van der Molen et al. (2009)	Netherlands	177
	(5-year follow-up)		163
Plumbers	Eaves et al. (2016)	UK	55*
Scaffolders	Elders et al. (2004) (Baseline)	Netherlands	337
	(1-year follow-up)		209
	(2-year follow-up)		182
	(3-year follow-up)		144
Multiple trades	Rosecrance et al. (2001)	Hungary	193
	Gheibi et al. (2009)	Iran	110
	Deros et al. (2014)	Malaysia	60
	Alghadir and Anwer (2015)	Saudi Arabia	165
	Engholm and Holmström (2005)	Sweden	82,985
	Guo et al. (2004)	Taiwan	578
	Goldsheyder et al. (2002)	US	312
	Merlino et al. (2003)	US	996
Overall	**Mean prevalence**		

Figure 2.2 The 1-year prevalence of lumbar MSS in different construction trades

Three studies reported 1-year prevalence rates of various chronic MSS (Tables 2.1 and 2.3). Notably, chronic elbow and wrist MSS (18.8%), and chronic shoulder MSS (18.4%) were commonly found among American carpenters (Lemasters et al. 1998). For Indian construction workers, 1-year prevalence rates of chronic lumbar, neck and knee MSS were substantial with estimated rates of 92.0%, 48.0% and 47.0%, respectively (Bodhare et al. 2011). Additionally, 1-year prevalence rates of chronic knee MSS among Danish floorlayers and carpenter were 56.4% and 68.0%, respectively (Jensen et al. 2000).

Five studies reported the 1-year prevalence of activity-limiting MSS but the prevalence rates varied among populations (Tables 2.1 and 2.3). The estimated 1-year prevalence rate of activity-limiting lumbar MSS was 38.0% among American carpenters (Gilkey et al. 2007), while those of lumbar and neck MSS in Swedish construction workers were 24.3% and 8.6% respectively

(Burström et al. 2013). Among Indian construction workers, 1-year prevalence rates of activity-limiting MSS in lumbar (42.0%) and neck (21.0%) regions were most notable (Bodhare et al. 2011). Similarly, the 1-year prevalence of activity-limiting MSS among Nigerian construction workers were 48.2%, 26.5% and 25.3% for neck and upper limb, lower limb, and trunk and waist, respectively (Ekpenyong and Inyang 2014). Further, the two most common MSS that limited activity of Dutch scaffolders for several hours over the last 12 months were back (60.0%) and knee (37.0%) (Molano et al. 2001).

One study investigated two-year prevalence rates of MSS that required medical assistance in US roofers (Welch et al. 2008). It showed that lumbar (28.7%) and knee (15.0%) were most affected (Table 2.3). Two studies investigated the prevalence of chronic MSS over the entire career of construction workers. Specifically, chronic lumbar (56.0%), wrist/hand/finger (40.4%), and knee (39.4%) MSS were most prevalent among US iron-workers (Forde et al. 2005). Similarly, prevalence rates of chronic back (50.5%) and shoulder MSS (40.7%) were eminent in American construction apprentices thoughout their entire career (Kim et al. 2014). Additionally, Gilkey et al. (2007) found that the lifetime prevalence of activity-limiting lumbar MSS in US carpenters was 54.0%.

2.3.4 Trade-specific analysis

Many included studies did not provide stratified prevalence data that hampered comparison among various trades. Only 16 studies reported trade-specific MSS prevalence (Arndt et al. 1996; Boschman et al. 2012; Eaves et al. 2016; Ekpenyong and Inyang 2014; Elders and

Burdorf 2004; Forde et al. 2005; Gilkey et al. 2007; Hanklang et al. 2014; Jensen et al. 2000; Lemasters et al. 1998; Molano et al. 2001; van der Molen et al. 2009; Rothenbacher et al. 1997; Ueno et al. 1999; Visser et al. 2013; Welch et al. 2008). Unfortunately, given the divergent reports of period prevalence and inconsistent definitions of body parts and cases, no meta-analysis was conducted for each trade. Two studies found that lumbar pain was the most prevalent MSS among bricklayers (Boschman et al. 2012; Rothenbacher et al. 1997), although others reported that neck, upper limb, and legs MSS were predominant in bricklayers (Arndt et al. 1996; Ekpenyong and Inyang 2014). Similarly, lumbar MSS were the most ubiquitous in carpenters (Arndt et al. 1996; Eaves et al. 2016; Gilkey et al. 2007; van der Molen et al. 2009; Ueno et al. 1999), while MSS of knee (Rothenbacher et al. 1997) and upper extremity (e.g. wrist and elbow) (Ekpenyong and Inyang 2014; Lemasters et al. 1998) were also common. For electricians, MSS of lumbar (Burström et al. 2013; Ueno et al. 1999) and upper extremity (Ekpenyong and Inyang 2014) were most common. Similarly, MSS of lumbar (Visser et al. 2013) and knees (Jensen et al. 2000) were most prevalent among floorlayers. For iron-workers, lumbar (Forde et al. 2005; Ueno et al. 1999), wrist and shoulder (Ekpenyong and Inyang 2014; Hanklang et al. 2014) MSS were mostly reported. Likewise, plumbers mostly suffered from back (Arndt et al. 1996; Rothenbacher et al. 1997; Ueno et al. 1999), wrist and knees (Eaves et al. 2016) MSS. Additionally, lumbar pain (Arndt et al. 1996; Rothenbacher et al. 1997; Ueno et al. 1999) was prominent in laborers, painters, plasterers, pavers (van der Molen et al. 2009), roofers (Welch et al. 2008) and scaffolders (Elders and Burdorf 2004).

2.3.5 Gender analysis

There is a paucity of studies that reported gender-specific MSS prevalence. Thirteen out of the 35 included studies did not report the gender composition within the sample population (Table 2.1). Eight included studies recruited more than 85% of male participants. Two solely enrolled women construction workers (Hanklang et al. 2014; Telaprolu et al. 2013). Only two studies provided gender-segregated MSS prevalence data (Guo et al. 2004; Merlino et al. 2003). Both found that females had significantly higher 1-year prevalence of MSS (difference ranging from 0.9% in wrist to 30.1% in shoulder) as compared to their male counterparts.

2.3.6 Age-stratified analysis

Since the included studies used variable age group stratification methods, study designs and statistical analyses, no meta-analysis was conducted. The age range of construction workers in the included was large, ranging from a mean age of 17 (Rosecrance et al. 2001) to 71 years (Dong et al. 2012). Most studies reported both mean and standard deviation of participants' age, while only a few reported age ranges (Table 2.1).

Nine of the included studies provided age-stratified analysis on prevalence data of MSS in construction workers (Alghadir and Anwer 2015; Bodhare et al. 2011; Eaves et al. 2016; Hoonakker and van Duivenbooden 2010; Jensen et al. 2000; Telaprolu et al. 2013; Ueno et al. 1999; Welch et al. 2008; de Zwart et al. 1999). Five of them found no significant association between stratified age groups and MSS prevalence (Alghadir and Anwer 2015; Eaves et al. 2016; Jensen et al. 2000; Telaprolu et al. 2013; Welch et al. 2008). Conversely, one study proclaimed a trend of increasing MSS prevalence with age although no detailed statistical result was reported (Hoonakker and van Duivenbooden 2010). The remaining three studies found significant positive associations between age and point (Ueno et al. 1999; de Zwart et al. 1999) or 1-year (Bodhare et al. 2011) MSS prevalence.

Additionally, four studies investigated the relation between age and prevalence of MSS without using stratified age data. Three studies reported positive associations between age and MSS prevalence. Specifically, a longitudinal study reported a significant increase in the prevalence of low back pain over a 15-year period although the results were confounded by workers` job history and job exposures (Dong et al. 2012). Another study found that older Nigerian workers doubled the odds of suffering from work-related MSS than their younger counterparts (Ekpenyong and Inyang 2014). An Iranian study also found significant positive association between workers' age and MSS prevalence (Gheibi et al. 2009). However, a study on US ironworkers found that older age was significantly associated with a lower risk of lumbar MSS after adjusting for prior injuries and work duration (Odds ratio: 0.97) (Forde et al. 2005).

2.4 DISCUSSION

This is the first systematic review to synthesize the prevalence of MSS in the construction industry. Although 35 articles were included, their heterogenous period prevalence rates and case definitions prevented the meta-analysis of each period prevalence except for 1-year prevalence (defined as at least one episode of pain/MSS in the last year). Nevertheless, the meta-analysis showed that lower back had the highest mean 1-year prevalence of MSS (51.1%) among construction workers while hip/thigh had the lowest one (15.1%). Collectively, findings from different types of period prevalence consistently suggested that construction workers most commonly suffer from lumbar, knee, shoulder and wrist MSS.

While subgroup analyses were planned for MSS prevalence of all available construction trades, the lack of relevant information prevented these analyses. Intuitively, the prevalence of MSS is related to work conditions, work-related risk factors, cultures, and personal characteristics. For example, Asian construction workers prefer to squat during work as compared to those in western countries (Chung et al. 2003; Jung and Jung 2008), which may affect their body biomechanics (Umer et al. 2017b) and predispose them to task-specific MSS. Since certain work-related tasks (e.g. frequent bending and twisting, whole-body vibration and carrying load) may increase the risk of lumbar MSS, proper ergonomic interventions should be implemented to reduce the occurrence of lumbar MSS (Burdorf and Sorock 2016). Imperatively, the current review only identified a few studies reporting MSS prevalence in individual construction trades. Therefore, there is an urgent need to investigate MSS prevalence in different trades so that trade-specific prevention/treatment strategies can be developed and implemented.

While only two studies reported MSS prevalence of both genders in the construction industry (Guo et al. 2004; Merlino et al. 2003), both indicate that female workers are more susceptible to MSS. Although speculative, this phenomenon may be attributed to differences in between-gender physique (e.g. lower muscle strength in females) (Miller et al. 1993), genetic pain coping (Bartley and Fillingim 2013), or the higher reliance on male anthropometric data for designing workspace/tools (Pheasant 1996). Importantly, with the increasing global trend of female participation in the labor force (Kinoshita and Guo 2015), it is crucial for stakeholders to investigate causes underlying differential MSS prevalence, and adopt preventive measures to minimize the risk of work-related MSS in both genders.

The current review highlights an age-related MSS trend that deserves further investigation. Thirteen included studies examined the relation between ages of construction workers and MSS prevalence with or without providing age-stratified prevalence data. Six of them concluded a non-significant association between the two variables (Alghadir and Anwer 2015; Eaves et al. 2016; Forde et al. 2005; Jensen et al. 2000; Telaprolu et al. 2013; Welch et al. 2008), while seven found a significant association between them (Bodhare et al. 2011; Dong et al. 2012; Ekpenyong and Inyang 2014; Gheibi et al. 2009; Hoonakker and van Duivenbooden 2010; Ueno et al. 1999; de Zwart et al. 1999). Despite the inconsistent findings, it cannot downplay the importance of clarifying the association between age and work-related MSS in construction workers. It is known that the proportion of older workforce is increasing in many industrialized countries (Samorodov 1999). Older workers commonly experience decline in physical work capacity (Kenny et al. 2008), cardiac output (Fitzgerald et al. 1985), muscle strength and mass (Thomas 2010). Physical decline alongside the presence of MSS will increase the risk of work injury in older workers who usually have higher rehabilitation demands (Schwatka et al. 2012). Importantly, literature suggests that previous occupational biomechanical exposures (e.g. twisting and bending) can increase the risk of future episodes of low back pain in older/retired workers (Plouvier et al. 2015). Accordingly, future studies should clarify the relation between age and work-related MSS, and develop strategies to minimize the propensity of MSS in older workers.

2.5 LIMITATIONS

Like other reviews, this study has several limitations. First, given the heterogeneous populations, case definitions, work-tasks and study designs of the included studies, the estimated 1-year prevalence should be interpreted with caution. Specifically, the current meta-analysis defined pain cases as having at least one episode of pain/MSS in the last year. The use of such a lenient case definition for meta-analysis without considering other factors (e.g., pain intensity, frequency, duration, work-related disability, or work absence) might have limited the generalizability of the meta-analysis results (Bedouch et al. 2012). Previous epidemiological research has shown that using different case definitions (e.g. based on pain intensity or frequency) to evaluate the MSS prevalence of a given population would lead to different conclusions (Beaton et al. 2000; Hegmann et al. 2014; Village 2000). Although using a more specific case definition (Table 2.1) in the current meta-analysis could have improved the generalizability and homogeneity of findings specific to the case definition, such approach would have also excluded many primary studies from the meta-analysis. To improve future meta-analyses, future epidemiological studies should use standardized case definitions to evaluate the prevalence of MSS in the construction industry. Second, since many included studies adopted self-reported prevalence without validated medical examinations, their reported prevalence might have been underestimated/overestimated. Third, 29 out of the 35 included studies did not report non-respondents' characteristics, which might represent a group with distinct MSS prevalence. Fourth, since included studies used inconsistent study protocols and period prevalence, future studies should adopt standardized measurement tools and study protocols to enable between-study comparisons.

2.6 IMPLICATIONS

Despite the limitations, this review has strong implications for construction managers, ergonomists, policy makers and researchers. The results signify that more than half of the construction workforce face lumbar MSS, nearly one-third of them face knee, shoulder and wrist MSS annually. These figures underscore the necessity of deriving relevant policies and developing/implementing effective prevention strategies to attenuate the prevalence of work-related MSS in the construction industry.

CHAPTER 3

IDENTIFICATION OF BIOMECHANICAL RISK FACTORS FOR THE DEVELOPMENT OF LOW BACK DISORDERS DURING MANUAL REBAR TYING[2]

3.1 INTRODUCTION

Musculoskeletal disorders (MSDs) are prevalent in construction industry (Boschman et al. 2012). Approximately 33% of annual work absenteeism in the American construction industry are related to MSDs (BLS 2013). Compared to workers in different construction trades, rebar workers are at a higher risk of experiencing low back disorders (LBDs) (Albers and Hudock 2007). Hunting et al. (1999) reported that low back injuries were the most prevalent musculoskeletal injuries in rebar workers. Likewise, another survey on 981 American rebar workers revealed that the prevalence of low back problems was the highest (56%) among all reported MSDs (Forde et al. 2005).

The high prevalence of LBDs in rebar workers may be attributed to their prolonged non-neutral trunk working posture. An early observational study (Burdorf et al. 1991) revealed that rebar workers in the precast unit of five construction sites worked in non-neutral postures for 37% of the total observation time. Similarly, other observational studies found that rebar workers at

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[2] This chapter is based on a published study and being reproduced with the permission of ASCE.
Umer, W., Li, H., Szeto, G. P. Y., and Wong, A. Y. L. (2017). "Identification of Biomechanical Risk Factors for the Development of Lower-Back Disorders during Manual Rebar Tying" *Journal of Construction Engineering and Management* 143(1).

different construction projects maintained non-neutral trunk postures for approximately 40% to 48% of their working time (Buchholz et al. 2003; Forde and Buchholz 2004). Since working in a static extreme trunk flexion (Solomonow et al. 2003) or in a non-neutral trunk posture for more than 10% of the working time (Punnett et al. 1991) will increase the risk of developing LBDs, rebar workers are prone to LBD development.

While the absolute low back loads of rebar workers may not be substantial, their prolonged static working postures may pose threat for LBDs. Albers and Hudock (2007) estimated that low-back compression load at the L5/S1 joint was lower than the NIOSH (The National Institute for Occupational Safety and Health) defined hazardous load of 3400N during the rebar work on a bridge. However, performing repetitive rebar works in a severely flexed trunk posture throughout the day may lead to high cumulative forces over the years, which will increase the risk of developing LBD (Coenen et al. 2013; Marras et al. 2010; Seidler et al. 2001).

More importantly, workers with prior low back injuries are prone to recurrent LBDs. Forde et al. (2005) found that rebar workers with a previous low-back injury were 6.7 times more prone to LBDs. As such, proper ergonomic intervention is warranted (Forde et al. 2005). Unfortunately, since prior ergonomic studies on rebar workers only used observation approach to assess rebar workers' working postures, they could not provide quantifiable data to understand the biomechanical characteristics of rebar works (e.g. range of movements or muscle activity), which are essential for the evaluation of temporal changes in biomechanical risk factors following ergonomic interventions.

3.2 APPLICATION OF ERGONOMIC ASSESSMENT METHODS IN THE CONSTRUCTION INDUSTRY

Four assessment techniques have been adopted to examine ergonomic risk factors of construction workers in the research literature: 1) self-reported, 2) observation-based, 3) camera-based, and 4) direct measurements. Self-reported technique involves distributions of questionnaires to workers to assess their MSDs or conduction of face-to-face interviews by an investigator. However, since this method relies on subjective (self-reported) assessments, it is subjected to biases (e.g. recall bias).

Observation-based technique requires an experienced observer to use a work-sampling technique to evaluate the relative positions of various body segments of a worker in order to estimate the potential ergonomic risk factors for developing MSDs (Buchholz et al. 1996; Hajaghazadeh et al. 2012; Mebarki et al. 2015). This technique is common in ergonomic research because it involves minimum disturbance to the worker, and does not require sophisticated equipment. Unfortunately, this method relies heavily on the observer's experience and judgement, and the inter-rater reliability of this assessment is questionable.

Camera-based approach has been used to identify occupational hazards and unsafe postures at construction sites (Ray and Teizer 2012; Seo et al. 2014; Starbuck et al. 2014). While camera-based assessments allow remote analysis of construction tasks without disturbing the work process, it is prone to occlusion and requires direct line of sight for proper recording. Further, this approach cannot differentiate whether a person is standing stably or is struggling to regain balance (Chen et al. 2014). Additionally, those depth cameras cannot work properly to detect postures of construction workers under bright light conditions (Chen et al. 2014).

Direct measurement technique includes attachments of sensors or devices to the worker in order to identify potential risk factors of MSDs in both laboratory and work field environment. Cheng et al. (2012) and Gatti et al. (2010) used physiological status monitoring devices to measure heart rate and torso angle in addition to real-time location of construction workers in a laboratory environment. Alwasel et al. (2013) devised joint angle measurement devices to monitor MSDs risk factors for construction workers. Jebelli et al. (2012) and Yang et al. (2014) used inertial measurement units to identify near-miss fall incidents and assessment of fall risks for construction activities in a laboratory setting. Recently, Chen et al. (2014) presented a framework by fusing inertial measurement units with Kinect to detect hazards during construction activities like lifting and carrying loads. While this technique might help identify work-related risk factors for MSDs, no research has adopted this technique to assess ergonomic risk factors of rebar workers.

3.3 CURRENT UNDERSTANDING OF ERGONOMIC RISK FACTORS IN REBAR WORK

While there is no guideline regarding the optimal working postures for rebar workers, the International Organization for Standards (ISO) has published standards regarding the optimal static working posture to minimize the risk of developing MSDs in healthy adults (ISO 11226:2000) . The standards specify the safe limits for the angles of various body parts, and their respective holding times for static working postures involving no or minimal external forces at the job sites.

Although the ISO standards for optimal static working postures can be applied to rebar workers, prior research approaches (using questionnaires or observation-based method) could not quantify the actual postures of rebar works (Marras et al. 2010). Therefore, it remains unclear whether certain rebar works (e.g. rebar tying) meet the ISO standards for optimal static working postures. Additionally, since previous research only considered trunk posture of rebar workers in the sagittal plane, other potential risk factors for LBDs (e.g. the lateral movement/axial rotation of the trunk, or the trunk muscle activity during rebar works) have yet been studied. Importantly, although the analysis of trunk inclination angles provides the kinematic data of a given working posture, it is recommended to analyze the concurrent trunk muscle activity in order to help understand the effects of a particular construction activity on the corresponding spinal biomechanics or future MSD development (Wang et al. 2015a).

Given the above, it is essential to use quantitative biomechanical assessments to measure both joint motions (kinematics) and muscles` activity (kinetics) during the high-risk rebar work so as to identify the risk factors for LBD development in these workers. Although previous research has identified rebar tying as the high risk task for LBD development, different rebar workers may adopt many different postures during rebar typing.

In order to identify the common working postures during rebar tying, several site visits were conducted locally. Three typical postures were identified: stooping, one-legged kneeling and squatting position (see Figure 3.1: (a), (b), and (c)). These observed working postures differ from those reported in literature. Specifically, workers in western countries mainly perform the task using tools in standing or stooping with full trunk flexion, while Asian workers commonly squat during rebar tying. Of the three working positions, squatting was the most commonly observed one during the site visits conducted. On average, a worker could stay in the squatting position for 3 to 4 hours in an 8-hour shift. The second most commonly observed posture was stooping followed by one-legged kneeling.

Since the observed static awkward postures during rebar tying may impose considerable risks for developing LBDs, it is imperative to conduct a biomechanical analysis to compare the respective kinetic and kinematic data so as to guide the future ergonomic intervention. Given the complexity and variability of the construction site environment, laboratory research is considered to be an appropriate first step to examine work-related biomechanics within a standardized and controlled environment prior to conducting subsequent field study.

Given the above, the objective of the current study was to compare the differences in trunk biomechanical characteristics of the three postures during simulated rebar typing in a laboratory setting.

(a) Stooping (b) One-legged kneeling (c) Squatting

Figure 3.1 Three postures of rebar tying

3.4 METHODS

3.4.1 Participants

Ten healthy male participants aged between 18 and 60 years were recruited from the Hong Kong Polytechnic University using convenient sampling. Exclusion critiera were a history of low back pain, the Oswestry Disability Index $\geq$ 20%, and low back pain intensity > 2 out of 10 on an 11-point numeric pain rating scale where 0 means no pain and 10 means the worst imaginable pain (Wong et al. 2015a). Before the data collection, experimental procedures were explained to the participants and their written consent was obtained.

3.4.2 Experimental design and setup

This is a cross-sectional study. Participants were instructed to perform simulated rebar typing tasks in three working postures (stooping, one-legged kneeling and squatting) in a laboratory.

The participants were instructed to kneel on the right knee for the one-legged kneeling task. Ten plastic pipes of 2 cm diameter were arranged in form of a mesh (Figure 3.2). The spacing between pipes were set to 12 cm center-to-center. Spacers were used to provide concrete cover of 4 cm as depicted in the simulation setup.

The participants had to complete 2 sets of rebar tying in the front 3 rows of the simulation setup while they should keep their feet within a defined area (40cm by 50cm) located at one side of the pipe mesh setup. The same procedure was repeated for each of the three postures. It took on average approximately 6 to 8 minutes to complete the rebar tying in a given posture. The sequence of the postures was randomized for all participants. A 5-minute break (decided based on pilot tests) was given between different postures to prevent fatigue. An 11-point numeric pain rating scale was used to collect subjective perception of pain at different body parts before, and after performing the rebar tying in each posture. A body diagram was used to facilitate the participants in describing the pain at different body regions.

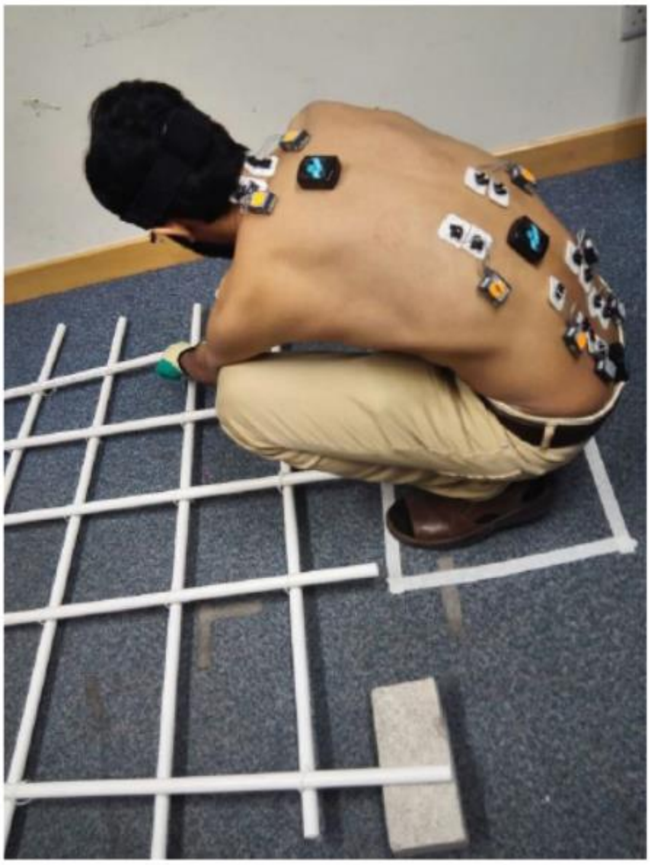

Figure 3.2 Rebar tying simulation setup. Participants performed the task while keeping their legs within the assigned area

3.5 DATA ACQUISITION

3.5.1 Kinematics measurements

The Noraxon MyoMotion system (Noraxon, USA) was used to capture the spinal motions in three dimensions. Three inertial measurement unit motion sensors were attached to the T4, T12, and S1 levels (Figure 3.3). The kinematics data was captured at a rate of 100 Hz. Inertial measurement units are small and portable devices (often termed as motion sensors) that estimate spatial orientation of a body segments by combining the outputs of multiple electromechanical sensors (accelerometers, gyroscopes, and/or magnetometers) through specific sensor fusion algorithms. Such algorithms can overcome the limitations of each individual sensor component and provide more precise motion tracking. Thoracic kinematics were defined by the relative movement between the sensors placed between the T4 and T12 levels, while lumbar kinematics were defined by the relative movement between the sensors placed between the T12 and S1 levels (Figure 3.3). At the beginning of the session, a physiotherapist guided the participant to maintain an erect standing posture. In this position, all the spinal angles of the participant were calibrated as the “zero” degree reference of the spinal segments in the three Cartesian planes. All the subsequent movement data were referenced to the “zero” degrees.

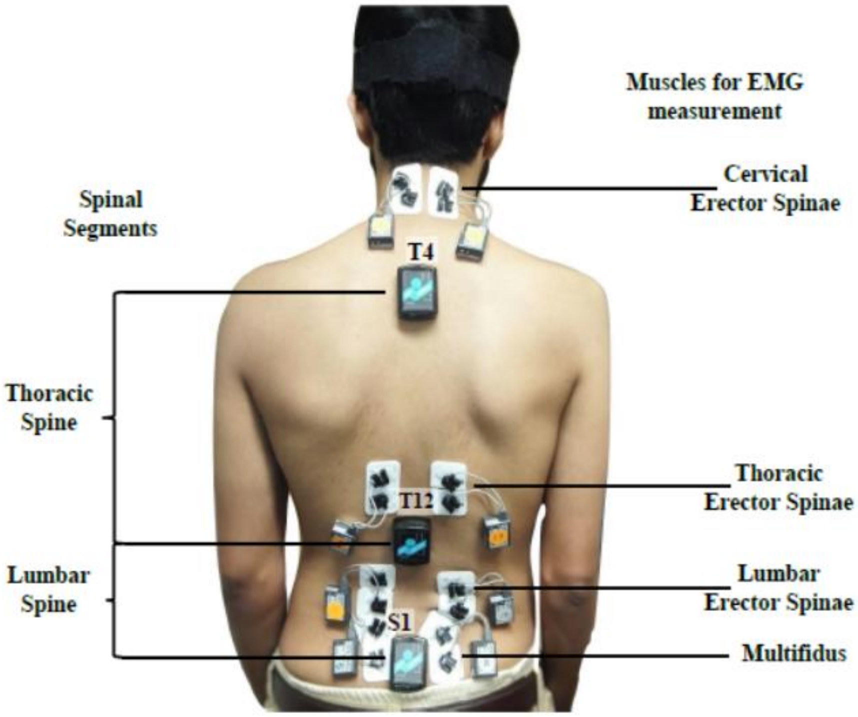

Figure 3.3 Spinal segments, surface EMG electrodes and motion sensors placement

3.5.2 Measurements of surface electromyography (sEMG)

A 16-channel wireless Noraxon TeleMyo sEMG system (Noraxon USA Inc., USA) was used to record the muscle activities of the rebar workers. Standardized skin cleansing procedures (use of sand paper, alcohol swabs and shaving if necessary) were used to minimise the impedance of surface electrodes to below 10 kΩ levels (Xie et al. 2016). The data was recorded at a sampling frequency of 1500 Hz whereas CMRR was 100db. Eight pairs of electrodes were attached to the bilateral erector spinae (ES) at the cervical, thoracic spine and lumbar spine, as well as at bilateral multifidus muscles (Figure 3.3, Table 3.1). The surface electrodes were 15mm in diameter with inter-electrode distance of 20mm. The erector spinae and multifidus muscles were examined as they directly impact the load on the spine (Jin et al. 2009; Wang et al. 2015b).

Table 3.1 Muscle action and electrode placement

Muscle	**Electrodes Location**	**Muscle`s action**
Cervical Erector Spinae	2cm laterally from C5 level	Extension of the neck
Thoracic Erector Spinae	5cm laterally from T9 level	Extend /Maintain thoracic lumbar against gravity or applied load
Lumbar Erector Spinae	5cm laterally from L3 level	Extend /Maintain lower back against gravity or applied load
Multifidus	2cm laterally from L4 level	Maintain lumbar spine segmental stability

Upon completion of the simulated rebar tasks, the participant was instructed to perform maximum voluntarily contractions (MVCs) of various erector spinae and multifidus muscles. Specifically, the prone participant was instructed to maximally extend the trunk and neck against manual resistance for 5 seconds (Konrad 2005). Three 5-second MVCs were performed for each target muscle while the corresponding sEMG signals were collected. A 20-second rest was given between MVCs (Hong et al. 2008). The maximum sEMG signal of each target muscle was identified using a 1000ms moving window passing through the three MVCs, and this value was adopted as the 100% MVC to which the experimental data were normalised. The technical data acquired in the current experiment are summarized in Table 3.2.

Table 3.2 Summary of data acquired in the experiment

Types of data collected	**Measurement method**
Muscle activity from bilateral cervical erector spinae, thoracic erector spinae, lumbar erector and multifidus muscles	Wireless surface electromyography sensors
Flexion/extension, lateral bending and axial rotation angles of the thoracic and lumbar spine	Wireless motion sensors
Subjective pre and post rebar tying pain score	11-point numeric pain rating scale

3.6 DATA ANALYSIS

Kinematics data from the motion sensors and kinetics data from sEMG were synchronized using Noraxon MR3.8 (Noraxon USA Inc., USA) software, which was also used for offline data analysis.

Kinematics data was processed without any smoothing or filtering. Positive and negative values of kinematics data denoted opposite directions. Flexion and extension were considered as positive and negative, respectively. Right and left lateral bending in the frontal plane were termed as positive and negative, respectively. Similarly, clockwise and counter clockwise rotation were labelled as positive and negative, respectively (Figure 3.4).

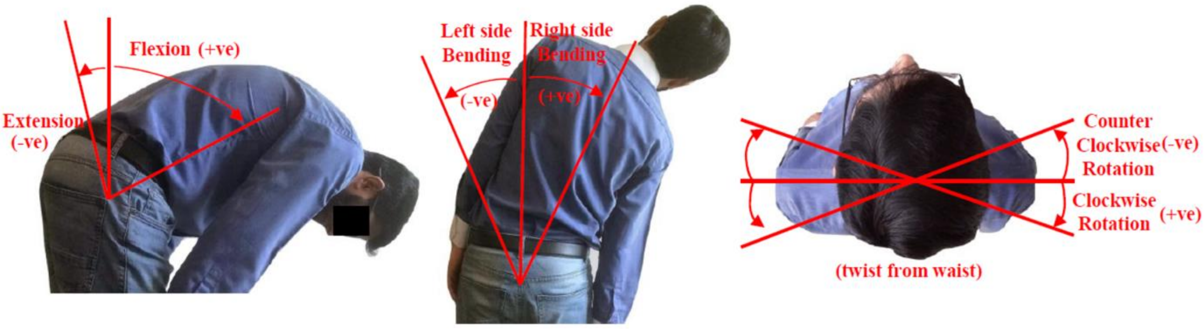

Figure 3.4 Trunk movements in the three cartesian planes

The raw sEMG data was processed by the Finite Impulse Response filter to remove electrocardiography signal. The signals was also bandpass filtered between 20 Hz and 250 Hz to remove the noise associated with biological and non-biological artefacts, and a notch filter was used to remove the electronic noise at 50 Hz. Then the signal was full-wave rectified and smoothen using 50 ms mean window. The resulting sEMG data of each muscle collected during the three experimental trials was normalized to the respective sEMG values during MVCs and averaged. The sEMG activity from each pair of bilateral muscles were averaged for analysis because Wilcoxon signed-rank tests indicated no significant difference between left and right side sEMG values except for the thoracic ES muscles, which showed greater right side activity than left side in all postures. Separate analyses of median left and right thoracic ES sEMG values were done to compare the activity of these muscles in the three postures. However no significant difference was seen across the three postures. As such, only averaged muscle activity for all bilateral muscles are reported in this chapter.

Amplitude Probability Distribution Function (APDF) was used to study the amplitude variations of kinematics and kinetics data during the three work tasks (Szeto et al. 2005). The 10th percentile, 50th percentile (median) and 90th percentile were computed for APDF as the representative data collected for the experiments. The 50th percentile is used as an indicator of the average value of a given dependent variable during the data collection period in each posture, whereas the difference between 10th and 90th percentiles is a measure of range of movements of joint segment kinematics during the data collection period in a given posture.

3.6.1 Statistical analysis

Repeated measures analyses of variance were used to examine differences between dependent variables (kinematics or kinetic data) in three different tying postures. Specifically, the posture during the simulated rebar work was chosen as the independent variable whereas APDF data for sEMG and spinal movements were the dependent variables. Post-hoc pairwise comparisons were conducted with Bonferroni adjustment. Spearman rank correlation tests were planned to investigate the correlations between the highest thoracic/low back pain intensity and the corresponding median trunk angles or average normalized sEMG activity of each trunk muscle during each of the three postures. The significance value was set at $p < 0.05$. SPSS version 19.0 (IBM, NY, USA) was used for all of the statistical analysis.

3.7 RESULTS

Ten male volunteers were recruited from the Hong Kong Polytechnic University (mean age: 28.9±4.1 years; mean body mass index: 23.36±2.80 kg/m^2). Their mean Owestry Disability Index score was 5.64±4.90%. Three participants reported mild bilateral knee pain after the stooping posture (mean score 1.2 out of 10). All participants reported mild to moderate right knee pain (mean score 3.7 out of 10) after the one-legged kneeling except one participant. Seven participants complained of mild bilateral knee pain (mean score 2.9 out of 10) in squatting posture. None of the participants reported thoracic/low back pain (mean score 0 out of 10) in any of the rebar tying posture.

3.7.1 Spinal movements comparing three postures in rebar tying

Table 3.3 shows the median trunk angles and range of movements in different planes in the thoracic and lumbar regions during the simulated tasks. The median lumbar flexion angle in the three postures ranged from 54° to 58°, while median thoracic flexion angles were < 10° in the three postures. Unlike the flexion angles, the median lateral bending and axial rotation angles were similar in the lumbar and thoracic regions (Table 3.3). The median lateral bending and axial rotation angles in both segments ranged from 0.63° to 4.13°. The lumbar region demonstrated that lateral bending had the largest range of movements during rebar tying as compared to the corresponding variations in flexion and axial rotation in all working postures.

Table 3.3 Median angles and standard deviations for rebar tying postures (± SD)

Angles (Degrees)	Lumbar Region			Thoracic Region		
	Flexion	Lateral	Axial	Flexion	Lateral	Axial
Stooping						
10% APDF	54.45	-8.67	-0.45	3.24	-6.58	-6.23
50% APDF	58.41*	-2.77	1.56	7.91	-3.04	-2.65
90% APDF	60.92	3.34	3.44	11.33	0.32	0.79
Range of movements	6.47	12.02	3.89	8.08	6.90	7.02
One-legged kneeling						
10% APDF	44.29	-12.44	-2.54	3.48	-7.72	-6.94
50% APDF	54.21*	-4.13	0.84	7.45	-2.77	-1.23
90% APDF	58.23	4.89	4.28	10.47	2.74	5.18
Range of movements	13.34	17.21	7.01	7.15	10.64	12.84
Squatting						
10% APDF	50.74	-9.76	-5.78	4.87	-7.46	-7.30
50% APDF	56.23	-2.29	-0.63	8.61	-2.64	-2.24
90% APDF	60.34	4.26	4.69	11.17	2.19	3.16
Range of movements	9.60	14.02	10.47	6.30	9.66	10.46

Note: Positive values indicate flexion, rightwards lateral bending and clockwise rotation. Negative values indicate leftwards lateral bending and anti-clockwise rotation. APDF = Amplitude Probability Distribution Function, *indicates that there was a significance difference between stooping and one-legged kneeling at $p<0.05$). The effect of BMI on the above variables was studied retrospectively, no significant effect was found.

Regarding the differences in kinematics of the three postures, stooping posture had the highest median lumbar flexion angle (58.4°) during rebar tying while one-legged kneeling showed the smallest median lumbar flexion (54.2°) (Table 3.3). The post-hoc test revealed that only median lumbar flexion angle in stooping was statistically larger than that in one-legged kneeling (mean difference =4.2^{o}, 95% confidence interval (CI) ranged from 0.13^{o} to 8.3^{o}, eta square 0.38). No statistically significant difference was noted in median lumbar lateral bending/axial rotation angles, or in any of the thoracic kinematics in the three postures.

Overall, lumbar segment exhibited larger range of movements in flexion and lateral bending during rebar tying, whereas thoracic spine showed greater range of movements for axial rotation (Figure 3.5) during rebar tying. The range of movements of lumbar lateral bending and axial rotation, as well as the range of movements of thoracic lateral bending and axial rotation were the smallest during stooping (Figure 3.5). Working in one-legged bending had significantly larger range of movements in lumbar lateral bending and axial rotation, as well as thoracic lateral bending and axial rotation as compared to stooping (mean difference = 5.2^{o}, 3.12^{o}, 3.74^{o}, 5.82^{o} and eta square 0.75, 0.73, 0.77, 0.66 respectively). Similarly, squatting posture depicted significantly larger range of movements of lumbar and thoracic axial rotation (mean difference = 3.46^{o}, 3.44^{o} and eta square 0.68, 0.77 respectively) and larger range of movements in thoracic lateral bending (mean difference 3.74^{o}, eta squared 0.77) with reference to stooping.

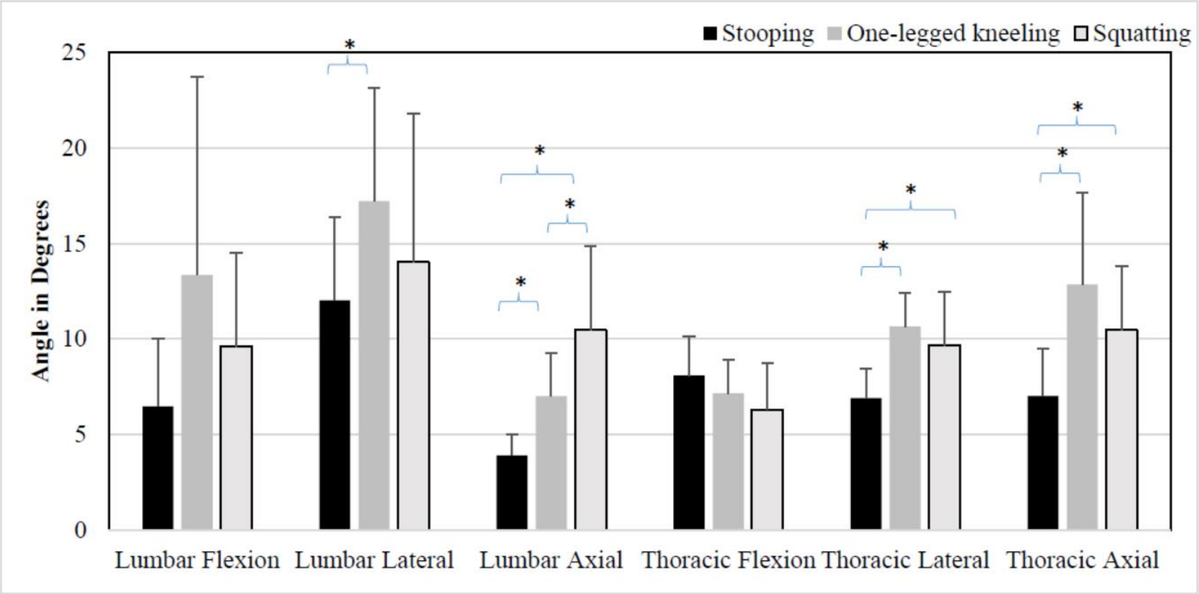

Figure 3.5 Range of movements of joint segments in three Cartesian planes at the lumbar and thoracic region during the performance of rebar tying in three postures

Note: Lumbar lateral = lumbar lateral bending; lumbar axial = lumbar axial rotation; thoracic lateral = thoracic lateral bending; thoracic axial = thoracic axial rotation; * $p < 0.05$; the error bar indicates standard deviation. The effect of BMI on the above variables was studied retrospectively, no significant effect was found.

3.7.2 Differences in muscles` activity during rebar tying in three different postures

Table 3.4 depicts the normalized sEMG activity of different muscles based on the 10th, 50th, and 90th percentiles of sEMG amplitude in the three postures. The activity of the muscles ranged from 0.57% to 25.16% of MVC values. Across all working postures, the cervical ES had the largest absolute values of muscle activity, followed by thoracic ES.

Table 3.4 The 10th, 50th And 90th percentile of normalized muscle activity at the cervical, thoracic and lumbar regions during rebar tying in three different postures (± SD within each percentile)

Muscles	Stooping			One-legged kneeling			Squatting		
	10% APDF	50% APDF	90% APDF	10% APDF	50% APDF	90% APDF	10% APDF	50% APDF	90% APDF

Cervical ES	8.42 (2.38)	13.75 (4.26)	22.70 (7.39)	8.59 (3.37)	14.37 (4.89)	23.29 (7.25)	8.98 (2.97)	15.01 (4.68)	25.16 (7.66)
Thoracic ES	2.60 (2.52)	8.03 (6.50)	21.74 (15.60)	3.60 (3.47)	9.60 (7.24)	22.8 (16.24)	3.43 (3.95)	8.41 (6.40)	18.79 (10.85)
Lumbar ES	0.26 (0.42)	1.48 (0.76)	8.99 (5.12)	1.04 (1.81)	6.54 (6.83)	21.09 (13.37)	0.93 (1.77)	4.42 (4.38)	14.06 (9.78)
Multifidus	0.57 (1.22)	1.75 (1.77)	7.09 (4.38)	1.47 (2.37)	5.67 (6.88)	19.16 (12.2)	1.15 (1.95)	4.34 (4.67)	12.55 (10.47)

Note: ES = Erector Spinae; APDF = Amplitude Probability Distribution Function. The effect of BMI on the above variables was studied retrospectively, no significant effect was found.

The median values of lumbar ES activity during one-legged kneeling and squatting were significantly larger than that during stooping [mean difference= 5.1% MVC (95% CI= 0.64 to 9.48% MVC), eta square 0.43 and 2.9% MVC (95% CI= 0.13 to 5.75% MVC), eta square 0.38 respectively] (Figure 3.6). Similarly, multifidus muscles tended to show higher median muscle activity during one-legged kneeling and squatting than stooping (eta square 0.33 and 0.34, p values ranged from 0.06 to 0.07 respectively). Conversely, no significant difference was found in median cervical ES nor thoracic ES activities across all postures.

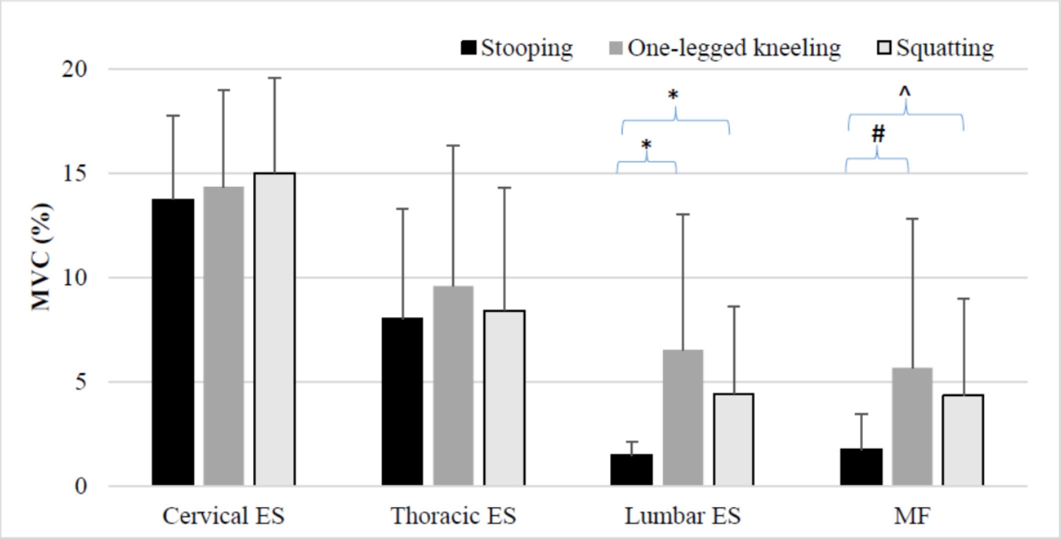

Figure 3.6 Comparison of median muscle activity (50th % APDF) in spinal muscles

Note: * indicates $p < 0.05$; ^ indicates $p = 0.06$; # indicates $p = 0.07$; MVC= maximum voluntarily contraction; ES= erector spinae; MF= multifidus; bars indicate standard deviation. The effect of BMI on the above variables was studied retrospectively, no significant effect was found.

3.7.3 Correlations between low back pain intensity and trunk kinematics or trunk muscle activity

Since none of the participants experienced spinal pain during the rebar tying postures, no correlation analysis was conducted to investigate the correlation between low back pain intensity and trunk kinematics or trunk muscle activity.

3.8 DISCUSSION

Occupational safety management has always been an important concern to construction managers. High prevalence of musculoskeletal disorders among the construction workers hamper the productivity and occupational safety of the industry globally. Construction managers need to have a better understanding of the physical and biomechanical demands of various construction trades so that better policies and/or interventions can be introduced to minimize the risk of musculoskeletal disorders at the workplace. The current study is the first of its kind to quantify the biomechanical characteristics of three common rebar tying postures. The results showed that performing rebar tying in stooping posture resulted in significantly larger median lumbar flexion angles and significantly smaller median muscle activity of lumbar ES and multifidus muscles as compared to one-legged kneeling and squatting postures. Conversely, there was no significant difference in kinematic and kinetic data between one-legged kneeling and squatting posture.

3.8.1 Spinal kinematics during rebar tying

The results of the current study, for the first time, indicate that rebar tying demands large lumbar flexion (approximately 60-65°) irrespective of the working posture. The lumbar flexion angles exceed the recommended limits (60^o) suggested by ISO 11226 for static working postures (ISO 11226:2000). Previous observation-based studies for construction activities only stratified trunk bending angles into different categories (e.g. >45° or severe flexion) and considered the entire trunk as single straight line segment (Buchholz et al. 1996; Forde and Buchholz 2004; Hajaghazadeh et al. 2012; Lee and Han 2013).The current study overcame these limitations and quantified spinal angles at different trunk segments based on the relative movements of multiple motion sensors placed along the spine. The findings provide an indirect explanation for the high prevalence of LBDs in rebar workers. The results suggest that this method can be adopted for studying the physical demands of rebar work on the spinal joints and muscles at the actual worksite.

The current results also highlight that rebar tying tasks require the participants to work over a moderate range of lumbar lateral bending (25-30° including left and right side range of movements) and axial rotation (15-20° including clockwise and anti-clockwise range of movements). The end range of motion of lateral bending and axial rotation during the simulated tasks are approximately 30% to 40% of the normal total thoracic or lumbar range of motion in healthy individuals (Van Herp et al. 2000; Oatis 2004). Since asymmetric trunk inclination together with end range forward bending may increase the risk of LBDs (Szeto et al. 2013), the non-neutral working postures of rebar tying may increase the risk of future back injury. In addition, because there was only limited variations in trunk flexion angles in all postures during rebar tying (e.g. < 10° on average), it implied that rebar workers may need to remain in a relatively static and excessive flexion posture during rebar tying, which might heighten the risk of LBDs development (Garg 1992; Neumann et al. 1999).

3.8.2 Spinal muscle activity during rebar tying

Lumbar ES and lumbar multifidus were the only two muscles that demonstrated significant (or almost significant) differences in activity among different postures. This observation may be attributed to the possibility that biomechanical demand for cervical or thoracic paraspinal muscles during rebar tying in different postures are comparable. Since the lumbar region contributes to the majority of the trunk inclination, the relative differences in kinematics of neck or upper trunk in different postures may be minimal. As such, only lumbar paraspinal muscles demonstrate distinct muscle activity in different postures specifically, the differences in posture-related trunk muscle activity can be explained by the flexion-relaxation phenomenon, which involves a myoelectric silence of lower back muscles when an asymptomatic individual bends forward fully in a standing position (see below).

3.8.3 Differences in trunk biomechanics in the three postures

Among the three rebar tying postures, stooping involved the largest median trunk flexion angle (approximately 65°) but the lowest sEMG activity of back muscles (lumbar ES and multifidus). The median activities of lumbar ES and multifidus during rebar tying in stooping were approximately 20 to 40% of the respective muscle activity in the other two postures. This observed ‘myoelectric silence’ of lumbar muscles during stooping can be explained by the flexion-relaxation phenomenon (Ahern et al. 1990; McGill and Kippers 1994; Shirado et al. 1995). It is known that as an asymptomatic individual bends to the end range of trunk flexion in standing, the passive spinal structures (e.g. spinal ligaments) will become taut and take up the loading of the body with minimal back extensor activity. While this phenomenon is common in asymptomatic individuals (Solomonow et al. 2003), it substantially increases the loading on facet joints and the anterior shear stress on the lumbar vertebrae (Kent 2006, p. 265; McGill and Kippers 1994). Solomonow et al. (2003) found that prolonged static trunk flexion caused creep in the viscoelastic lumbar structures and resulted in subsequent spontaneous spasms of multifidus muscles, which indicated protective muscle responses to micro-damage of spinal tissues (e.g. ligaments). Although flexion relaxation phenomenon in stooping may not appear in sufferers with low back pain, these sufferers may need to recruit more back extensors in order to support the trunk in a stooping posture, which may increase the risk of back muscle fatigue after prolonged stooping. Since the authors` pilot observational visits have revealed that stooping is the second most commonly adopted rebar tying posture, it is conceivable that this posture may predispose some rebar workers to develop/maintain LBDs.

Although the one-legged kneeling rebar tying posture showed the smallest median trunk flexion angle (approximately 60°), the absolute values of median sEMG activity of lumbar ES and multifidus were the highest. This observation implied that lumbar muscles were activated to resist the flexion moment in this posture. Furthermore, the range of movements in lateral bending and axial rotation of the thoracic and lumbar regions during one-legged kneeling posture were significantly greater than those of the stooping posture (Figure 3.5). This indicates that one-legged kneeling posture involves non-neutral trunk postures. If such asymmetrical trunk posture is adopted repetitively, it may increase the risk of future LBDs (Szeto et al. 2013). Importantly, all participants complained of mild to moderate pain over the kneeling knee after performing several minutes of rebar tying in the one-legged kneeling posture. This highlights that working in one-legged kneeling posture may increase the risk of both low back and knee pain.

The absolute values of spinal kinematics and sEMG data during squatting were in between those for stooping and one-legged kneeling postures. Although this observed angle is smaller, it still exceeds the recommended static trunk working posture limit suggested by the ISO 11226 standard (60°) (ISO 11226:2000). Importantly, the authors` pilot construction site visits revealed that rebar workers performed rebar tying in squatting posture for an average 3 to 4 hours per duty shift. Prolonged squatting not only may increase the risk of LBDs but also may reduce blood circulation to the lower extremities and increase tensile stresses in the knee intra-articular structures. Altogether, these factors may contribute to fatigue and MSDs of back and lower extremities. (Basmajian and Deluca 1985).

Collectively, the results of this study have showed that all the tested postures involve extensive lumbar bending while one-legged kneeling has an additional disadvantage of asymmetrical trunk posture. Prolonged working in these postures may explain the high prevalence of LBDs in rebar workers. The current findings warrant ergonomic intervention to minimize the risk of LBDs development in these workers.

3.9 LIMITATIONS

Although the study has deepened the current knowledge regarding the biomechanical risk factors of LBDs in rebar workers, there were some limitations. Firstly, this study was performed in a laboratory environment. Future on-field studies should be conducted to confirm the findings. Secondly, since the asymptomatic participants were novel to rebar tying and each of their work tasks only lasted for 6 to 8 minutes, the results should be interpreted with caution. Future research should quantify the trunk kinematics and trunk muscle activity of rebar workers during a typical work shift of 3 to 4 hours. Thirdly, the current experimental protocol might be insufficient to elicit spinal pain/discomfort in the participants. Given the short duration of the task, thoracic/low back pain was not experienced by the participants. Interestingly, mild to moderate knee pain/discomfort was reported by some participants during the rebar tasks. Future studies should examine the biomechanics of both the trunk and lower extremities during the rebar tying task so that the effects of different postures on different body parts can be comprehensively investigated. Despite these limitations, the findings have revealed that the trunk flexion angle in all postures exceeded the recommended ISO 11226 standard for static work. Fourthly, like other ergonomic studies in the construction industry (Pan and Chiou 1999; Vi 2003), the current sample size was relatively small. Despite this limitation, significant differences in spinal biomechanics among different rebar tying postures was noted. Based on the results, an ad-hoc sample size analysis was conducted. The analysis revealed that a sample of 13 participants would be sufficient to demonstrate significant difference in activity of lumbar erector spinae and multifidus muscles among the three postures.

3.10 WAYS TO ALLEVIATE LBD RISK FACTORS

Based on the current results, a number of recommendations can be considered to improve the spinal biomechanics of rebar workers. Postural variation has been recommended for workers who maintain prolonged static working postures because holding a particular posture in an anti-gravity position for a prolonged duration will increase the risk of postural tissue overload (Delleman and Dul 2007). Rebar workers should understand this concept, and practice regular variation of their working postures. Postural training and education should be provided to emphasize the importance and techniques of postural variations. Since both one-legged kneeling and squatting can increase the risk of knee degeneration/pain, knee pads or small stool can be distributed to workers so that they can switch between different postures (e.g. one-legged kneeling of alternate knee or sitting). Strengthening and endurance exercises can also be introduced to target specific back and lower limb muscles (Parker and Worringham 2004).

Other interventions involving the modification of equipment and daily routine can be introduced. Prefabricated rebar mesh can be used to decrease the exposure of rebar tying in highly-flexed posture during hectic climate conditions of construction sites. Ergonomic smart stools, such as power rebar tier (Albers and Hudock 2007), can be introduced as a technical intervention to allow the workers to perform rebar tying in a neutral standing posture. Further, the rebar tying task can be scheduled in between other less physically demanding activities (e.g. bending and cutting of steel bars) so as to minimize back and leg muscles fatigue secondary to prolonged postures.

CHAPTER 4

A LOW COST ERGONOMIC INTERVENTION FOR MITIGATING PHYSICAL AND SUBJECTIVE DISCOMFORT DURING MANUAL REBAR TYING[3]

4.1 INTRODUCTION

Work-related Musculoskeletal disorders (MSDs) are a substantial burden on the construction industry. A recent systematic review (Umer et al. 2017a) found that more than 50% of the construction workers suffer from symptoms of low back MSDs annually around the globe. The review also noted that approximately one-third of the construction workforce face symptoms of knee, shoulder and wrist MSDs. These MSDs impose substantial direct and indirect costs (Lehtola et al. 2008), work absenteeism (Rinder et al. 2008), schedule delays and lost time claims to the industry (Inyang et al. 2012). Multiple studies have reported the high direct and indirect costs of traumatic and non-traumatic MSDs in the construction industry (Pandey et al. 2012), including loss of productivity (van der Molen et al. 2009), increased insurance premium (Inyang et al. 2012) and permanent disability (Welch et al. 2009). During the year 2014, MSDs resulted in one-third of all work absenteeism related to illness and injuries in the US construction industry (BLS 2015a). In Canada, Alberta Construction Safety Association

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Umer, W., Li, H., Szeto, G. P. Y., and Wong, A. Y. L. (2017). "A Low-Cost Ergonomic Intervention for Mitigating Physical and Subjective Discomfort During Manual Rebar Tying" *Journal of Construction Engineering and Management 143*(10)

reported that 41.9% of all accepted lost time claims and 46.8% of total injury claims were related to MSDs in 2008 (ACSA 2009).

Work-related MSDs among construction workers are highly related to physically demanding work tasks (Cheng et al. 2013), which exposes these workers to numerous ergonomic risk factors. These risk factors include heavy lifting and carrying, jerky movements, vibrations, and repetitive works in prolonged awkward work postures (Buchholz et al. 1996; Forde and Buchholz 2004; Umer et al. 2017b; Welch et al. 2009). These factors overload the workers` musculoskeletal system and increase the workers` vulnerability to work-related MSDs (Inyang et al. 2012). By reducing or eliminating these risk factors, the propensity of work-related MSDs can be controlled. It is generally agreed that effective technological and ergonomic interventions are crucial for the mitigation of prevalent MSDs in the construction industry (Lehtola et al. 2008; Rinder et al. 2008). However, since each construction trade has a unique set of tasks that may expose the workers to specific ergonomic risk for certain MSDs (Choi et al. 2014), ergonomic interventions should be task specific (Wang et al. 2015a; West et al. 2016).

Among workers in different construction trades, rebar workers are highly vulnerable to MSDs because of their task contents (Ontario data:1994-1998; Schneider and Susi 1994; Silverstein and Kalat 1999). In particular, manual rebar workers frequently need to bend forward in stooping or squatting posture in order to tie reinforcement bars with metal tie-wires on the floor (Dababneh et al. 2000). Observational ergonomic studies have revealed that rebar workers remain in non-neutral trunk postures for up to 58% of the workday when they opt for stooping (Buchholz et al. 2003; Forde and Buchholz 2004; Saari et al. 1978). A recent biomechanical study also found that rebar tying in a stooping posture led to flexion-relaxation phenomenon of lower back, which deactivates back muscles and may result in increased loading stress on passive torso tissues (e.g. ligaments or facet joint capsules) (Umer et al. 2017b). As such, prolonged and repetitive highly flexed trunk posture is known to be a risk factor for back MSDs (Garg 1992; McGill and Kippers 1994; Neumann et al. 1999). In Asian culture, squatting is preferred to stooping for rebar tying (Chung et al. 2003; Jung and Jung 2008). In such posture, lower extremities are subjected to surge in postural load (Buchholz et al. 1996; Genaidy et al. 1994). Since squatting increases the contact pressure at knees at the end-range of knee flexion, this biomechanical factor can increase the risk of knee MSDs (Kivimäki et al. 1992; Thun et al. 1987). Additionally, squatting posture may affect the blood circulation of lower extremities (Basmajian and Deluca 1985), which may cause discomfort or compromise functional performance of workers. Given that many postural-related physical risk factors are modifiable, task-specific ergonomic interventions should be implemented (Forde et al. 2005; Vi 2003) to alleviate the high physical workload of manual rebar tying.

To reduce physical workload of the trunk and knees during rebar tying, different commercially available wearable ergonomic devices may be used although the adoption rate is low (Weinstein et al. 2007). These ergonomic interventions include, but are not limited to, Bending Non-Demand Return (BNDR) (Ulrey and Fathallah 2013), Happyback (ErgoAg Company, Aptos, CA) and Personal Lift Assist Device (PLAD) (Lotz et al. 2009). These exoskeletons provide anti-gravity moment to reduce trunk muscular workloads. Although these devices were primarily designed for the agriculture and manufacturing industry rather than the construction industry, the inventors claim that these devices can be used in other physically demanding jobs (e.g. rebar tying) (Ulrey and Fathallah 2013). However, rebar workers rarely use these devices (especially those working in the fastest growing Asian construction market, Horta et al. 2013). To understand the reasons for not adopting these interventions by Asian rebar workers, one of the authors (WU) interviewed four veteran construction project managers in Hong Kong, who have been working in the Asian industry for at least 20 years. These managers were chosen because their experience in project management and their knowledge on construction work-site characteristics, workers` behavior, work demands of construction tasks enabled them to provide comprehensive and pragmatic overview on the issues. The interviews revealed several reasons for the reluctance in adopting ergonomic interventions in the industry: inability to use these devices in squatting, high cost, difficulty in handling and storing these tools, and difficulty in repairing and maintenance. Importantly, rebar workers dislike wearing any ergonomic tools that irritate their body parts during the hot and humid season, which is common in Asia.

To reduce the physical discomfort of Asian workers during rebar tying in squatting, it is essential to develop a low cost and comfortable wearable ergonomic tool. To this end, the authors derived an idea of attaching a stool (10 to 15 cm height) to the pants of rebar workers using self-adhesive Velcro straps (Figure 4.1). This inexpensive tool allows the workers to work in a low sitting posture instead of squat. Having discussed with the interviewed project managers, they unanimously supported the use of this pragmatic tool. Accordingly, the objective of the present study was to compare the physical and subjective responses of asymptomatic individuals during simulated rebar tying in low sitting and squatting. The findings might have a great potential to improve the health and practice of rebar workers.

Figure 4.1 Attachment of a stool to the trousers using self-adhesive Velcro straps

4.2 METHODS

4.2.1 Participants

To evaluate the effectiveness of the “squatting-stool” for rebar tying, fourteen healthy male participants aged between 18 and 40 years were recruited. The exclusion criteria were a previous history of cardiac and pulmonary disorders, current disability of lower back and lower extremity (identified using modified Oswestry Disability Index scores > 20%, Wong et al. 2015), and inability to rate discomfort using self-perceived discomfort ratings (Gescheider 1985; Han et al. 1999). The experimental procedures were approved by the Human Research Ethics Committee of The Hong Kong Polytechnic University.

4.2.2 Experimental procedure

The current experiment adopted a randomized crossover study design in a single visit. Following the detailed explanation of the experiment, written consent was sought from eligible participants. While surface electromyography (sEMG) was used to measure trunk and leg muscle activity, motion sensors and oximeter were used to monitor trunk movement and leg blood circulation, respectively. Prior to the simulated rebar tying task, participants performed a series of reference isometric contraction (RIC) tests of trunk and leg muscles in order to estimate the post-task muscle fatigue (Figure 4.2). Participants were then randomly assigned to perform the simulated rebar tying task for 12.5 minutes in one of the two postures: (1) squatting; and (2) low sitting (stool-squatting). Participants needed to report their self-perceived discomfort every 2.5 minutes throughout the rebar tying task. Participants underwent the RIC tests immediately after the task to evaluate muscle fatigue. Thereafter, participants were given a 20-minute sitting break before repeating the entire testing procedures with the untested posture.

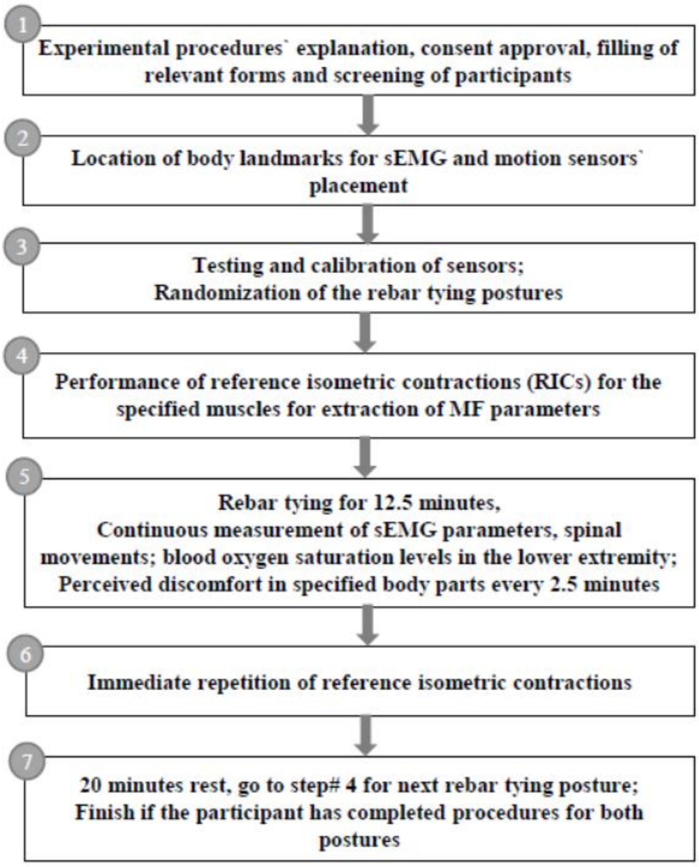


Figure 4.2 Experimental flowchart

Note: sEMG = surface electromyography; MF = median frequency

4.2.3 Reference Isometric Contractions (RICs)

Each participant performed three 5-second RICs involving the lower back, thigh and calf muscles. A 5-second rest was given between contractions (Lotz et al. 2009). The primary purpose of the RIC test was to compare post-task changes in median frequency (MF) of sEMG signals of different muscles, where decrease in MF indicated muscle fatigue (as explained in the section *Muscle Activity* below). Secondly, the amplitude of sEMG signals of different muscles during the pre-task RIC test was used to normalize the respective sEMG signals collected during the simulated rebar tying task (see below).

The RIC test of lower back muscles involved a modified Sorensen test (Coorevits et al. 2008; Dedering et al. 2000; Mannion and Dolan 1994). Specifically, the participant laid prone on a bench such that his upper body was unsupported (i.e. outer border of the anterior iliac crest was at the edge of the bench) (Figure 4.3a). The participant was instructed to keep his hands touching his ears with elbows out to the side at the same level as the trunk, during the test. An examiner fixated the participant's legs during the test.

(a) For lower back muscles

(b) For thigh muscles (c) For calf muscles

Figure 4.3 Performance of reference isometric contractions (RICs) for the muscles under study

To perform RIC test of the thigh muscles, the participant was instructed to perform three forward lunges with alternative legs (Pincivero et al. 2000). The participant should keep his back straight, arms beside the body, and the non-lunging (rear) knee slightly off the ground during the lunges (Figure 4.3b). The lunge distance of each participant should be equal to the distance between the anterior superior iliac spine and the respective medial malleolus.

The RIC test of calf muscles involved the performance of an alternative heel rise of each leg (Kasahara et al. 2007; Österberg et al. 1998). The participant raised his heel off the ground (Figure 4.3c) while he could touch his index fingers slightly against a wall for balance.

4.2.4 Simulated rebar tying

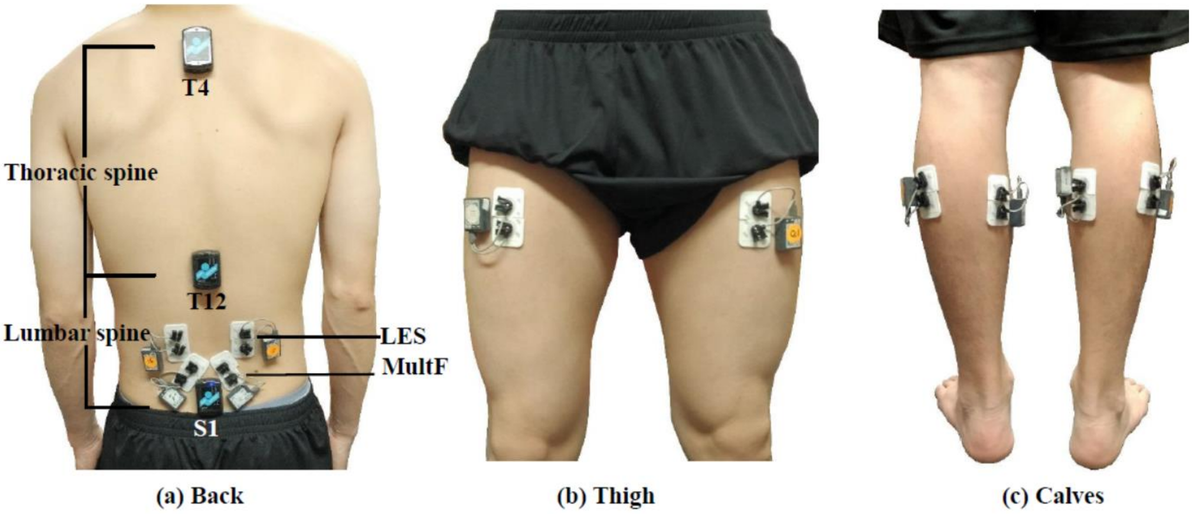
The simulated rebar tying tasks could be performed with or without a stool. To meet individual comfort, participants could choose a plastic stool, either 10cm or 15cm high. Although the originally planned duration of rebar tying task was 20 minutes, the pilot testing on two participants revealed that participants requested to stop the task before the stipulated time due to extreme discomfort. As such, the duration of rebar tying was shortened to 12.5 minutes in each posture. 12.5 minutes was chosen because it was a multiple 2.5 minutes (the time interval for evaluating self-perceived discomfort ratings).

The simulated rebar tying was conducted on a mesh of 5 by 5 plastic pipes of 1.2m length, separated from each other by a center-to-center distance of 20cm as described elsewhere (Umer et al. 2017b). Participants were instructed to repetitively tie rebar using pigtail tool and tie-wires in the first three rows of the simulation setup unless the stipulated time had elapsed. To evaluate the effects of prolonged squatting/low sitting posture on the participant's physical responses, the participant was not allowed to significantly alter the body posture and position (e.g. standing up). However, slight movements were allowed to accomplish the task.

4.2.5 Measurements

a. Muscle Activity

The trunk and leg muscle activity was measured by a 16-channel wireless surface electromyography (sEMG) system (TeleMyo, Noraxon USA, Arizona). Five pairs of muscles were evaluated including bilateral lower back muscles (lumbar erector spinae at the L3 level, and lumbar multifidus at the L5 level), bilateral anterior thigh muscles (rectus femoris) and bilateral calf muscles (gastrocnemius lateralis and gastrocnemius medialis). Surface electrodes were adhered to target muscle locations as recommended by *Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles* (SENIAM, 2005, Figure 4.4). Standardized skin preparation (including shaving, abrading with sandpaper and cleaning with alcohol swabs) was performed on the target sites to ensure the skin impedance below 10kΩ. Disposable bipolar electrodes with a diameter of 15mm and an inter-electrode distance of 20mm were used. The sampling rate and common mode rejection ratio were 1,500 Hz and 100 dB, respectively. The sEMG activities of all muscles during RIC tests and rebar tying tasks were measured.



(a) Back (b) Thigh (c) Calves

Figure 4.4 sEMG and motion sensors` placement on various body parts

Note: T4, T12 and S1 refers to body landmarks of various spinal levels; LES = lumbar erector spinae; MultF = multifidus; for lumbar erector spinae (a), the electrodes were placed at L3 level of lumbar spine (5cm laterally from midline); for multifidus, electrodes were placed along the line joining caudal tip posterior iliac spine to L1-L2 joint (2cm laterally from midline at L5 level); for rectus femoris (b), at 50% of the line distance formed by joining anterior iliac spine and superior part of patella; for gastrocnemius lateralis (c), at one third of the line length formed by joining the head of fibula and the heel and at the most prominent bulge of the muscle for gastrocnemius medialis muscles (SENIAM 2005).

Muscle fatigue secondary to rebar tying was estimated from the decrease in MF of sEMG signals during the RIC tests before and after the task (Basmajian and Deluca 1985; Mannion and Dolan 1994; Potvin and Norman 1993). This method has been widely used in biomechanical studies to quantify neuromuscular fatigue of lumbar (Coorevits et al. 2008; Mannion and Dolan 1994), thigh (Longpré et al. 2015; Pincivero et al. 2000) and calf muscles (Kasahara et al. 2007; Wim Ament et al. 1993) during functional tasks.

b. Trunk Kinematics

Spinal movements during the rebar tying task were captured by the MyoMotion system (Noraxon USA, Arizona). Three motion sensors were placed at the T4, T12 and S1 spinous processes (Figure 4.4). The spinal segment between T4 and T12 was defined as the thoracic spine whereas the segment formed between T12 and S1 sensors was determined as the lumbar spine. Motion data was sampled at 100 Hz. An examiner first guided each participant to maintain an erect standing posture, where the thoracic and lumbar angle was calibrated as zero degree. The trunk segmental flexion angle measured during rebar tying were referenced to this calibration.

c. Lower Extremity Blood Circulation

Blood circulation in the lower extremities was indirectly quantified by measuring the oxygen saturation level (SpO_2) in arterial blood using an oximeter. A perfusion resistant sports grade oximeter (MightySat Pulse Oximeter 9900, Masimo Corporation, Irvine, CA) was placed on the right big toe and data was collected at a rate of 0.5 Hz. The big toe was cleaned by alcohol swabs prior to placing the oximeter for continuous monitoring of SpO_2 levels during rebar tying.

Initially, this measurement was not planned in the experiment. However, during the pilot trial on two participants, they complained of numbness in their legs after a few minutes of squatting. As squatting posture is known for decreasing blood circulation in lower extremities (Basmajian and Deluca 1985), the leg numbness experienced by the participants might be associated with compromised blood circulation (Ogata and Whiteside 1982; Skobelkin et al. 1990), As such, blood circulation measurement was added in the current study.

d. Self-perceived Discomfort

The subjective perceived discomfort of each participant was measured by the method of Magnitude Estimation. Magnitude Estimation has been widely used to estimate perceived discomfort in psychophysical research (Chung et al. 2003). In the current study, participants utilized whole numbers to rate discomfort levels in various parts of the body (lower back, upper legs, lower legs, and whole body) every 2.5 minutes. The participants chose any arbitrary number (such as zero) to express their discomfort at the beginning of each task. As the task continued and the discomfort increased, the participant could continue to report higher numbers (such as 40, 50, 100 and so on) at each time point, to indicate the heightened self-perceived discomfort (Han et al. 1999). To compare the discomfort rating among participants, min-max normalization was used where minimum and maximum discomfort values were used as references for normalization (Chung et al. 2003). The normalized self-perceived discomfort was calculated as follow

$$PD_{ij} = \frac{x_{ij} - Min_j}{Max_j - Min_j} \times 100\% \ \ (eq\ 4.1)$$

where PD_{ij} is the normalized self-perceived discomfort rating for i^{th} reading of the j^{th} participant, x_{ij} is the non-normalized i^{th} discomfort rating for the j^{th} participant, Min_j and Max_j are minimum and maximum discomfort rating perceived by the j^{th} participant throughout the experiment.

To evaluate the participant's capability in making correct ratio judgments for Magnitude Estimation, two protocols of "line production" and "numerical estimation" were used. For "line production", the participant was instructed to draw seven lines with appropriate lengths to represent seven given random numbers. For "numerical estimation", the participant was asked to estimate the length of seven presented lines (Chung et al. 2003). Separate linear regression analyses were performed for the two protocols by logarithmic plotting of the information provided by the examiner (i.e. random numbers or the length of lines) versus the corresponding participant's responses (Han et al. 1999). If the slopes (i.e. regression coefficients) of the two lines of a given participant were not significantly different from the value of 1.0 (Gescheider 1985), the participant was deemed to be able to make correct ratio judgements. Elsewise, the corresponding data was not included in data analysis.

4.2.6 Data processing

Noraxon MyoResearch MR3.8 (Noraxon USA Inc., USA) software was used for all sEMG signal processing. The software was specifically chosen since it was provided by the sEMG hardware manufacturer. Raw sEMG data during rebar tying were filtered to remove electrocardiography signals using adaptive filter methods, bandpass filtered at 20-500 Hz, notched filtered at 50 Hz to remove electrical noise, and then smoothen using 50 ms root mean square (RMS) moving window (Xie et al. 2016). The maximum sEMG signal of a given muscle during the pre-task RIC test was identified by applying a moving window of 1000ms with a step size of 50ms to the sEMG signals. To enable between-participant comparison, the sEMG data of each muscle recorded during rebar tying was normalized to and expressed as the percentage of the respective maximum sEMG signal at the pre-task RIC test (%RIC).

Amplitude Probability Distribution Function (APDF) was used to compare the muscle activity in the two rebar tying postures. APDF is commonly used to study variations in muscle activity during a certain task (Szeto et al. 2005). Specifically, 50% APDF was used to indicate average muscle activity during the rebar tying task (Xie et al. 2016). Although sEMG data were captured from both sides of muscles, paired t-tests with false detection rate (FDR, see below) correction revealed no significant difference in the amplitude of sEMG signals from both sides of any given muscle. Therefore, left and right side values were averaged for further statistical analysis.

To calculate MF from a raw sEMG power spectrum, each 5-second RIC test was divided into five 1-second segments (without overlapping). A Hanning window was applied to the sEMG signals of each 1-second segment followed by the calculation of MF using Fast Fourier Transformation. The five MF values during each RIC test were averaged to obtain a single MF value (Lotz et al. 2009). As three repetitions of RIC tests were performed for each muscle, MF values of these three RIC tests were averaged for subsequent statistical analysis (Lotz et al. 2009). The post-task MF value of each muscle was then normalized to pre-task MF values (considered as 1.0) to identify fatigue.

Spinal movement data from the motion sensors were smoothened using Kalman filter prior to statistical analysis. The average thoracic, lumbar, and total trunk flexion angles at 50% APDF of the two rebar tying postures were compared. Blood oxygen saturation (SpO_2) values obtained through oximeter were unfiltered. The temporal changes in SpO_2 values between the two rebar tying postures were estimated from the differences in SpO_2 values at 10%, 50% and 90% APDF.

4.2.7 Statistical analysis

Table 4.1 summarizes various statistical tests conducted on different variables of interest in the current study. Multiple paired t-tests with false detection rate (FDR) correction were used to compare the between-posture difference in the average sEMG activity (50% APDF) of various muscles. The correction was applied to control type-I errors (false positives) when multiple t-tests are performed. FDR was chosen instead of the overly conservative Bonferroni adjustment because it was more suitable for multiple comparisons (Benjamini and Hochberg 1995; Lotz et al. 2009). One-way repeated measures analyses of variance (ANOVA) were used to explore the differences in the normalized pre- and post-rebar tying MF values. Rebar tying postures were chosen as the independent variable, whereas pre- and post-task MF values were the dependent variables. Post-hoc tests involved paired t-tests with FDR correction. Similarly, the differences in the spinal flexion angles and SpO_2 values between the two rebar tying postures were analyzed by multiple paired t-tests with FDR correction. Two-way repeated measures ANOVA was used to investigate the effect of time and stool condition (independent variables) on the normalized self-perceived discomfort ratings (dependent variable). Significant main effects were explored by using paired t-tests. SPSS (version 19.0, IBM Corporation, Armonk, NY) software was used for the statistical analysis with significance value set at $p < 0.05$.

Table 4.1 Summary of the statistical tests conducted in the current study

Variables under consideration	**Statistical tests conducted**	**Objectives of the tests**
Muscle activity	Paired t-tests (with FDR correction)	To identify changes in muscle activations between the two rebar-tying postures
MF (sEMG)	One-way repeated measures ANOVA, paired t-tests for post-hoc analysis	To quantify post-task muscle fatigue
Spinal flexion angles	Paired t-tests (with FDR correction)	To compare trunk flexion angles during rebar tying
SpO_2 levels	Paired t-tests (with FDR correction)	To quantify temporal changes in SpO_2 levels of lower limbs during rebar tying
Self-perceived discomfort	Two-way repeated measures ANOVA, paired t-tests for post-hoc analysis	To compare the self-perceived discomfort levels of the two postures at various time points during rebar tying

Note: MF = median frequency; sEMG = surface electromyography; SpO_2 refers to blood oxygen saturation levels; FDR = false detection rate; ANOVA = analysis of variance

4.3 RESULTS

The fourteen participants (including two participants in the pilot testing) had a mean age of 27.6 years (SD ± 4.2 years, 10 participants aged between 20 and 29 years and 4 participants aged between 30 and 39 years) and BMI 22.7 kg/m^2 (SD ± 1.5 kg/m^2). The mean and standard deviation of the participants' Oswestry Disability Index score was 2.3 ± 4.0%. All participants chose the stool with a height of 15 cm. When tested, all participants were found able to make correct ratio judgements.

4.3.1 Muscle activity

Figure 4.5 demonstrates the normalized 50th percentile sEMG amplitudes of the various muscles (along with standard deviations) during rebar tying in the two postures. The average sEMG activities of different muscles during rebar tying varied between 1.2% and 3.8%RIC. The lumbar muscles tended to show the least activity whereas gastrocnemius lateralis muscles showed the highest magnitude of activity.

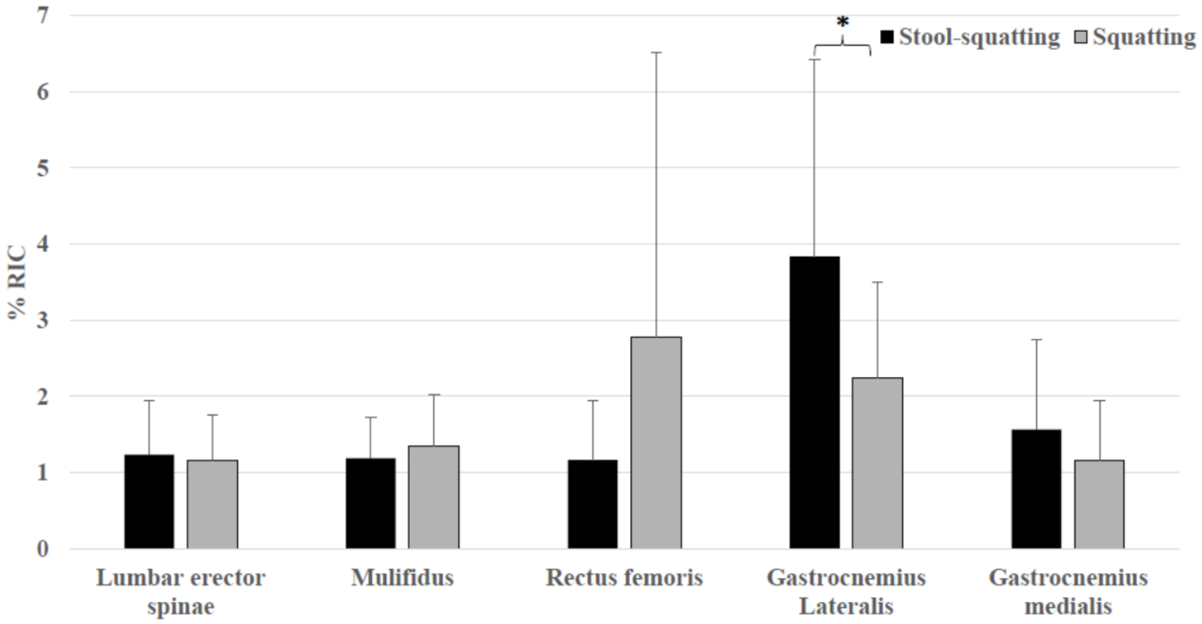


Figure 4.5 Muscles` activity comparison between two rebar tying postures for average activation levels (50% APDF)

Note: * indicates $p < 0.05$; RIC = reference isometric contraction; bars indicate standard deviation. The effect of BMI on the above variables was studied retrospectively, no significant effect was found on the results.

Lower back muscles (i.e. lumbar erector spinae and multifidus) and the calf muscle - gastrocnemius medialis exhibited no significant difference in activity during rebar tying in the two postures. The thigh muscle, rectus femoris, tended to have a higher absolute muscle activity in the squatting posture as compared to stool-squatting (a mean difference of 1.6%RIC, p=0.12). On the contrary, gastrocnemius lateralis muscles showed significantly higher muscle activity during stool-squatting rebar tying than squatting rebar tying task [mean difference = 1.6%RIC (95% CI = 0.1 to 3.1%RIC)].

The pre- and post-task changes in normalized MF in the two rebar tying postures are depicted in Figure 4.6. Depending on the muscles, there were variations in post-rebar tying MF values (ranging from a decrease of 4.3% in right lumbar erector spinae after stool-squatting to an increase of 3.9% in right gastrocnemius lateralis after squatting rebar tying). However, one-way repeated measures ANOVA revealed no significant temporal changes in pre-task, post-squatting, and post-stool-squatting MF.

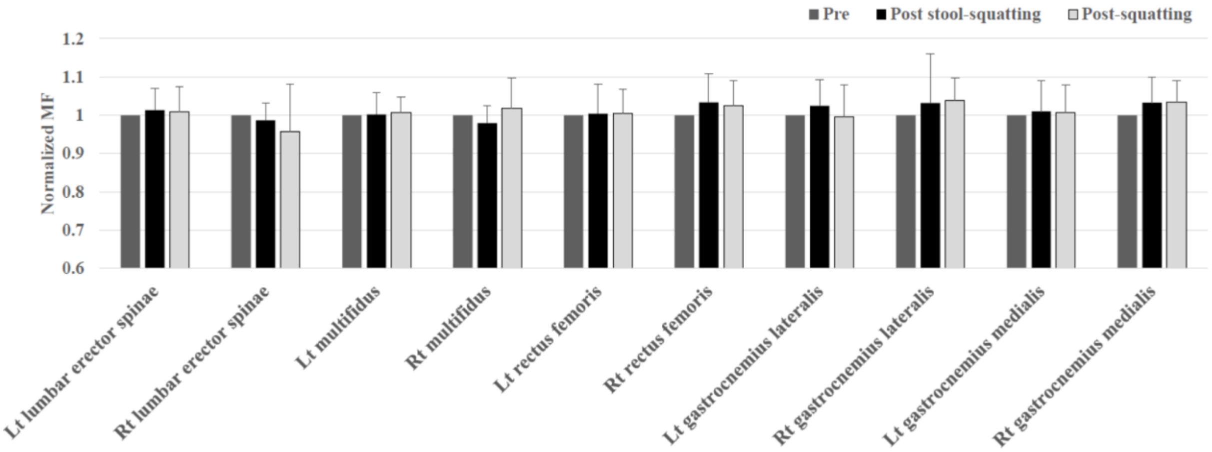


Figure 4.6 Pre and post-task normalized median frequency analysis for the two rebar tying postures

Note: MF = median frequency; Lt= left side muscle; Rt= right side muscle; bars indicate standard deviation. The effect of BMI on the above variables was studied retrospectively, no significant effect was found on the results.

4.3.2 Trunk kinematics

The average total trunk flexion angles at 50% APDF were 57.3º and 66.0º for rebar tying with and without stool, respectively (Figure 4.7). For both rebar tying postures, the average total trunk flexion angles were mainly contributed by lumbar flexion (average values of 43.0º to 48.8º), whereas thoracic flexion only contributed to less than 18º in both postures. Squatting demonstrated significantly larger thoracic, lumbar, and total trunk flexion angles as compared to stool-squatting rebar tying. Specifically, the mean difference was 3.0º for thoracic flexion

(95% CI = 0.2º to 5.7º), 5.8º for lumbar flexion (95% CI = 1.3º to 10.3º) and 8.7º for total trunk flexion (95% CI = 5.6º to 11.9º).

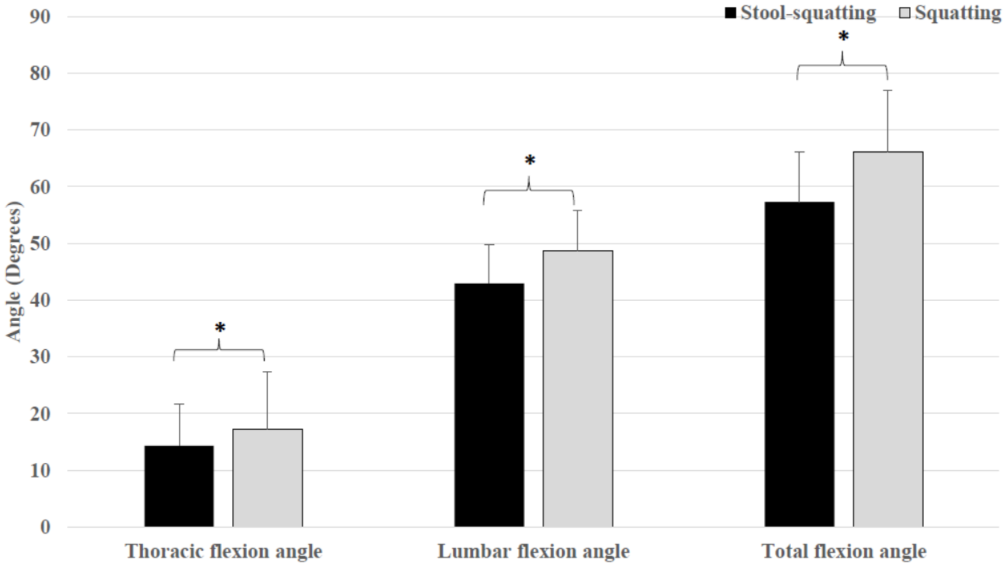


Figure 4.7 Comparison of spinal flexion variables

Note: * indicates $p < 0.05$; bars indicate standard deviation. The effect of BMI on the above variables was studied retrospectively, no significant effect was found on the results.

4.3.3 Lower extremity blood circulation

Figure 4.8 depicts the lower extremity SpO_2 values at 10%, 50% and 90% APDF of the two rebar tying postures. The SpO_2 values varied from 73.9% to 96.8%. Regardless of the APDF percentile chosen for the comparison, rebar tying using the stool demonstrated significantly larger SpO_2 values than rebar tying in squatting. Specifically, the mean difference in SpO_2 values for 10%, 50% and 90% APDF of the two rebar tying postures was 13.2% (95% CI = 5.2 to 21.2%), 10.6% (95% CI = 4.1 to 17.2%) and 7.1% (95% CI = 1.2 to 12.9%), respectively.

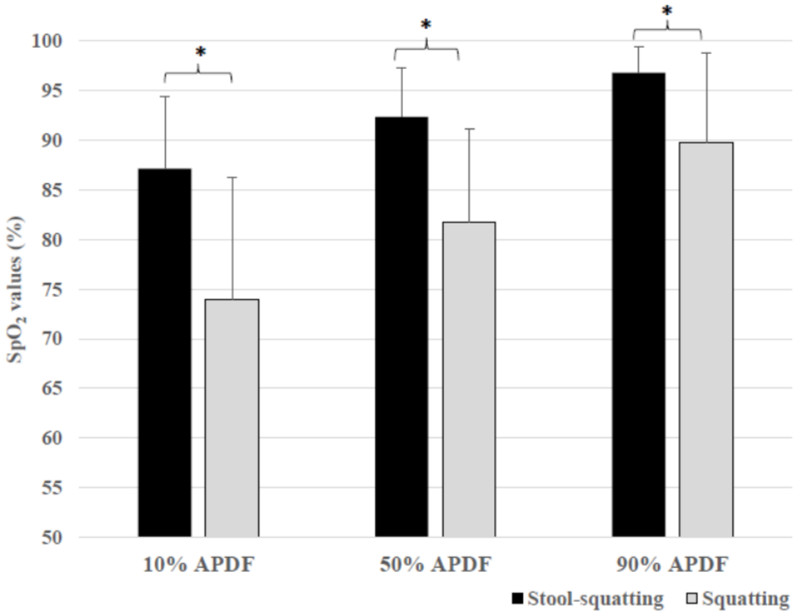


Figure 4.8 Comparison of blood oxygen saturation levels (SpO2)

Note: * indicates $p < 0.05$; APDF = amplitude probability distribution function. The effect of BMI on the above variables was studied retrospectively, no significant effect was found on the results.

4.3.4 Self-perceived discomfort

Two-way repeated measures ANOVA revealed significant interaction between stool condition and time ($p < 0.01$, Table 4.2) for various body parts (i.e. lower back, upper legs, lower legs, and whole body) examined in this study. Post-hoc tests revealed that the use of a stool yielded significantly lower (better) self-perceived discomfort ratings of all aforementioned body parts as compared to squatting. These differences began from the first 2.5 minutes to the end of the task (Figure 4.9). The maximum difference in the normalized self-perceived rating for rebar tying with and without stool was noted at lower legs toward the end of experiments [mean difference = 65.1% (95% CI = 50.8 to 79.3%)]. On the other hand, there was minimum difference in lower back discomfort at the end of the tasks [mean difference = 23.9% (95% CI

= 10.0 to 37.9%)]. For upper legs and whole body, normalized self-perceived discomfort ratings at end of the experiments varied in two rebar tying postures with a mean value of 44.5% (95% CI = 33.3 to 55.6%) and 53.9% (95% CI = 40.1 to 67.6%) respectively (Figure 4.9).

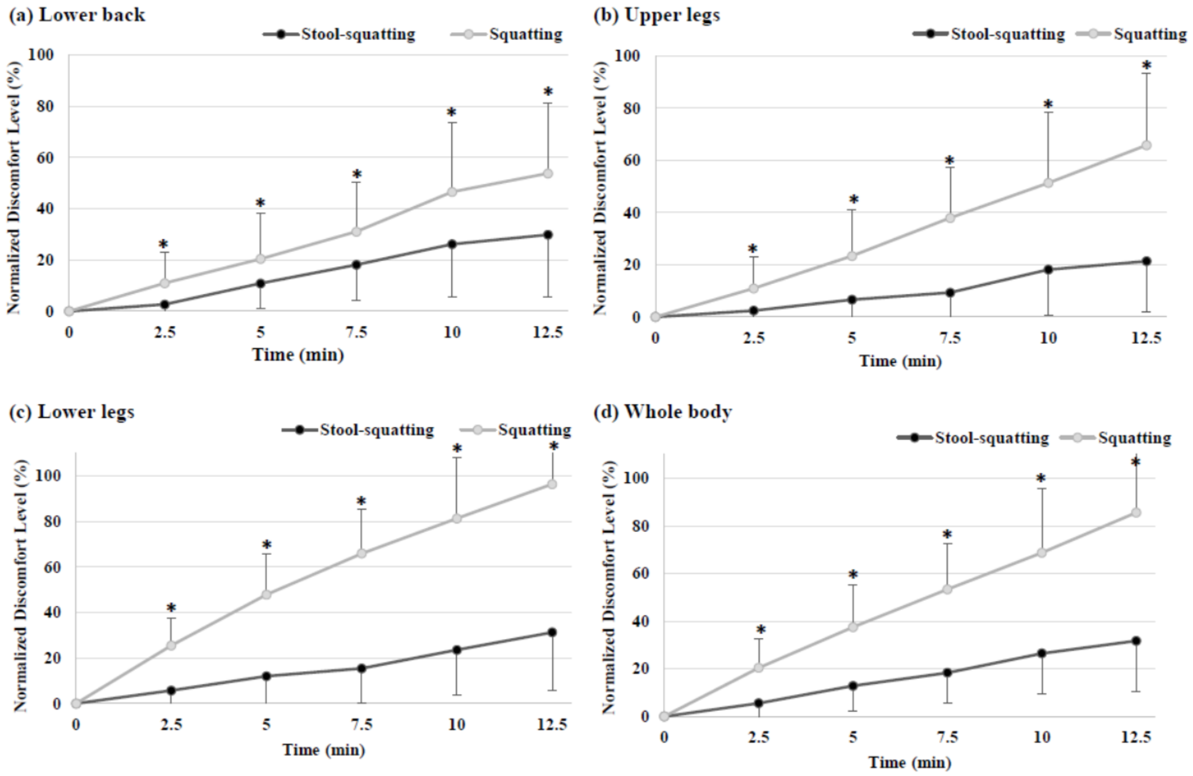


Figure 4.9 Normalized self-perceived discomfort ratings comparison between the two postures

Note: where * indicates $p < 0.05$; bars indicate standard deviation

Table 4.2 ANOVA results for discomfort rating

Body part	Factors		
	p (stool condition)	p (time)	p (stool x time)
Lower back	.001	<.001	.008
Upper legs	<.001	<.001	<.001
Lower legs	<.001	<.001	<.001
Whole body	<.001	<.001	<.001

4.4 DISCUSSION

The current results indicate that multiple biomechanical and physiological measurements are necessary to understand physical demands of occupational work tasks comprehensively. Specifically, the two rebar tying postures elicited comparable muscle activity and muscle fatigue in back and lower limb muscles. However, trunk kinematics, blood circulation and self-perceived discomfort significantly differed between the two postures. Importantly, the current findings suggest that a small change in work practice may bring significant ergonomic benefits.

4.4.1 Muscle activity

The normalized average sEMG amplitude of various muscles during simulated rebar tying indicated that the tasks did not involve extensive muscle activity irrespective of the adopted posture (i.e. muscle activity was less than 4%RICs in all muscles) (Figure 4.5). However, this does not imply that such small muscle activity cannot induce neuromuscular fatigue. Literature suggests that tasks involving sustained contractions as low as 2% of maximum voluntary contraction in the lumbar erector spinae muscles can significantly decrease tissue oxygen levels, and cause muscle fatigue that may lead to work-related MSDs in the long run (McGill et al. 2000). Further, the comparison of muscle activity in the two rebar tying postures reveals a tradeoff between the thigh and calf muscles. Specifically, rectus femoris muscles showed larger average activity in the squatting posture whereas gastrocnemius lateralis muscles were more active during stool-squatting rebar tying. These results concur with those from Sriwarno et al. (2007) who also reported this shift in thigh and calf muscle activity between squatting and stool-squatting postures for a paper cutting task. Unfortunately, Sriwarno et al. (2007) did not investigate the neuromuscular fatigue and blood circulation of lower limbs, which might improve the understanding of differences in biomechanical and physiological demands of lower extremities in the two postures. Further, the negative MF findings suggest that both rebar tying tasks did not induce neuromuscular fatigue of lumbar and calf muscles (Figure 4.6). It indicates that the increases in self-perceived discomfort following the rebar tying task (especially in the squatting posture) may be unrelated to local muscle fatigue of lower extremities.

4.4.2 Trunk kinematics

The use of a stool during stool-squatting rebar tying helped reduce the average total trunk flexion angle by approximately 9º as compared to squatting (Figure 4.7). This ergonomic tool helps restore the trunk flexion angle back to the limit (60º) recommended by the international organization for standards (ISO) for static working postures [ISO 11226:2000 (*ISO 2006*)]. Sriwarno et al. (2007) also reported a decrease in trunk flexion after using a stool for a paper cutting task as compared to squatting posture. However, their findings could not be directly compared with the present study given the discrepancy in the definitions of “trunk” in the two studies. Despite significant reduction in the total trunk flexion angle in the current study, no significant differences in the muscle activity or normalized MF values of lower back muscles between the two rebar tying postures were observed. This finding may be attributed to the flexion-relaxation phenomenon which involves myoelectric silence of lumbar paraspinal muscles when asymptomatic individuals maintain an almost fully flexed lumbar spine (McGill and Kippers 1994; Shirado et al. 1995). Literature suggests that such silence in lower back muscle activity starts at around 50º of trunk flexion (Solomonow et al. 2003). With the mean trunk flexion angle of > 55º and lower back muscle activity of < 1.5%RIC in the current study, the flexion-relaxation phenomenon might occur during both rebar tying tasks. The notion is further supported by previous studies that found a significant decrease in paraspinal muscle activity during passive sitting postures (i.e. slump sitting) as compared to active sitting (Sullivan et al. 2002, 2006).

4.4.3 Lower extremity blood circulation

To the knowledge of the authors, no prior study has compared the lower extremity SpO_2 levels between the two rebar tying postures. The significantly higher SpO_2 values of legs during stool-squatting rebar tying as compared to squatting (Figure 4.8) indicate a potential temporary ischaemia of lower extremities in the squatting posture. As a result, this may reduce the oxygen supply (local hypoxia) to skeletal muscles which is necessary for their normal functioning. It is well known that reduced oxygen supply to muscle tissues can adversely affect human muscle performance (e.g. increased rate of muscle fatigue, and decreased time to exhaustion and muscle numbness (Chung et al. 2003; Cymerman et al. 1989; Hepple 2002)). The local hypoxia of lower limb muscle during squatting rebar tying might explain the significant temporal increases in self-perceived discomfort during the squatting rebar tying despite the absence of decreases in MF values. It also explains the lower self-perceived discomfort during stool-squatting rebar tying given the better blood circulation of lower extremities.

4.4.4 Self-perceived discomfort

As aforementioned, the difference in self-perceived discomfort in the two postures could be associated with differential decreases in blood circulation in lower extremities. Additionally, different body weight transfer mechanisms might explain the difference in self-perceived discomfort ratings. Sriwarno et al. (2007) revealed that using a stool in squatting could significantly reduce the feet-ground reaction force up to 25% by providing an alternate path for body weight transfer through a stool. Overall, these findings substantiated that the effect of stool significantly decreased the self-perceived discomfort rating and this beneficial effect became more obvious as time elapsed (Figure 4.9).

4.5 IMPLICATIONS

Work-related MSDs are one of the leading causes of occupational disability among construction workforce (Arndt et al. 2005). Ergonomic interventions are one of the effective avenues for preventing MSDs in the construction industry (Denis et al. 2008). Construction professionals, specifically project managers and policymakers can play a vital role in this regard. By deepening their understanding of physical demands and postural practices employed by workers in various construction trades, it may help identify the root causes of the trade specific MSDs and derive new solutions to alleviate high physical workload in each trade. For instance, the current results help construction professionals recognize a simple stool can reduce discomfort of manual rebar tying in Asian culture.

The use of such a squatting-stool might serve even a wider construction worker community. As most Asian construction workers squat down to undertake work tasks near or at ground level (e.g. floor dismantling, tile fixing, welding and electrical works) (Figure 4.10). Given the simplicity and low cost of the squatting-stool, it may have a great potential to be widely adopted among Asian construction workers.


(a) Floor dismantling

(b) Tile fixing

(c) Welding

(d) Electrical works

Figure 4.10 Other construction tasks requiring squatting postures

Although the results of the current study might help alleviate the physical workload of manual rebar tying, the use of squatting-stool should be a part of a wider management policy rather being the only strategy for managing MSDs. Other work-related MSD management approaches such as regular muscle strengthening and stretching exercises (Parker and Worringham 2004), postural variation, adjustment of the work schedule to make physically demanding tasks intermittent should also be included in a broader mitigation scheme (Umer et al. 2017b). Additionally, manufacturing alternatives such as offsite prefabrication might be considered to eliminate the need of onsite fabrication/assembling of certain items, which demands strenuous physical work and/or awkward postures.

4.6 LIMITATIONS

Despite these promising findings, future research is warranted. First, the biomechanical effectiveness of the squatting-stool and its acceptance/feasibility should be verified in actual rebar workers at construction sites. Second, the biomechanical and physiological effects of prolonged use of squatting-stool (three to four hours work shift) should be investigated prior to its onsite adoption. Third, the design of the squatting-stool should be refined. For example, the interviewed construction project managers suggested the legs of the stool to be modified to prevent the legs from being stuck in the rebar mesh. Other design variables of the stool (e.g. material, height, weight and foldability) should also be considered.

Although the use of the stool has resulted in significant physical and self-perceived benefits, the outcomes indicate that squatting-stool rebar tying still requires large trunk flexion (mean flexion angle = 57º). This underpins the necessity of improving this domain. Power tying tools may have the potential to solve this shortcoming by allowing rebar workers to perform rebar tying in standing (Albers and Hudock 2007; Vi 2003). However, power tying tools also have their drawbacks including higher initial cost, frequent maintenance cost, inability to handle all sizes of rebars (in terms of diameter), substantial weight, need for special tying wire, operational vibrations, and loss of productivity in case of machine breakdown (Albers and Hudock 2007; Dababneh et al. 2000; Vi 2003). It is hoped that future power tools will solve some or all of these limitations. Alternatively, semi-automatic ergonomic tools could be developed to replace electric motors with hydraulic/mechanical components so as to lower the cost and weight of these tools. Nevertheless, till then squatting-stool could serve as an interim low-cost intervention which can significantly mitigate the physical workload in manual rebar tying.

CHAPTER 5

PROACTIVE SAFETY MEASURES: QUANTIFYING THE UPRIGHT STANDING STABILITY AFTER SUSTAINED REBAR TYING POSTURES[4]

5.1 INTRODUCTION

Fall accidents (FAs) are one of the major barriers to achieve occupational safety in the construction industry worldwide. During 2015, FAs were the major fatal injuries in the US construction industry (BLS 2016b). Similarly, they were the leading cause of fatal injuries in the New Zealand construction industry from 2006 to 2009 (DoL 2011). Chinese and Hong Kong construction industries share the same trend, where more than 50% of construction site accidents involved FAs (Chan et al. 2008; Yung 2009). In addition to fatal FAs, non-fatal FAs have also raised a great concern in the industry. It was estimated that non-fatal FAs in the US construction industry caused an average of 10 days of sick leaves between the period of 1992 and 2000 (Bobick 2004). Likewise, the highest number of compensation claims filed for non-fatal injuries in the Hong Kong construction industry from 2004 to 2008 were associated with FAs (Li 2009). Given that FAs can delay/disrupt the construction schedule, decrease

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Umer, W., Li, H., Szeto, G. P., and Wong, A. Y. (2018) “Proactive safety measures: Quantifying the upright standing stability after sustained rebar tying postures” *Journal of Construction Engineering and Management* 144(4)

productivity, increase economic burden and deprive the supply of skilled workers (Earnest and Branche 2016), there is a pressing need to lower the risk of FAs in the construction industry.

Since more than three-fourth of total FAs are attributed to specialty trade contractors (Huang and Hinze 2003; Kang et al. 2017), specific attentions should be given to individual trades to reduce FAs. Ironworkers (including both structural steel and rebar workers(BLS 2015b) are known to have an increased risk of FAs (Huang and Hinze 2003; Kang et al. 2017). For instance, the incidence rate of fatal falls in the US construction industry was the highest among ironworkers between 2003 and 2008 (Dong and Wang 2011). An injury record also revealed that US rebar workers had a significantly higher incidence of FAs than workers in other construction trades (Hunting et al. 1999). In order to prevent FAs, it is paramount to identify causative behaviors/work practices in the industry that cause the loss of balance (Antwi-Afari et al. 2017; Hsiao and Simeonov 2001). During rebar tying, workers may face multiple personal (e.g. risky behavior), environmental (e.g. height of work, availability of personal protective equipment or weather) and task-specific risk factors that may lead to FAs. While personal and environmental factors may vary significantly among individuals or construction sites, the identification and modifications of task-specific risk factors may mitigate the risk of falls in rebar workers. Task-specific risk factors include, but not limited to: (1) rebar tying in awkward postures with periodic posture transitioning (DiDomenico et al. 2016; Jebelli et al. 2016); (2) working at height (e.g. tying rebar for retaining walls, deck of bridges or multistory buildings) (CPWR 2013); (3) traversing uneven work surfaces (Hunting et al. 1999); and (4) work-related fatigue (Pline et al. 2006).

Prolonged awkward work postures may affect the standing balance of rebar workers. Observational studies have reported that rebar workers spend up to 48% of their worktime in non-neutral (flexed, laterally bent and/or twisted) trunk postures (Forde and Buchholz 2004). Of various awkward postures, squatting and stooping are the two most prevalent postures for manual rebar tying (Umer et al. 2017b). Research has shown that prolonged squatting/stooping postures can elicit back and leg fatigue (Umer et al. 2017b) that may compromise standing stability and balance (DiDomenico et al. 2010b). Theoretically, volitional postural transitions from non-neutral work postures to standing can disturb the functioning of vestibular and/or somatosensory system (Gauchard et al. 2001), which can be further disturbed by the presence of simultaneous work tasks or other environmental risk factors for falls at construction sites (DiDomenico et al. 2016). Importantly, since some rebar workers need to work in an environment with a small base of support (e.g. a scaffold) that prevents them from using stepping strategy for maintaining standing balance (Robinovitch 2003), the impact of awkward rebar tying postures on the post-task standing balance of these workers may be more profound (DiDomenico et al. 2011).

Although different rebar tying postures may have differential impacts on the post-task standing balance, the effects or underlying mechanisms of various rebar tying postures on the ensuing standing postural controls remain undetermined. Recent studies have shown that squatting, stooping, and stool-sitting rebar tying postures elicit different back/leg muscle activity and lower limb circulation (Umer et al. 2017a; b). It is plausible that these physical changes may be related to changes in post-task standing balance. Since an in-depth understanding of these relations may help develop proper ergonomic interventions to minimize the risk of FAs in rebar workers, the objectives of the current study were to compare the effects of various prolonged rebar tying postures (squatting, stooping, and stool-sitting) on the ensuing standing stability metrics, as well as to determine the relations among back and leg muscle activity, lower limb circulation during rebar tying, and the subsequent standing stability.

5.2 LITERATURE REVIEW

Risk factors for FAs can be classified into three domains: personal, task-related and environmental factors (Hsiao and Simeonov 2001). To identify various risk factors for FAs, many approaches have been documented in the literature. These include (1) site observations (Hallowell and Gambatese 2009), (2) construction site plan and schedule based risk identification (Saurin et al. 2003), (3) investigation of case reports and accidents archival data (Nadhim et al. 2016), (4) semi-structured interviews with the workers involved in FAs (Bentley et al. 2006), and (5) use of virtual reality and 4D computer aided designs (Chantawit et al. 2005). Based on these risk identification strategies, multiple ways are suggested to prevent FAs. These include, but are not limited to, (1) the installation of safety nets, guardrails, personal fall arrest systems and fall protection plans (Hsiao and Simeonov 2001), (2) the use of warning-line strategies and workers monitoring systems (Earnest and Branche 2016), (3) safety audits of construction sites (Kaskutas et al. 2009), (4) scheduled adjustment for safety risk allocation (Yi and Langford 2006) and (5) integration of Building Information Modelling (BIM) with safety checklists to identify potential risks (Zhang et al. 2013).

Although many strategies have attempted to reduce the risk of FAs, FAs remain to be one of the largest contributors of construction accidents (Nadhim et al. 2016). A possible reason for the difficulty in mitigating FAs may be related to the current methods of risk identification (Hsiao and Simeonov 2001). A predominant mitigation approach relies on reviewing the archival data and reports to identify the risk factors. However, this approach may not reveal the actual causes of FAs because the results can be confounded by biases originated from reporters' background, experiences, responsibilities and beliefs (Dekker et al. 2011), and/or the investigators' subjective interpretation of injury reports (Nadhim et al. 2016). Consequently, the retrospective nature of this approach might not be always successful in establishing true cause-effect relations (Dekker et al. 2011). Likewise, other common risk mitigation strategies (e.g. site plan and observation based methods) might not always reduce fall risks because the ever-changing environment of construction sites and resources increase the difficulty in identifying and mitigating fall hazards.

While task-related accident risks for construction activities comprise a large proportion of overall safety risk at a construction site, there is a paucity of research quantifying the task-specific risk factors (Hallowell and Gambatese 2009). Quantifying task-related risks for falls are an important step to reduce FAs, especially for rebar workers who have a higher rate of FAs (Dong and Wang 2011; Hunting et al. 1999). Since rebar tying requires workers to work in a sustained posture, such prolonged activity may increase the fall risk upon post-task upright standing (DiDomenico et al. 2016). Recently, Jebelli et al. (2016) quantified effects of postures (standing and squatting) and carrying weights on postural stability metrics. They found that standing while carrying the load or wearing an asymmetrically loaded toolbelt could result in significantly better stability as compared to performing these tasks in a squatting posture. However, their tasks were limited by the short duration (30 seconds only), absence of construction task simulation, and no post-task balance measurement. DiDomenico et al. (2011) also attempted to quantify the effect of different postures on standing balance. They revealed that the standing balance of individuals after 120 seconds of stooping or squatting posture was better than that after 120 seconds of two-legged kneeling. However, their study was limited by the short duration of maintaining the target posture without performing any simulated work tasks. Importantly, DiDomenico et al. (2011) assessed the standing balance control based on the balance metrics in 1 second, which was deviated from the recommended minimum duration for such test (i.e. 20 seconds) (Paillard and Noé 2015). Further, no study has investigated the physical responses during the performance of a simulated task in a target posture, which may help explain the divergent postural responses among various postural conditions.

5.3 METHODS

5.3.1 Participants

Thirteen male individuals with a mean age of 27.5 ± 4.4 years and a mean body mass index of 22.8 ±1.5 kg/m^2 participated in the experiment. To be eligible for the study, the participant should have a normal or corrected vision, no known balance problems, and the absence of any musculoskeletal disorders in the past 12 months (DiDomenico et al. 2011).

5.3.2 Procedure

The current experiment adopted a crossover study design in a single laboratory visit (Figure 5.1). The experimental procedures were explained to the participant and a written consent was sought prior to data collection. The participant was then instructed to perform three sets of reference contractions (RCs) for bilateral lumbar, thigh and calf muscles while the respective surface electromyography (sEMG) signals were measured. The sEMG signals of the target muscles during RCs were used to normalize the respective muscle sEMG during subsequent simulated rebar tying tasks. The participant was then instructed to stand still barefooted on a force plate for 20 seconds with feet apart at shoulders' width and hands resting aside while looking straight forward at a target (DiDomenico et al. 2011). Prior to the force plate data collection, the outline of the feet placement was traced on a piece of paper adhered to the force plate so as to guide subsequent feet placements. Afterwards, the participant performed simulated rebar tying in one of the three postures (squatting, stooping or stool-sitting, Figure 5.1) in a randomized manner. During the rebar tying, muscle sEMG activity and right toe circulation as measured by an oximeter were being monitored. Immediately after the rebar tying, the participant was instructed to repeat the 20-second standing test on the force plate. Participants were instructed to rest on a chair with backrest for 20 minutes before being randomized into one of the remaining two rebar tying work postures. They repeated the same experimental procedure until all three work postures were completed.

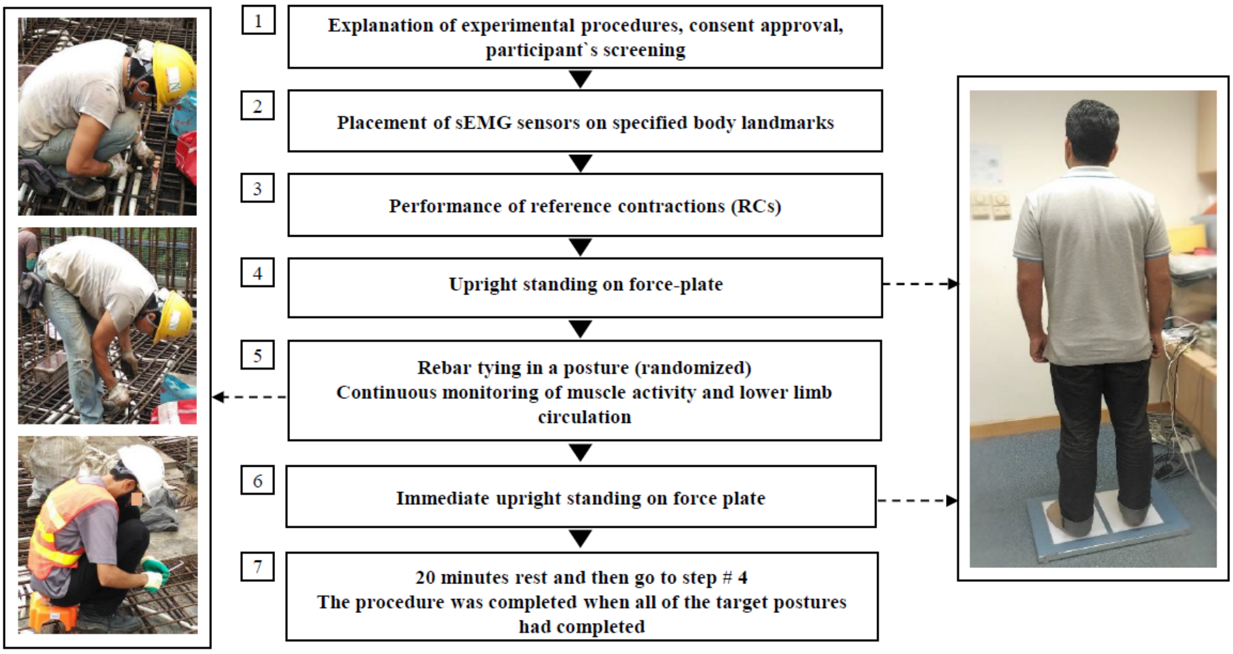


Figure 5.1 Experimental procedure

Note: sEMG= surface electromyography

a. *Reference Contractions (RCs)*

Three sets of reference contractions (RCs) were performed for lower back, and bilateral thigh and calf muscles separately (Umer et al. 2017a). Briefly, each set consisted of three 5-second isometric contractions separated by a rest period of 5 seconds. For lower back muscles, participants performed a modified Sorensen test, which required them to hold their unsupported trunk while lying prone on the bench edge. The RCs for thigh muscles involved one-by-one performance of lunge test with the rear knee (non-lunging) just off the ground. For the calf muscles, participants were instructed to perform an alternated single leg heel-rise test. During heel-rise test, participants could use index fingers to gently touch the wall to maintain balance.

b. *Rebar Tying Simulation*

The simulated rebar tying was performed using a pigtail tool and tie wires. The setup comprised a mesh of 5-by-5 plastic pipes of 1.2m length separated from each other by 0.2m center-to-center to replicate reinforcement steel mesh. The experiment involved making ties at the first three rows of the replicated mesh. To assess each distinct rebar tying posture, the participants were not allowed to rest or alter their work posture. However, natural movements required for rebar tying were allowed.

Initially, each rebar tying posture was planned to last for 20 minutes. However, the two participants involved in pilot testing requested to shorten the duration because of severe lower leg discomfort. The reported lower leg discomfort increased more rapidly in stooping posture than squatting. Accordingly, the duration for rebar tying was shortened to 12.5 minutes for squatting and stool-sitting, and 5 minutes for stooping. The specific duration of 12.5 and 5 minutes were chosen because these values were multiples of 2.5, which was the chosen interval to solicit perceived discomfort scores in another study (Umer et al. 2017a). For stool-sitting, each participant was given an option to choose a stool with either 10cm or 15cm in height. All participants chose the one with 15cm in height.

5.3.3 Instrumentation

The pre- and post-task standing stability of the participant was evaluated using a portable multicomponent force plate with four load cells (Kistler 9286AA, Kistler Instrument Corp., Winterthur, Switzerland). The data was sampled at 1000Hz. Muscle activity during RCs and rebar tying simulation was measured by a wireless sEMG system (TeleMyo, Noraxon USA, Arizona) at a sampling frequency of 1500Hz with a common mode rejection ratio of 100dB. Bipolar disposable electrodes with a diameter of 15mm and inter-electrode distance of 20mm were placed at five locations of muscles. The target locations of electrode placements for each muscle (Table 5.1) were chosen in accordance with the recommendation of *Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles* (SENIAM 2005). Each muscle site was shaved, abraded with sandpaper and cleaned with alcohol swabs prior to the electrode placement to keep skin impedance below 10kΩ. Lower limb circulation was measured in terms of the oxygen saturation level (SpO_2) in the plantar digital artery of the right toe. Specifically, a sports grade perfusion resistant pulse oximeter (MightySat Pulse Oximeter 9900, Masimo Corporation, Irvine, CA) was clipped on the right toe to collect data at 0.5Hz throughout the rebar tying simulation.

Table 5.1 Target location for sEMG electrode placement (SENIAM 2005)

Bilateral muscle	**Electrode placement**
Erector spinae	L3 level of the lumbar spine (5cm laterally from midline)
Multifidus	Aligned with a line joining from the caudal tip posterior iliac spine to the L1-L2 joint (2cm laterally from the midline at the L5 level)
Rectus femoris	At 50% of the line distance formed by joining the anterior iliac spine and the superior part of a patella
Gastrocnemius lateralis	At one third of the line distance formed by a line joining the head of fibula to the heel
Gastrocnemius medialis	At the most prominent bulge of the muscle

5.3.4 Dependent variables

a. Standing stability metrics

Balance stability of a person can be defined as an individual's ability to restore or maintain upright posture (Maki et al. 1990). It is usually quantified by the magnitude of postural sway that refers to the displacement of an individual's center of mass (Schiffman et al. 2006). Center of pressure (COP) is the vertical projection of an individual's center of mass and is one of the most widely used indices to measure postural sway using the force plate data (Prieto et al. 1996). The current study used two types of COP metrics to examine the pre- and post-task standing stability of the participant: (1) global metrics, and (2) time-to-stabilize (TTS). Global metrics characterize the magnitude of COP traces in the time and frequency domains. A large magnitude of any of these variables indicates a poor postural/balance stability (Paillard and Noé 2015). Whereas TTS refers to the duration required by an individual to recover from postural instability (Johnson et al. 2003). As such, a larger TTS indicates an increased risk of FAs (DiDomenico et al. 2016).

Three global metrics were chosen in this study to investigate the pre- and post-task standing stability. These metrics included: (1) COP mean velocity (defined as distance covered by COP in a unit time, in anterior-posterior (AP) and medio-lateral (ML) direction separately), (2) total path length (defined as total distance covered by COP in 20-secs) and (3) 90% eclipse area (defined as an eclipse which can encompass 90% of all of the COP coordinates during a period of 20-sec) . All of them are believed to be highly correlated to changes in COP (Prieto et al. 1996). These metrics were calculated to identify the most appropriate parameter for future posture-induced standing instability studies. Prior to calculation of COP metrics, the raw force plate data was filtered using a second-order Butterworth filter with a cut-off frequency of 3 Hz.

The global COP sway metrics for 20-second pre- and post-task upright stance were calculated as follow:

$$Mean\ Velocity_{AP} = \frac{\sum_{n=1}^{N-1} |AP[n+1] - AP[n]|}{t}$$ (eq 5.1, Prieto et al. 1996)

$$Mean\ Velocity_{ML} = \frac{\sum_{n=1}^{N-1} |ML[n+1] - ML[n]|}{t}$$ (eq 5.2, Prieto et al. 1996)

$$Total\ path\ length = \sum_{n=1}^{N-1} [(AP[n+1] - AP[n])^2 + (ML[n+1] - ML[n])^2]^{1/2}$$ (eq 5.3, Prieto et al. 1996)

$$90\%\ eclipse\ area = \pi\chi_2^2 \sqrt{\lambda_1\lambda_2}$$ (eq 5.4, Prieto et al. 1996)

AP[n] and ML[n] are COP coordinates in AP and ML directions, respectively. n refers to nth value and N is the last value in the respective force plate dataset. t is the time duration for COP data collection. χ_2^2 is the chi-square cumulative distribution function with two degrees of freedom at 90% probability and $\lambda_1\lambda_2$ are eigen values of sample variance-covariance matrix (Schubert and Kirchner 2014). Although pre-task standing stability was computed for each rebar tying posture, separate one-way repeated measures analyses of variance (ANOVA) revealed no significant temporal difference in any pre-task COP global metrics across all postures. This indicated that the 20-minute rest period between two rebar tying simulation tasks was sufficient to allow recovery from post-task standing instability, if any. Therefore, three pre-task stability values for each global parameter were averaged for subsequent comparisons with the respective post-task COP global parameter.

Post-task TTS (calculated separately for AP and ML directions) was estimated by calculating the time taken by COP to return to stable velocity. Stable velocity was defined as COP velocity lying within 3 times of standard deviations of the pre-task velocity within an epoch of 25 milliseconds identified using a moving window of 1ms. A customized MATLAB program (Version 2015a, MatchWorks, Inc., Natick, MA, USA) was used for all COP data processing.

b. Physical measures

Respective muscle activity in the three rebar tying postures was compared using average muscle activations (50% amplitude probability function, APDF) (Umer et al. 2017b). The raw sEMG data was bandpass-filtered between 20 and 500Hz, notch filtered for the electrical noise of 50Hz, and smoothened using a 50ms root mean square (RMS) moving window. sEMG data was then normalized to the maximum sEMG signals during RCs (identified using 1000ms moving window and step size of 50ms) to enable within-subject comparison of various rebar tying postures (using 50% APDF) and represented as a percentage of RC maximum sEMG. Noraxon MyoResearch MR3.8 (Noraxon USA Inc., USA) software was used for sEMG data processing. Although sEMG data was collected bilaterally from target muscles, multiple paired t-tests with false detection rate (FDR, (Benjamini and Hochberg 1995)) correction revealed no significant difference between left and right side muscle activity for all rebar tying postures. Accordingly, left and right-side muscle activity data was averaged for further statistical analysis. Lower limb circulation data was expressed as average SpO_2 values (50% APDF) during each rebar tying posture.

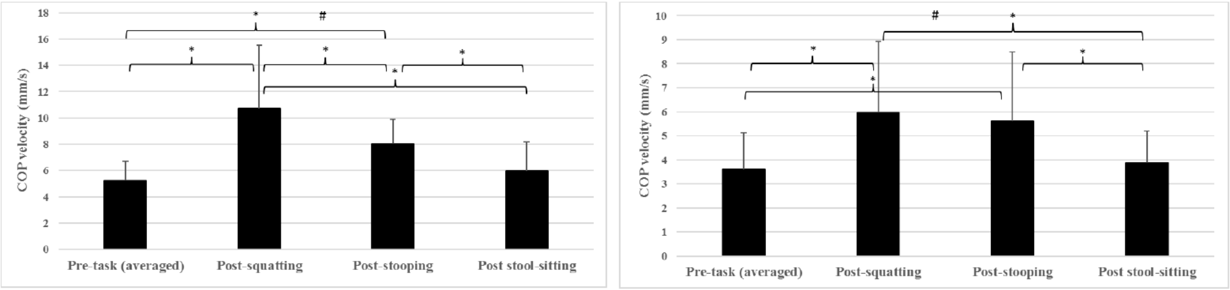
5.3.5 Statistical analysis

Separate one-way repeated measures ANOVAs were used to compare various averaged pre- and post-task COP global metrics, and TTS for the three postures. Rebar tying postures were chosen as between-group variable whereas various COP global metrics and TTS were the within-group variables. Paired t-tests with FDR correction were used for post-hoc pairwise comparisons. Similarly, separate one-way repeated measures ANOVAs and post-hoc paired t-tests (with FDR correction) were used to compare average muscle activity of different muscles and lower limb circulation across the three postures. All statistical analyses were conducted using SPSS (Version 19.0, IBM Corporation, Armonk, NY) software with significance level set at 0.05. Additionally, in order to examine the variability in standing stability metrics of individual participants, the between-participant differences in various baseline (pre-task) and standing balance stability metrics following different postures were visually inspected.

5.4 RESULTS

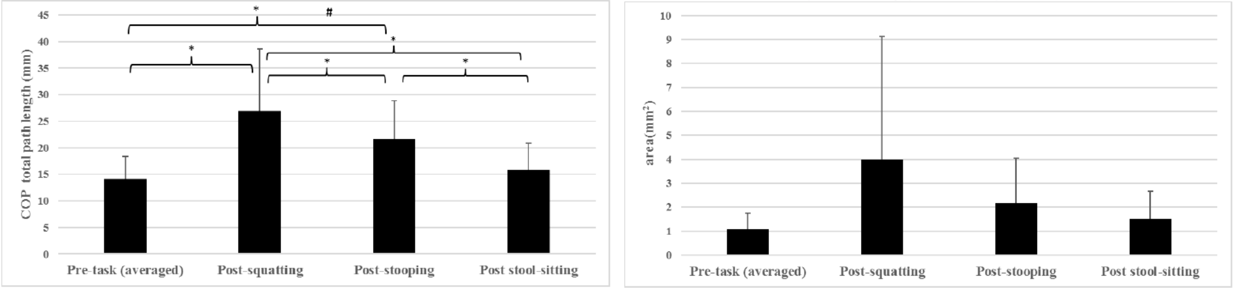
5.4.1 Standing stability metrics

Repeated measures ANOVA revealed a significant difference among the pre- and post-task postural sway values for all global metrics ($p<0.01$), except the 90% eclipse area ($p = 0.09$) (Figure 5.2). Post-hoc tests indicated that COP velocity in the AP direction and the total path length found significant differences in post-task postural controls among all rebar tying postures. Specifically, the squatting posture caused the worst post-task standing stability (as indicated by COP velocity in the AP direction and the total path length) while stool-sitting had no significant adverse effect on standing stability. However, COP velocity in ML direction could not discriminate any difference in post-rebar tying postural balance deficits between squatting and stooping postures (Figure 5.2b). The COP 90% eclipse area also indicated a greater imbalance for post-squatting and post-stooping standing task than post-stool sitting but no significant difference was observed, which could be attributed to a large variance of data and a relatively small sample size. Overall, all global metrics indicated that pre-task upright standing had the least absolute postural sway, followed by post stool-sitting, post-stooping and post-squatting rebar tying.



a) COP velocity (AP direction)

b) COP velocity (ML direction)



c) COP total path length

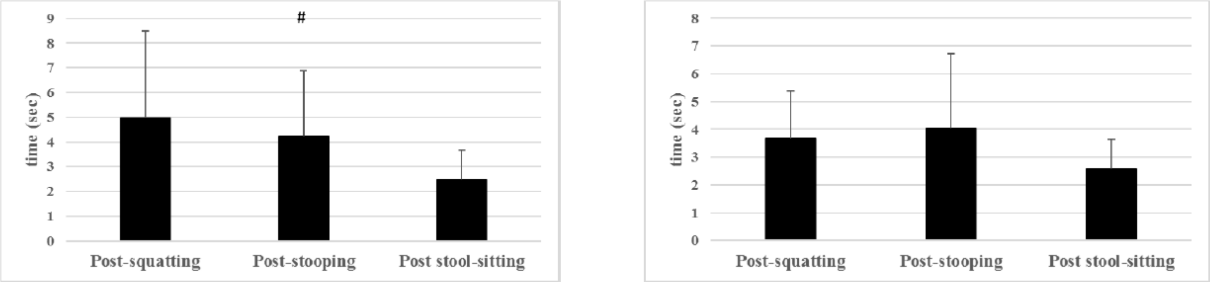
d) COP 90% eclipse area

Figure 5.2 Pre- and post-task differences in upright standing stability

Note: # indicates significant results for one-way repeated measures ANOVA (analysis of variance); * indicates $p < 0.05$ for post-hoc paired t-tests (with FDR (false detection rate) correction); COP= center of pressure; AP= anterior-posterior direction; ML= mediolateral direction; bars indicate standard deviation

Although COP velocity in the AP direction and the total path length displayed similar statistical differences among various rebar tying postures (Figure 5.2a and 5.2c), only the post-hoc test results of COP total path length are reported here to avoid unnecessary repetition of similar findings. Specifically, post-squatting COP total path length was significantly greater than pre-task, post-stooping and post-stool sitting postural sway values [mean differences were 12.8 mm (95% CI= 6.7 to 19.0 mm), 5.2 mm (95% CI= 0.9 to 9.5 mm) and 11.1 mm (95% CI= 5.6 to 16.6 mm), respectively]. While post-stooping standing demonstrated significantly larger COP total path length than the respective pre-task and post stool-sitting values [mean difference = 7.6 mm (95% CI= 3.4 to 11.9 mm) and 5.9 mm (95% CI= 2.7 to 9.2 mm) respectively], the difference between pre-task and post stool-sitting postural sway was non-significant, regardless of the COP sway parameter used.

Similar to global metrics, TTS also varied distinctly among the three postures (Figure 5.3). The stool-sitting rebar tying task induced the smallest TTS on standing (2.5 and 2.6 seconds for AP and ML directions, respectively), followed by stooping (4.2 and 4.0 seconds) and squatting postures (5.0 and 3.7 seconds). One-way repeated measures ANOVA revealed a significant between-posture difference in TTS in the AP direction ($p = 0.04$). However, post-hoc pairwise comparison tests (with FDR correction) could not differentiate among various post-task TTS values, Specifically, TTS (AP direction) for post stool-sitting was 2.5 seconds shorter than post-squatting ($p = 0.09$) and 1.8 seconds shorter than post-stooping rebar tying ($p = 0.07$). The non-significant results might be attributed to a large variance in TTS values and a relatively small sample size (Figure 5.3).



a) TTS (AP direction)

a) TTS (ML direction)

Figure 5.3 Time-to-stabilize for various rebar tying postures

Note: # indicates significant results for one-way repeated measures ANOVA (analysis of variance); TTS= time to stabilize; AP= anterior-posterior direction; ML= medio-lateral direction; bars indicate standard deviation

Individual pre- and post-task postural sway (in terms of COP total path length) are shown in Figure 5.4. Participants showed a large variation in pre-task total path length, ranging from 8.6 mm (participant 2) to 23.5 mm (participant 9). Post-task increase in baseline (pre-task) total path length for different rebar tying postures did not reveal a clear trend across participants. Some of the participants experienced a relatively smaller increase in post-task total path length, whereas the other depicted a much larger increase. Specifically, five participants (participant number: 4,6,8,9 and 10) exhibited a maximum post-rebar tying increase in COP total path length by 70% of averaged pre-task postural sway. Three participants (participant number: 1,5 and 11) showed a maximum post-task increase in total path length by 70% to 100% of the pre-task total path length, and four participants (participant number: 2,7,12 and 13) demonstrated a maximum increase of 100% to 150% in baseline COP total path length. Participant number 3 even exhibited a 300% increase in post-rebar tying COP total path length as compared to its baseline.

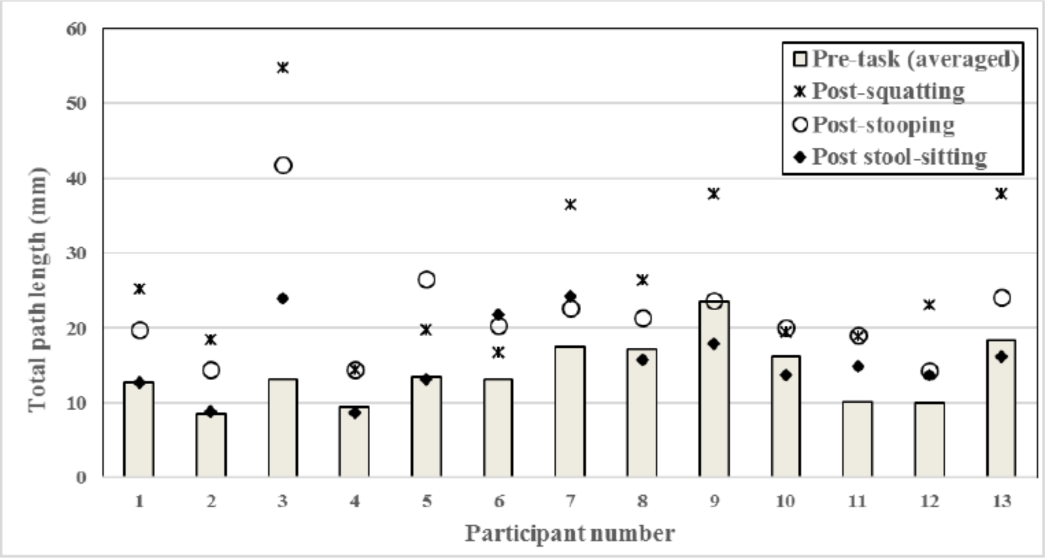


Figure 5.4 Post-task increase in total path length across the participants

5.4.2 Physical measures

Normalized sEMG of the lower back and major lower limb muscles during rebar tying are shown in Figure 5.5. Generally, the average muscle activity during the stooping posture was the largest regardless of muscle observed. One-way repeated measures ANOVA revealed a significant difference in sEMG activity among various postures for all muscles. Post-hoc tests revealed that sEMG of multifidus, gastrocnemius lateralis and gastrocnemius medialis during stooping were significantly larger than the respective values during squatting and/or stool-sitting (Figure 5.5), while the sEMG activity of rectus femoris during stooping posture was significantly larger than that of stool-sitting posture.

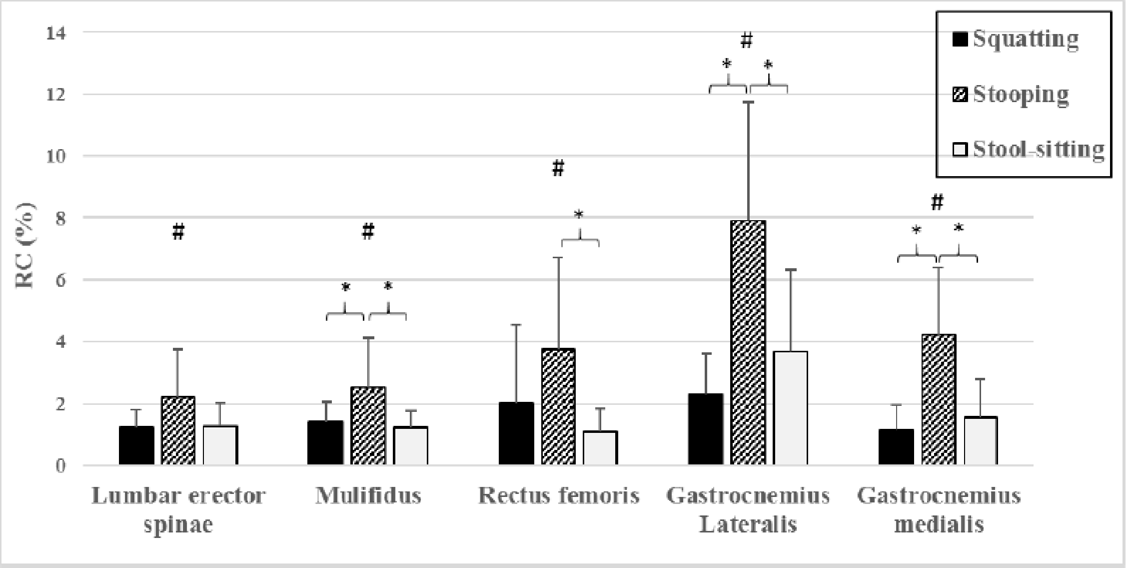


Figure 5.5 Average muscle activity (50% APDF) during rebar tying

Note: # indicates significant results for one-way repeated measures ANOVA (analysis of variance); * indicates $p < 0.05$ for post-hoc paired t-tests (with FDR (false detection rate) correction); RC= reference contraction; bars indicate standard deviation

One-way repeated measures ANOVA also showed that the average lower limb circulation (50% APDF of SpO_2 values) significantly differed across the three postures ($p = 0.001$) (Figure 5.6). Specifically, the stooping and stool-sitting postures had significantly better blood circulation than squatting with the mean differences of 8.9% (95% CI= 3.6 to 14.1%) and 11.3% (95% CI= 4.3 to 18.2 %), respectively.

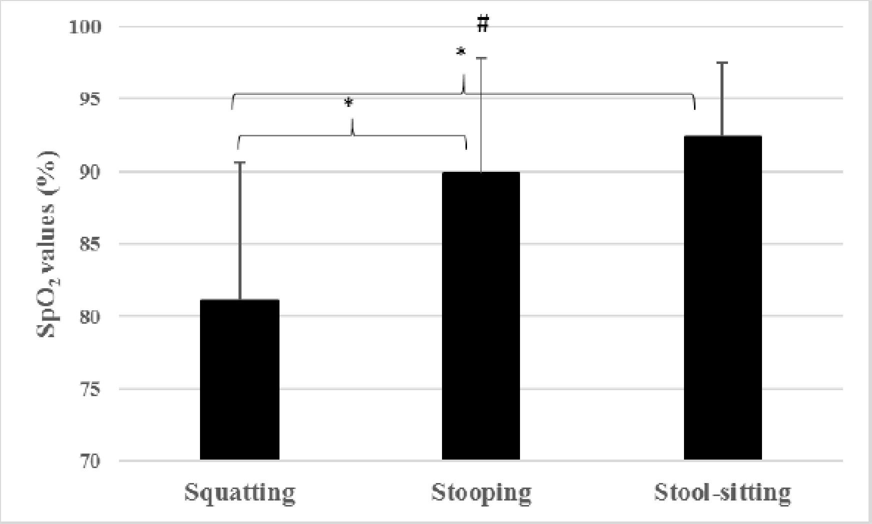


Figure 5.6 Lower limb circulation variation among rebar tying postures

Note: # indicates significant results for one-way repeated measures ANOVA (analysis of variance); * indicates $p < 0.05$ for post-hoc paired t-tests (with FDR (false detection rate) correction)

5.5 DISCUSSION

From the management perspective, it has been suggested that what cannot be measured, cannot be managed (Cioffi 2006). In other words, the quantification of risk factors for FAs is essential for minimizing relevant occupational safety hazards. This study is the first one to quantify the standing balance ability following various prolonged rebar tying postures and to evaluate the effect of an ergonomic stool on reducing standing instability. The results highlighted that work postures could significantly affect post-task postural stability and a simple ergonomic intervention could minimize such adverse effects.

5.5.1 Effects of work postures on standing balance

The post-rebar tying stability metrics indicated that traditional work postures (squatting and stooping) induced significant increases in several COP global metrics, while the use of a sitting-stool significantly minimized the post-task postural sway (Figure 5.2). Since an increased postural sway following a work task may indicate an elevated risk of falling (Pline et al. 2006), These findings substantiate the use of a simple ergonomic intervention during rebar tying to minimize the balance disturbance in rebar workers. Rebar tying is a labor-intensive construction trade, which largely depends on the manual execution of work tasks. These tasks may expose rebar workers to multiple risk factors of FAs (such as carrying heavy rebars or walking on the rebar mesh). Fortunately, rebar workers can modify their methods to perform their work so that better post-task standing postural control can be achieved. In fact, the modification of such human-factor or adoption of ergonomic based mitigation strategies have been suggested to be profoundly efficacious in reducing FAs in the construction industry (Robinovitch 2003).

The TTS results highlight the importance of standing balance recovery time after getting up from prolonged work postures (Figure 5.3). Since multiple environmental factors (such as adverse environmental conditions, working on slopes and heights) at construction sites may increase the risk of FAs (Earnest and Branche 2016) by affecting TTS after finishing a work task, construction managers/foremen should be aware of these factors and provide rebar workers with ample recovery time prior to their involvement in another risky tasks (such as transporting heavy rebars). Importantly, this awareness should be imparted to frontline workers through education and training, which are known to be an effective and proactive forefront measure against FAs (Nadhim et al. 2016).

The great variability in pre- and post-tasks standing balance of participants (Figure 5.4) implies variable risks of FAs for individuals. Since increased postural sway is an indicator of elevated risk of ankle sprains in the teenagers (Trojian and McKeag 2006) and falls in the older population (Piirtola and Era 2006), this might suggest that workers with larger baseline sway may be at a greater risk of FAs. Nevertheless, the pre-task postural sway may not necessarily predict the post-task sway. For example, Participant number 3, 5 and 10 demonstrated similar pre-task COP total path lengths (13.1 to 16.1mm) but their individual responses to rebar tying postures were very diverse. For instance, Participant number 10 showed a maximum increase of 24% in COP total path length after the stooping task, while Participant number 5 had a 96% increase in baseline COP total path length following the same task. Interestingly, the post-stooping COP total path length of Participant number 3 was 219% higher after post-stooping. These results signify the importance of examining individual outcomes alongside conducting group analysis for this type of balance studies. Collectively, despite the individual differences, it is generally agreed that a person with a larger post-task increase in postural sway is more likely to fall (Lin et al. 2009).

5.5.2 Physical changes compromise standing balance

Physical measures, as used in this study help better explain the distinct effects of various postures in affecting target muscles and blood circulation. In particular, a stooping posture was associated with significantly higher muscle activity in bilateral lower back, thigh and calf muscles as compared to squatting and stool-sitting postures (Figure 5.5). As such, sustained work-task postures with large muscle activity could easily cause muscular discomfort, fatigue and post-transition loss of balance (Pline et al. 2006). Importantly, despite relative low activity of lumbar muscles during stooping (average activity ≈ 2% of RC sEMG), such low lumbar muscle activity can still cause neuromuscular fatigue. Mcgill et al. (2000) suggested that work tasks entailing exertion of lower back muscles as low as 2% of maximum voluntary contraction can elicit fatigue after sustained for a long duration, which in turn may induce postural instability during standing (Lin et al. 2009). Moreover, transitioning from a sustained stooping work posture (involving tilting and non-neutral head postures) to a standing posture may compromise the ability of the vestibular system to anticipate the orientation of gravity (Paloski et al. 2006), making a rebar worker more vulnerable to FAs.

Contrary to stooping, squatting rebar tying posture involves significantly less muscle activations in the lumbar and calf muscles (Figure 5.5) and does not require full trunk flexion as required in stooping. However, opting for a squatting posture during rebar tying can significantly compromise the blood circulation in the lower extremities (Figure 5.6). Reduced blood circulation in the muscles is linked to poor muscle endurance and an increased rate of muscle fatigue (Hepple 2002). Besides, decreased blood circulation in the legs can adversely affect joint proprioception that decreased standing balance (DiDomenico et al. 2010b). In short, prolonged squatting may leave rebar workers more susceptible to FAs.

On the contrary, working in stool-sitting posture has multiple physical advantages over traditional rebar tying postures. It involves significantly less muscle activity for both trunk and leg muscles as compared to stooping (Figure 5.5) and better lower limb circulation as compared to squatting (Figure 5.6). These physical responses might explain the non-significant changes in the post-task postural sway (Figure 5.2) and minimum TTS (Figure 5.3) as compared to other rebar tying postures.

5.6 IMPLICATIONS

Safety against construction FAs demands a comprehensive set of strategies. Current onsite fall protection measures rely on the use of passive protection systems. In many instances, these measures are either nonpragmatic or unavailable (Hsiao and Simeonov 2001; Kang et al. 2017), leaving construction workers vulnerable to FAs. To better prevent FAs, conventional protection methods should be supplemented with some proactive measures such as Prevention through Design (PtD). The PtD concept involves identification of safety hazards during the design phase of construction activities and taking proactive measures to counter/avoid safety hazards (Dewlaney and Hallowell 2012). Aside from early diagnosis of various safety hazards, PtD should also include management of anticipated fall risk factors (task, environment and person related) such as prolonged awkward work postures during rebar tying. Essentially, as this study persuasively shows that the PtD concept can be used to improve the design of construction activities and ultimately reduce the number of accidents.

5.7 LIMITATIONS

Although the current study has deepened the knowledge pertaining to potential loss of balance among rebar workers, there are some limitations that should be addressed in future studies. First, participants involved in the current experiment were inexperienced rebar workers. Accordingly, future research is warranted to compare the findings in experienced rebar workers. Second, this experiment only tested a single duration of rebar tying postures. Future studies should evaluate the impacts of different time durations of work postures on the resulting standing balance of rebar workers. Collectively, the results from these studies may help design proper work-rest schedule to avoid substantial fatigue and/or loss of balance, which may lead to FAs (Pline et al. 2006). Third, the current study only explored the effects of various rebar tying postures on static balance. Future studies should explore how dynamic balance is affected by prolonged working postures.

Fourth, while exploratory studies are essential to identify individual risk factors for FAs, the importance of their interactions cannot be downplayed. Multiple risk factors could present simultaneously at a typical construction site. In fact, FAs are barely the consequence of a single risk factor (Dekker et al. 2011). Hence, future studies should explore FAs from a holistic approach by investigating multiple risk factors simultaneously (i.e. task, environment and personal factors). Lastly, while many FAs on construction sites have been attributed to loss of balance (Hsiao and Simeonov 2001), no quantitative tool has been developed to quantify the baseline and post-task/post-work shift postural stability of construction workers onsite. Although force plates which have been widely used in laboratory-based studies to evaluate standing balance, it is not feasible to use force plates at construction sites given their substantial weight and other requirements (such as allied electronic/power equipment, leveled and firm surfaces for measurements). As such, new tools should be developed to measure onsite postural stability of the construction workers in different times of the day and under different circumstances. This may enable early identification of workers with poorer postural control, and the prescription of tailor-make postural control exercises or balance training measures for these workers.

CHAPTER 6

DEVELOPMENT OF A TOOL TO MONITOR BALANCE OF CONSTRUCTION WORKERS FOR PROACTIVE FALL SAFETY MANAGEMENT

6.1 INTRODUCTION

Around the globe, fall accidents are a substantial burden and an impediment to accomplish occupational safety in the construction industry. During the year 2015, falls accounted for 40% of the total fatal accidents in the US private construction industry (BLS 2016a). In the UK, almost one-half of the all industrial fatalities every year are associated with construction fall accidents (Cameron et al. 2007). Likewise, the fatal fall accidents in the Australian construction industry accounted for more than one-third of all falls from height fatalities during 2003 to 2015 (Safe work Australia). Similarly, falls constitute a major proportion of accidents in the construction industry in China, Hong Kong, South Korea, Japan and Singapore (Chan et al. 2008; Poon et al. 2008; Yung 2009). While statistics indicate that falls result in a considerable number of fatal injuries, non-fatal fall injuries are also severely afflicting the global construction industry by placing significant economic, emotional and medical burden on the affected workers, their families and societies (Earnest and Branche 2016). In addition to the medical expenses, non-fatal falls cause losses to construction companies in forms of work absenteeism, productivity loss and compensation claims (Earnest and Branche 2016; Gillen et al. 1997). For example, a typical non-fatal fall accident caused an average of ten days of work absenteeism in the US construction industry from 1992 to 2000 (Bobick 2004). Likewise, the highest number of compensation claims filed in the Hong Kong construction industry were related to non-fatal falls (Li 2009). Taken together, reducing the risk of falls has become an important priority for researchers and practitioners alike in the construction industry.

6.1.1 Fall risk assessment in the construction industry

Various methods have been suggested in the literature for fall risk assessment in the construction industry. Traditionally, these include but are not limited to the review of fall archival data (Hu et al. 2011; Nadhim et al. 2016), interviews of fall affected workers (Bentley et al. 2006), site inspections (Hallowell and Gambatese 2009), schedule oriented site/work safety plans (Saurin et al. 2003), combined use of virtual reality and 4D construction plans (Chantawit et al. 2005; Hadikusumo and Rowlinson 2004) and Building Information Modelling (BIM) integrated safety rules approach (Zhang et al. 2013). Although considerable fall prevention efforts have been made, falls still outweigh the other reported construction accidents (Hanapi et al. 2013; Nadhim et al. 2016; Nguyen et al. 2016). One possible reason for this phenomenon may be ascribed to the shortcomings of traditional practices/techniques of fall risk identification, and passive fall protection measures (Hsiao and Simeonov 2001). For example, the use of archival data may not always reveal the actual cause of a fall incident because of probable bias, experiences and beliefs of the reporter and the subjective nature of interpretation (Dekker et al. 2011; Nadhim et al. 2016). Similarly, other methods (such as safety plans) cannot take into account of the dynamic interactions of workers, machinery and materials, which require real-time risk identification and mitigation methods (Rozenfeld et al. 2010; Umer et al.

2018b). More importantly, these risk methods do not consider personal fall risk factors (such as physiological traits, personal health, fatigue, age and body mass index) which are considered to be a major contributor to falls (Hu et al. 2011; Jebelli 2015; Nadhim et al. 2016).

Despite the shortcomings of existing risk identification methods, various fall protection measures have been implemented on construction sites. These include the use of personal fall arrest systems, installation of guardrails, deployment of safety nets (Chi et al. 2005; Hsiao and Simeonov 2001), hole (openings) coverings (Chi et al. 2005), warning-line systems (Earnest and Branche 2016) and fall risks scheduling for better risk management (Yi and Langford 2006). While these passive measures may prevent workers from falls, they cannot proactively identify risk factors for loss of balance, or distinguish workers with poor balance ability (Umer et al. 2018b) such that proper training or education can be given. Additionally, under certain situations, the deployment of aforementioned passive measures becomes nonpragmatic (such as working in a controlled decking zone) or these measures are not available to construction workers (Dong et al. 2017; Hsiao and Simeonov 2001; Kang et al. 2017), which in turn increases the risk of falls.

To better strategize against falls, it is essential to develop proactive strategies to identify task and environment related fall risks and to discern construction workers with poor balance controls (Earnest and Branche 2016; Jebelli 2015; Nadhim et al. 2016; Umer et al. 2018b). Given that many construction trades are labor intensive and physically demanding, these work tasks may leave the workers susceptible to fatigue, muscle pain and distraction which could afflict the balance of construction workers (Dzeng et al. 2014; Pline et al. 2006; Umer et al.

2017b, 2018b). For instance, it is not uncommon for construction workers to be involved in heavy manual material handling and working on sloped surfaces that can disturb their postural stability (Choi 2008; Davidson et al. 2009; Madigan et al. 2006; Umer et al. 2018b). If such fall risks can be identified proactively, remedial measures could be taken. For example, Umer et al. found that commonly adopted rebar tying postures in squatting or stooping may lead to the subsequent suboptimal control of standing balance (Umer et al. 2018b). Accordingly, they developed an ergonomic intervention using stool-sitting to significantly improve the standing balance after rebar tying tasks (Umer et al. 2018b). Furthermore, it is essential to identify fall risks in construction jobsites because multiple factors (personal, task-related and environmental risks) may present and interact concurrently. While each individual risk factor might have a minimal effect on balance control (DiDomenico et al. 2016), these factors may interact with one another to compromise the balance of workers (DiDomenico et al. 2010a; Sousa et al. 2014). In fact, since loss of balance is known to be a major cause of falls on construction sites (Chi 2016; Helander 1991; Hsiao and Simeonov 2001; Jebelli et al. 2016; Maki et al. 1990; Wong et al. 2016), it is paramount to proactively monitor the balance of the construction workers at different times of the day and plan appropriate mitigation strategies.

6.1.2 Recent related fall prevention studies in the construction industry

Traditionally, the fall prevention research in the construction industry was focused on optimum utilization of personal safety equipment and other allied fall protections. Lately, with recent technological advancement, efforts are underway to detect and mitigate fall risk factors before any accident occurs. Fall risk assessments have been used in health research for a long time. For example, balance assessments in community-dwelling elderly can provide information about the necessity of using walking aids and help caretakers taking care of seniors (Dzeng et al. 2014). Likewise, there is a pressing need to proactively identify fall risk factors in construction workers because fall incidents in the construction industry could cause serious injuries or fatality (Hsiao and Simeonov 2001; Jebelli et al. 2016). Dzeng and Chen (2014) studied the feasibility of detecting falls and fall portents (unsteady stepping, swaying or loss of balance) using mobile phone gyroscope and accelerometer. They reported that the accelerometer data was suitable for future fall and fall portent detection on actual jobsites. Jebelli et al. (2016) demonstrated that wearable inertial measurement units (WIMUs) are sensitive to differentiate between different static work postures. They recommended the development of a tool to monitor fall risk in future. Besides exploring fall portents and static postures, studies have also explored the feasibility of WIMUs to detect fall risks during walking. Jebelli et al. (2012, 2014) experimented with different walking tasks of varying difficulty levels to assess the capability of a WIMU in distinguishing them. They found that it was able to significantly differentiate difficult walking tasks from the easier ones. Similarly, Yang et al. (2016) successfully employed a semi-supervised learning algorithm to identity non-stable gait sections during simulated walking on iron beams using WIMUs. Likewise, Kim et al. (2017) and Yang et al.(2017b) showed that collective acceleration responses (acquired using WIMUs) from workers could be advantageous in identifying unsafe locations on a construction site. Building on this concept, they successfully experimented augmentation of the gait data with spatial (location) information to identify fall hazards on a worksite (Yang et al. 2017a). Recently Kim et. al (2018) illustrated the use of WIMUs to quantify and differentiate the risk of slipping caused by various coatings of steel beams. Collectively, these studies have advanced our understanding pertinent to pro-active monitoring of fall hazards and abnormal gait patterns.

6.1.3 Research gap

Despite aforementioned advances, to date, there is no readily available tool that can be deployed by site managers or foremen to evaluate the static or dynamic balance of the construction workers on site (Jebelli et al. 2016). Static balance ability is known to be a predictor of: falls in the elderly community (Piirtola and Era 2006), ankle sprains in teenagers (McGuine et al. 2000; Trojian and McKeag 2006) and prospective falls among construction workers (Umer et al. 2018b). Generally, the static balance test requires a person to stand as stable as possible to keep the movement of his center of gravity at a minimum, usually for a minimum duration of 20-second (Paillard and Noé 2015; Zurek et al. 2010). Traditionally, force-plates are considered as an industrial standard for static balance assessment. However, given their excessive weight and size, higher cost, and requirement of additional electronic and power components, it is not feasible to use them at construction sites (Liu et al. 2012).

Recent WIMU related fall prevention studies can be broadly classified into two categories: (1) static and (2) dynamic. Static studies primarily investigated the capability of using WIMU signals to differentiate different static work postures in a laboratory setting and to detect the risk of falls during stationary work tasks (Dzeng et al. 2014; Jebelli et al. 2016). On the other hand, dynamic studies explored the feasibility of using WIMUs to characterize gait patterns under different situations (e.g. normal walking, obstacle passing, walking on slippery surfaces, walking with a load) based on data collected from an individual (Jebelli et al. 2014; Yang et al. 2016) or a group of participants (Hyunsoo Kim et al. 2018; Jebelli et al. 2012; Kang et al. 2017; Yang et al. 2017a; b). Importantly, no previous studies have developed tools to evaluate static or dynamic balance of construction workers as to help identify individuals with poor balance skills and to plan appropriate preventive measures. Additionally, with respect to static balance, despite the ability of WIMUs to classify postures (Jebelli et al. 2016), it remains unclear whether they can detect subtle changes in static balance induced by construction tasks. In many instances, these changes may be unobservable by vision technologies but the detection of such changes may help predict the risk of fall in future.

Accordingly, this study aimed to develop a WIMU based tool to monitor the static balance of the workers for proactive fall safety management. For the said purpose, a three-stage study was conducted. Firstly, a laboratory study was conducted to validate the accuracy of WIMUs in measuring task/fatigue induced changes in the static balance with reference to a force-plate during a 20-second static balance test. Secondly, five experts were invited to determine the thresholds of static balance parameters for onsite balance classification of construction workers using the fuzzy set theory. Finally, based on those suggested thresholds, a mobile application was developed to link WIMU signals to a smartphone for onsite balance evaluation and further management perusal.

6.2 MATERIAL AND METHODS FOR VALIDATION OF WIMUS TO DETECT TASK/FATIGUE INDUCED CHANGES IN STATIC BALANCE

6.2.1 Participants

To validate the usefulness of WIMUs in detecting task/fatigue induced changes in static balance, thirteen male volunteers (university student and staff, mean age: 27.5 ± 4.4 years; mean body mass index: 22.8 ±1.5 kg/m^2) were recruited for the experiment. The volunteers were eligible for the study if they had (1) normal or corrected vision, (2) no known history of balance problems, and (3) no musculoskeletal disorders/pain in the past 12 months (Umer et al. 2018b). The current study was approved by the Human Research Ethics Committee of The Hong Kong Polytechnic University (Ref: HSEARS20160712003).

6.2.2 Experimental procedure

The cross-sectional study involved a randomized crossover design in a single visit (Figure 6.1). On arriving at the laboratory, the participant was briefed about the experimental procedures and a written consent was obtained. To start with, a WIMU was worn on the waist using a stretchable belt. Afterwards, the participant was instructed to standstill barefooted on a forceplate for a duration of 20 seconds with his feet shoulder`s width apart, arms resting aside while looking at a target placed in front of him at the eye level (Hapsari and Xiong 2016; Umer et al. 2018b). Two familiarization trials were given prior to data collection. Further, the feet placement was traced on a piece of paper adhered to the force plate to guide subsequent static balance trials (Schiffman et al. 2006). It was followed by a randomized simulation of rebar tying in one of the three postures of stooping, stool-sitting (15cm in height) and squatting. The three postures were chosen because rebar tying in these postures has shown to elicit divergent perceived discomfort levels (an indicator of whole-body fatigue) and post-task static postural stability (Umer et al. 2017a, 2018b). Immediately after rebar tying, the participant was instructed to repeat the static balance trial in the same way as performed before the rebar tying task. Subsequently, a 20-minute relaxed sitting was provided which was followed by the repetition of aforementioned procedures for the rebar tying task in the remaining two postures.

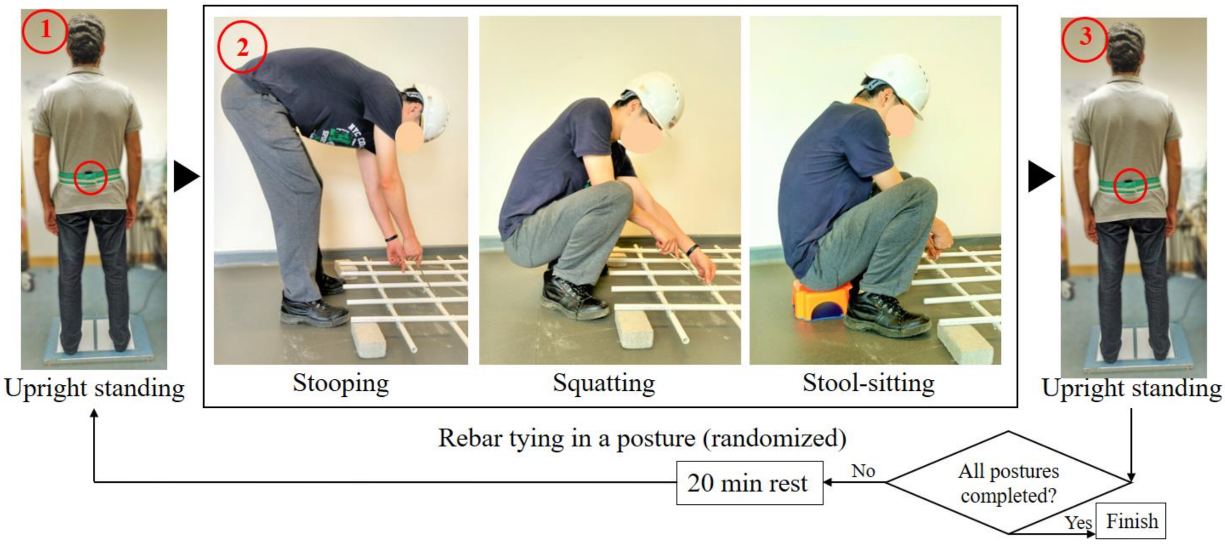


Figure 6.1 Experimental Procedure

6.2.3 Simulated rebar tying

Rebar tying was performed using a simulation setup made of five-by-five plastic pipes (Umer et al. 2017a; b). The pipes were 1.2m in length and were separated to each other with a center-to-center distance of 0.2m. The participant was instructed to tie simulated rebar using tie-wires and a pigtail tool repeatedly in the first three rows of the setup. During the experiment, the participant was not allowed to stand or change posture in order to keep the procedure standardized for all of the participants. The duration for rebar tying in each posture was initially planned to last for 20 minutes but the pilot testing revealed that the duration was too long to hold these postures continuously because of the severe discomfort in the legs (Umer et al. 2017a, 2018b). Noteworthy, the perceived discomfort levels during stooping posture increased at a much faster rate than the other two postures. Accordingly, the rebar tying duration was limited to 12.5 minutes for squatting and stool-sitting postures whereas for the stooping posture was reduced to 5 minutes. The specific figures of 12.5 and 5 were chosen because they were multiples of 2.5, which were the selected time interval to document perceived discomfort levels in a previous study (Umer et al. 2017a).

6.2.4 Instrumentation for data acquisition and variables of interest

For the static balance trials, a multicomponent forceplate (0.4m by 0.6m) with four load cells (Kistler 9286AA, Kistler Instrument Corp., Switzerland) was used to assess the postural stability of the participants while the rate of data collection was 1000Hz. The load cells registered ground reaction forces once a participant stood on it. The postural stability parameters were then calculated based on the variations in load cell readings arising from subtle body movements. Smaller body movements indicated better static balance. The forceplate data acquisition was synchronized with the acceleration data collection (1500Hz) from a WIMU (MyoMotion system, Noraxon USA) worn at the level of S1 spinous process using a stretchable belt. The WIMU was placed at the specified body landmark because this location closely represents an individual`s center of mass (Lindemann et al. 2011; Liu et al. 2012).

The static balance of a participant using the forceplate (considered as an industry standard) was evaluated using *total path length* metric of the center of pressure (COP). COP is the vertical projection of the center of an individual`s mass and usually measured using a forceplate (Duarte et al. 2000) whereas total path length is one of the widely used COP metrics for static balance assessment (Prieto et al. 1996). The raw data from the forceplate was filtered through a second-order Butterworth filter with a cut-off frequency of 3Hz prior to the calculation of the COP metric (Brown et al. 2001; Umer et al. 2018b). Afterwards, total path length was calculated as follow:

$$Total\,path\,length = \sum_{n=1}^{N-1} \left[(AP[n+1] - AP[n])^2 + (ML[n+1] - ML[n])^2\right]^{1/2}$$ (eq 6.1, Prieto et al. 1996)

In the above equation n and N refer to nth and last data set value of 20-second static trial, respectively while AP and ML refer to forceplate COP coordinates in anterior-posterior and mediolateral directions, respectively.

To compare with the total path length data on the forceplate, four WIMU metrics were computed to assess the 20-second static balance of the participants; namely resultant acceleration, horizontal plane velocity and displacement in the AP and ML directions. Multiple metrics were explored to ascertain which one of them would be more suitable for the balance monitoring tool. Resultant acceleration was calculated by computing root mean square of the acceleration values in the three planes of the accelerometer (Liu et al. 2012), whereas velocity and displacement related metrics were calculated by integrating the respective acceleration data in the corresponding planes (Lindemann et al. 2011; Mancini et al. 2012). A smoothing window of 1.3 seconds with a step size of 1.5 milliseconds was applied to the raw data prior to calculation of WIMU based metrics. Regardless of the metric used (forceplate based or WIMU), a larger magnitude (sway) indicates poor static balance and vice versa (Paillard and Noé 2015). The analyses revealed no significant difference among the various pre-task static tasks for any of the parameters. Accordingly, the three pre-task static balance values for each metric were averaged together for the subsequent analysis. Customized MATLAB programs (Version 2015a, MatchWorks, Inc., Natick, USA) were used for all static balance data processing.

6.2.5 Statistical analysis

To compare the performance of WIMU against the forceplate in detecting task/fatigue induced changes in the static balance, separate one-way repeated measures ANOVA were used to compare averaged pre-task and post-task static stability values for each of the aforementioned metrics. Statistically significant results were explored using post-hoc paired t-test with false detection rate (FDR) correction (Benjamini and Hochberg 1995). To further explore the suitability of each WIMU metric for the balance tool, the ability of each metric to discriminate different balance conditions (effect sizes) was compared using partial eta-squared statistic. Additionally, Pearson`s correlation coefficient was used to compare the correlation between each WIMU metric and forceplate based total path length data. The statistical significance level was set at 0.05 for all tests and SPSS (Version 19.0, IBM Corporation, USA) software was used for all statistical analyses.

6.3 RESULTS FOR USING WIMUS TO DETECT TASK/FATIGUE INDUCED CHANGES IN STATIC BALANCE

One-way repeated measures ANOVA revealed that all of the forceplate and WIMU based metrics were able to detect significant differences among pre- and various post-task static balance conditions. All of the force-plate and WIMU metrics indicated that pre-task test demonstrated least postural instability (sway) whereas rebar tying in squatting posture resulted in the worst stability except for WIMU based ML displacement, which indicated post-stooping balance to be the most unstable (Fig. 2). Additionally, paired t-tests (with FDR correction) for all of the metrics (force-plate and WIMU) indicated that using the stooping or squatting posture for rebar tying caused a significant deficiency in postural stability as compared to the respective pre-task static balance test results ($p<0.05$). Similarly, post-stooping and post-squatting sway was significantly larger than post-stool sitting sway ($p<0.05$). In contrast, stool-sitting posture did not have any significant detrimental effect on the static balance (the difference between pre-task and post-stool sitting sway was not statistically significant, $p>0.05$ for all metrics). Interestingly, while the force-plate based total path length found that the post-squatting sway was significantly larger than the post-stooping sway, none of the WIMU based metrics could statistically differentiate between these two conditions.

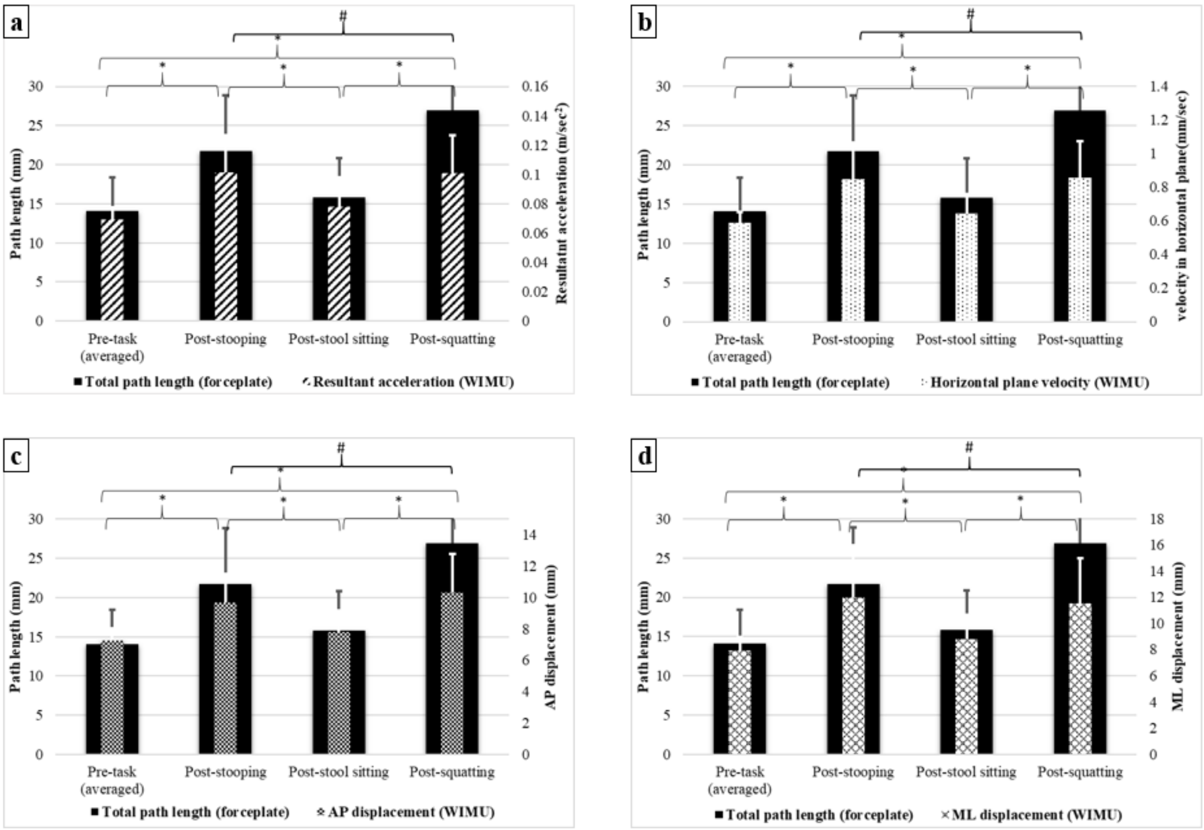


Figure 6.2 Pre- and post-task static balance as measured by forceplate and WIMU metrics for various rebar-tying postures

Note: * indicates significant post-hoc paired t-test results for both force-plate and WIMU data (with FDR (false detection rate) correction; $p < 0.05$); # indicates significant difference in the force-plate data only ($p < 0.05$); Bars indicate standard deviation; AP= anterior-posterior direction; ML= mediolateral direction; WIMU= wearable inertial measurement unit

Figure 6.3 depicts the effect size comparison among the various forceplate and WIMU metrics. The results showed that the forceplate based total path length was the most sensitive metric to discriminate among various stability conditions. Of all WIMU based metrics, the AP displacement had the highest discriminating power comparable to the total path length measured by the forceplate. Further, resultant acceleration and horizontal plane showed similar but relatively smaller effect size, whereas ML displacement demonstrated the least capability to discriminate various stability conditions.

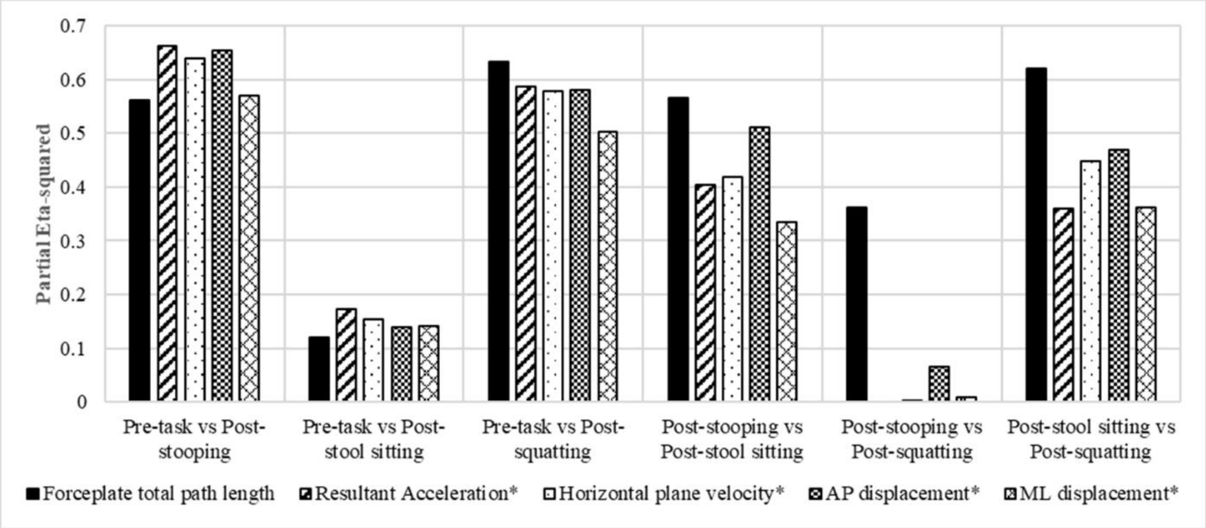


Figure 6.3 Effect size comparisons among various forceplate and WIMU metrics in discriminating various post-task static balance

Note: AP= anterior-posterior direction; ML= mediolateral direction; * indicates measured using a wearable inertial measurement unit (WIMU)

Separate Pearson`s correlation coefficient calculation for the forceplate based total path length data and each of the WIMU metrics revealed significant correlation for all of the WIMU based metrics ($p<0.05$, Figure 6.4). Specifically, the correlation was the strongest between total path length and AP displacement ($r = 0.69$), moderate between total path length and each of resultant acceleration and horizontal plane velocity ($r = 0.53$ for each) and weak between total path length and ML displacement ($r = 0.38$). Taken together, these results (Figure 6.2, 6.3 and 6.4) suggested that WIMU based AP displacement was the best parameter to detect the task/fatigue induced differences in static balance for future onsite balance assessment.

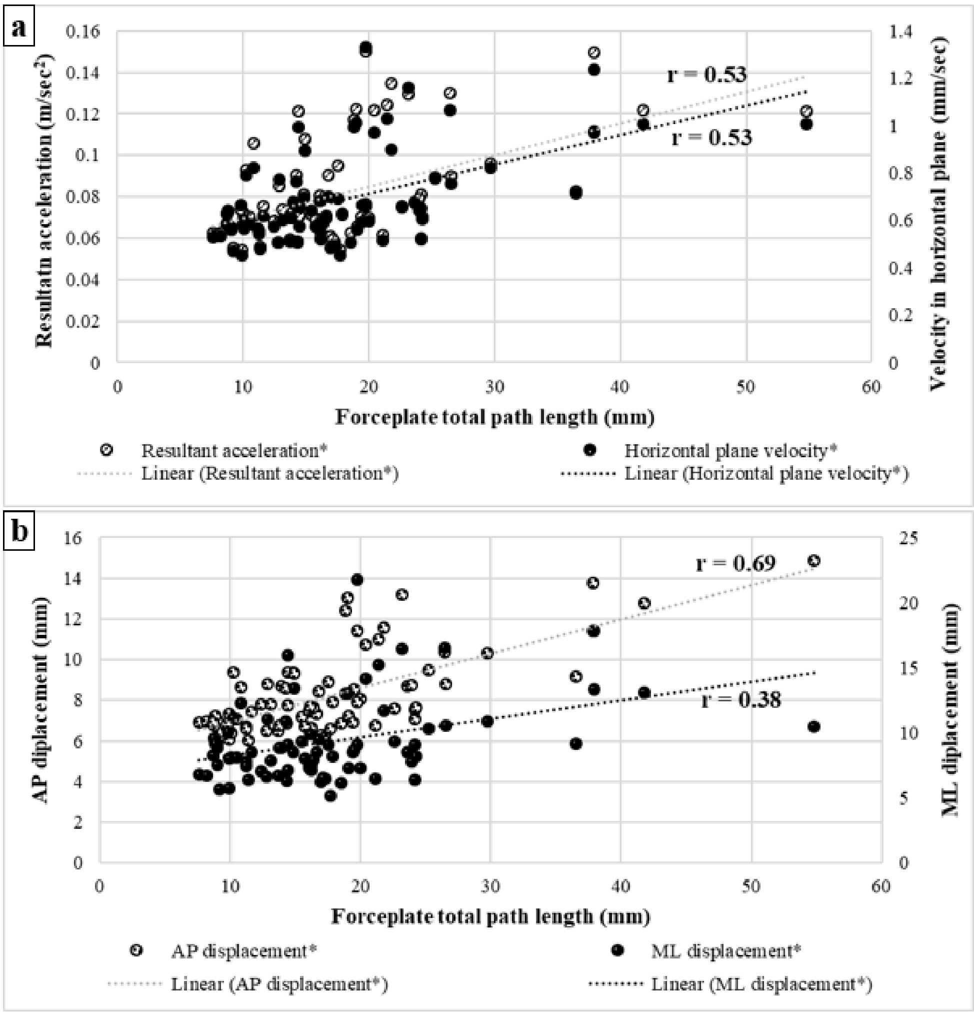


Figure 6.4 Pearson`s correlation coefficient comparisons among various WIMU metrics against forceplate data

Note: AP= anterior-posterior direction; ML= mediolateral direction; r= Pearson`s correlation coefficient; * indicates measured using a wearable inertial measurement unit (WIMU)

6.4 MATERIAL AND METHODS FOR DETERMINING THE THRESHOLD FOR STATIC BALANCE CONDITIONS

While an increased postural sway may indicate a higher risk of falls (Davidson et al. 2009; Madigan et al. 2006), there are no established objective methods/standards/cutoff values that can categorize the balance performance of a worker as “very good”, “good”, “poor” and “very poor”. To bridge this gap, this study adopted the fuzzy set theory, which allows decision making (characterization in this study) by applying mathematical operators and programming to the fuzzy information (Xia et al. 2011). Fuzzy set theory was chosen for threshold determination among other methods (e.g. analytic hierarchy process) because of its simplicity, easiness in soliciting response and better capability to handle the vagueness as inherent in this study (Biswas et al. 2008; Chameau and Santamarina 1987; Lee et al. 2005). The theory has been widely adopted in the domain of construction management for decision making in dealing with the prevalent vagueness and fuzziness in human concept formation and reasoning (Dikmen et al. 2007; Hsieh et al. 2004; Tah and Carr 2010; Xia et al. 2011). For the said purpose, five experts (professional rehabilitation science practitioners, involved in regular balance measurement of the patients) were contacted to provide opinions on the cutoff threshold for characterizing good and poor static balance. Five experts were deemed to be sufficient because a study conducted to assess the effect of number of assessors (5, 10, 15 and 22) found that five assessors could be sufficient to obtain a reasonable response using fuzzy set theory (Chameau and Santamarina 1987). Upon their consent, the study was explained and the data collected during the abovementioned experiment was shared with them. The experts were asked to assist in forming two sets of triangular fuzzy membership functions using the interval estimation method (Lee et al. 2005), which could be used for classifying static balance of the workers. Specifically, the first set of fuzzy membership function characterized pre-work shift static balance of the workers as; “very good”, ‘good”, “poor” and “very poor” based on the AP displacement data of WIMU. Similarly, the second set of fuzzy membership function characterized the relative increase in post-task/post-work-shift sway (percentage change in WIMU AP displacement) as “small”, “medium”, “large” or “very large”. Specifically, triangular membership functions were chosen for this work because they are easier to understand, use and process in a fuzzy environment (Chou and Chang 2008; Lam et al. 2010). A triangular fuzzy membership function was represented using three real numbers such that Ã = (L,M,U) where L,M, U are lower limit, modal (the strongest grade of membership) and upper limit values, respectively for a particular membership function (Hsieh et al. 2004). These limits are an expansion of the idea of confidence interval with varying degree of membership for a given WIMU-based AP displacement value. For a given x (AP displacement), there is a corresponding real number μÃ(x) ϵ [0,1], where μÃ(x) is the degree of membership of x for Ã, 1 refers to the full membership while 0 refers to the null membership. For the intermediate values, μÃ(x) is determined as follow:

$$\mu\tilde{A}(x) = \begin{cases} (\mathrm{x} - \mathrm{L})/(\mathrm{M} - \mathrm{L}), & \mathrm{L} \leq \mathrm{x} \leq \mathrm{M} \\ (U - x)/(U - M), & \mathrm{M} \leq \mathrm{x} \leq \mathrm{U} \end{cases} \quad (2)$$

Accordingly, each of the contacted experts was asked to provide three defining values for each stability condition of the two fuzzy membership functions. Additionally, no specific overlapping limit was imposed on the experts for the membership functions in order to capture the most suitable values for each stability condition as per their experience and knowledge.

6.5 RESULTS FOR THE DETERMINATION OF THRESHOLDS FOR STATIC BALANCE CONDITIONS

The fuzzy membership functions related response gathered from the experts was averaged for the final membership functions which could readily be used for the balance monitoring tool. Table 6.1 and 6.2 depict the subjective opinion of each of the experts for the two fuzzy membership functions. Based on the response, the final fuzzy membership functions are illustrated in Figure 6.5.

Table 6.1 Suggested values by the experts for pre-task/unfatigued characterization of static balance

Expert	Pre-task/unfatigued static balance AP displacement values (mm)			
	Very good	good	poor	Very poor
1	(0,0,7)	(4,7,10.3)	(8,11,15.5)	(14,17,40)
2	(0,6.5,8)	(7,18,29)	(28,35,41)	(40,42,50)
3	(0,1,6)	(6.5,16,21.5)	(15,26,29.5)	(28,35,49)
4	(0,3,8)	(7,13,19.5)	(16,20.5,25.5)	(23,30,51)
5	(0,5,10)	(7,17,20)	(18,25,42.5)	(32.5,42,55)
Final membership functions	(0,3.1,7.8)	(6.3,14.2,20.1)	(17,23.5,30.8)	(27.5,33.2,49)

Note: AP refers to anterior-posterior direction; each triplet represents the lower bound, strongest grade of membership and upper bound AP displacement values for each stability condition

Table 6.2 Suggested values by the experts for post-task/post-work-shift characterization of static balance

Expert	Post-task/post-work-shift increase in sway (%)			
	Small	Medium	Large	Very large
1	(0,5,10)	(7,14.5,20)	(18,45,70)	(60,100,150)
2	(0,5,10)	(9,20,55)	(50,70,110)	(100,120,200)
3	(-10,0,15)	(10,35,55)	(30,60,90)	(85,150,200)
4	(0,1,15)	(10,20,55)	(50,70,100)	(90,108,115)
5	(-5,5,20)	(10,25,60)	(45,80,150)	(100,190,250)
Final membership functions	(-3,3.2,14)	(9.2,22.9,49)	(38.6,65,104)	(87,133.6,183)

Note: AP refers to anterior-posterior direction; each triplet represents the lower bound, strongest grade of membership and upper bound AP displacement values for each stability condition

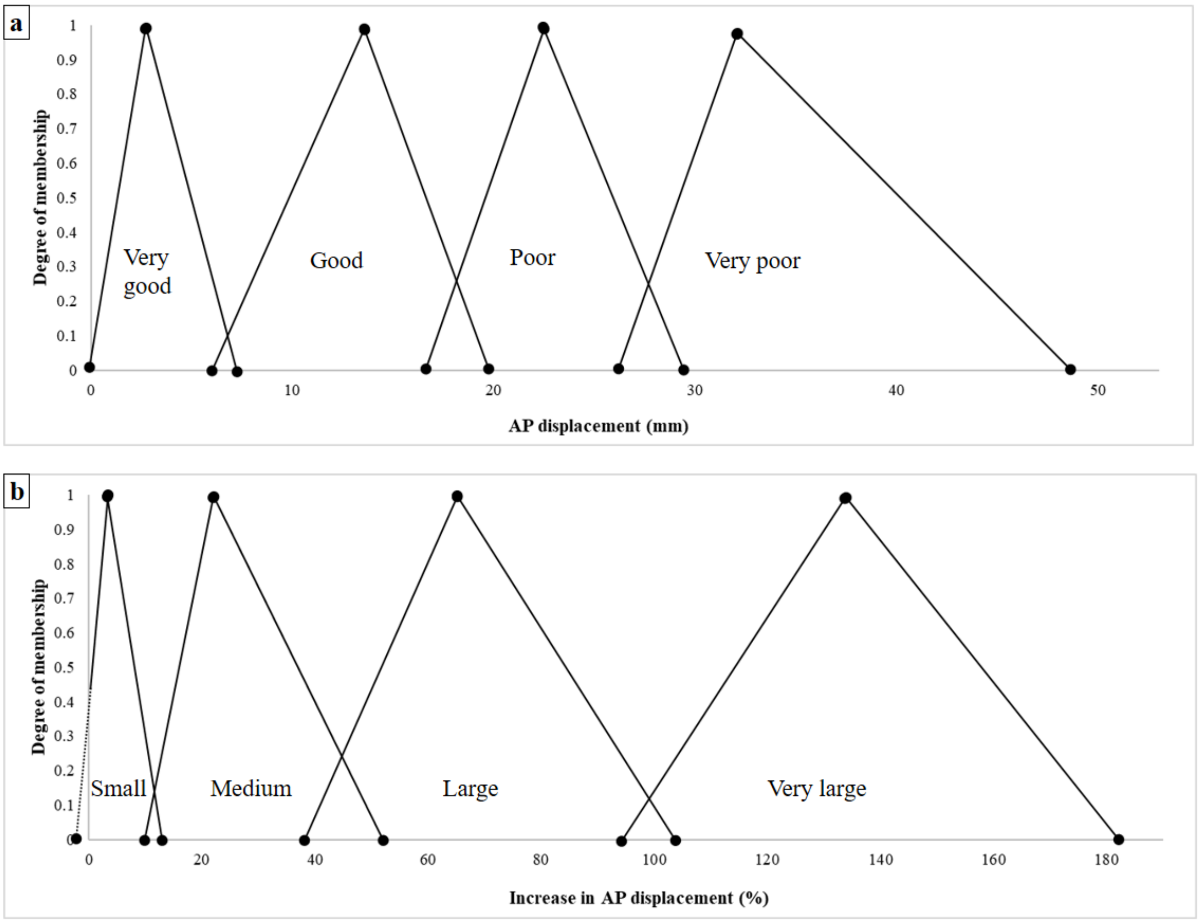


Figure 6.5 Fuzzy membership functions developed for the WIMU based balance monitoring tool

Note: AP refers to anterior-posterior direction; WIMU= wearable inertial measurement unit

6.6 MOBILE APPLICATION DEVELOPED FOR THE BALANCE MONITORING TOOL

Based on the fuzzy membership functions, a mobile application (Android) was developed to link a WIMU to a smartphone using Bluetooth and onsite deployment of the WIMU based balance monitoring tool. The interface of the mobile application is shown in Figure 6.6. Figure 6.6(a) indicates a list of construction workers registered in the application (the data used in the illustrations is fictitious). The time mentioned in front of each worker refers to the point in time of his registration in the application. Figure 6.6(b) illustrates the two construction trades (mason and rebar tying) as an example to which the registered workers belonged to whereas Figure 6.6(c) refers to the suggested times of the day for balance monitoring. Both the trades and the time of monitoring could be edited or added as per onsite requirements using the application interface. The established thresholds for the stability conditions obtained using the fuzzy set theory could be plugged-in/edited using an interface as shown in Figure 6.6(d). The interface for taking new static balance reading is shown in Figure 6.6(e). Prior to data collection, it is necessary to specify the worker and the time of monitoring. Additionally, Figure 6.6(f) and Figure 6.6(g) show two pie charts depicting the stability records of an individual worker and workers from a specific trade, respectively. Figure 6.6(h) shows the recorded changes in static stability of various workers of a specific trade after a particular work task/ post-work-shift. Once the stability related data is collected using the developed tool, it could be used in a number of ways for proactive fall prevention as explained in the next section (i.e. Discussion).

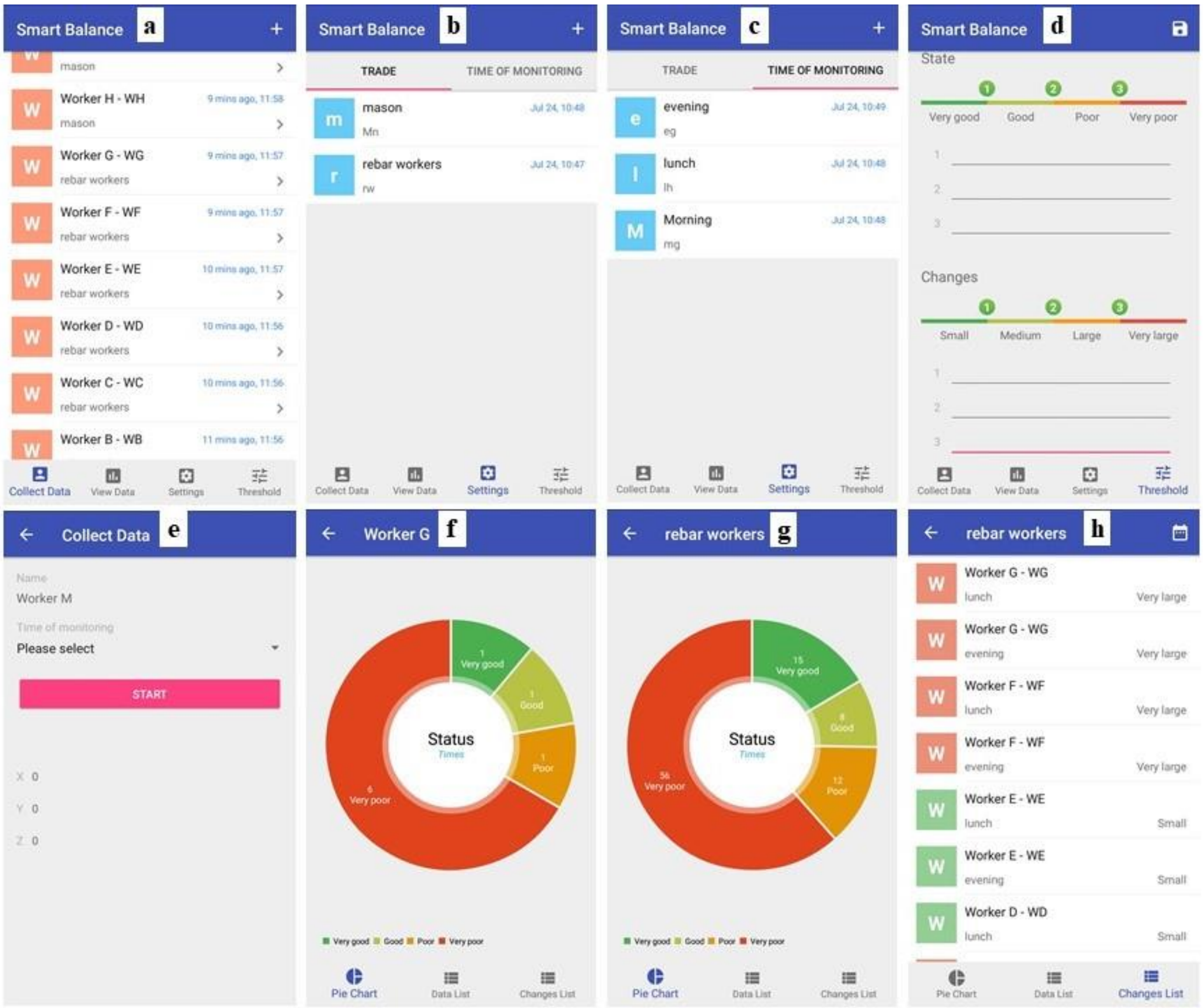


Figure 6.6 Mobile application developed for the balance monitoring tool

Note: All shown data is fictitious

6.7 DISCUSSION

This study, for the first time, developed a proactive WIMU based static balance assessment tool tailored for construction site workers. The tool utilized a small and lightweight WIMU along with a mobile application, which is expected to enhance its acceptance for onsite fall prevention by the construction industry (Liu et al. 2012).This will allow foremen/site managers to monitor the static balance of the construction workers using the 20-second static balance tests at different times of the day in order to keep a balance profile of the workers longitudinally.

Ultimately, the tool would enable them to identify the workers with consistent balance deficits that require relevant balance trainings.

6.7.1 Use of WIMUs to detect changes in static balance

The results of this study indicate that the WIMU based metrics are sensitive to differentiate distinct changes in balance conditions induced by rebar tying task in different work postures. Specifically, WIMU-based AP displacement was highly correlated to the total path length as measured by a forceplate in detecting task/fatigue induced changes in static balance (Figure 6.2(c), Figure 6.3 and Figure 6.4). It is noteworthy that although WIMU-based AP displacement indicated a greater post-squatting static sway than post-stooping sway. The AP displacement metric could not differentiate between the two balance conditions, which could be distinguished by the forceplate-based total path length (Figure 6.2(c) and Figure 6.3). This finding might be attributed to the fact that tasks inducing severe static instability (such as rebar tying in squatting and stooping postures in this experiment) may also require hip strategy to regain the balance in addition to ankle strategy (Figure 6.7) (Lindemann et al. 2011). Under such circumstances, there could be movements at the hip (sacrum) level without corresponding changes in COP parameters (Lindemann et al. 2011),that results in a reduction of association between the forceplate and WIMU parameters which might explain the aforementioned disparity.

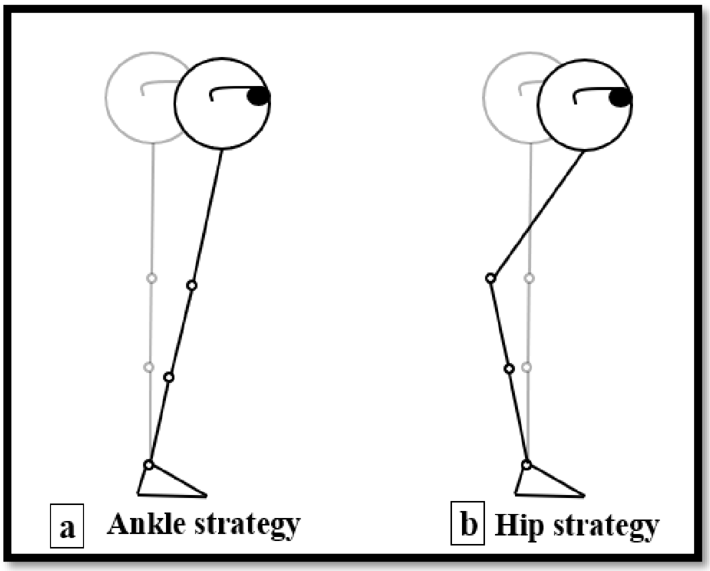


Figure 6.7 Strategies for regaining balance

6.8 IMPLICATIONS

Generally, most of the construction trades are physically demanding (e.g., prolonged and repetitive awkward postures, manual material handling, and operating heavy tools) (Inyang et al. 2012; Umer et al. 2018a; Wang et al. 2015a). As such, the daily tasks of different trades may predispose the workers to peripheral or whole-body fatigue. It is known that fatigue of individual body parts (such as ankle (Caron 2003), lower back (Davidson et al. 2009), shoulder (Nussbaum 2003), neck (Schieppati et al. 2003)) or whole-body (Springer and Pincivero 2009; Wilkins et al. 2004) could lead to loss of balance. Therefore, the developed tool will provide an opportunity to quantify the postural instability induced by any of these construction tasks, such as bricklaying, floor laying, carpentry or concrete laying.

Given that loss of balance is one of the major causes of fall incidents on the construction sites (Chi 2016; Hsiao and Simeonov 2001; Yang et al. 2016), the use of this developed tool may enable proactive balance monitoring for high fall risk workers/activities. For instance, previous studies have indicated that fall accidents happen more often in the afternoon (Chan et al. 2008; Hu et al. 2011), which could be attributed to highly demanding construction tasks leading to fatigue and associated poor balance control (Davidson et al. 2009; Umer et al. 2018b; Yang et al. 2016). As such, there is an increased need for monitoring of the workers in that time (Chan et al. 2008). Similarly, ageing workforce has been a serious challenge for the construction industry in a number of countries. Since, ageing is linked with a decline in work capacity, cognitive and proprioceptive skills and muscle strength (Kenny et al. 2008; Thomas 2010), aged workers more commonly suffer from fall accidents than their younger counterparts (Dong and Wang 2011). The developed tool in this study provides an innovative and pragmatic way to increase the fall risk surveillance in these situations.

Combined with the developed tool, Prevention through Design (PtD) (Dong et al. 2017; Gambatese et al. 2008) could be a more effective avenue to lower the risk of falls in the construction industry. For instance, by employing the tool, various task and environment related fall risks (e.g. height, equipment and gear, work-technique, visual stimuli) could be analyzed and their effect on the balance of the workers could be better understood. Subsequently, appropriate risk alleviation strategies could be adopted. Similarly, while three-quarters of all fall accidents involve specialty trades workers (Huang and Hinze 2003; Kang et al. 2017), PtD approach could be used to target the individual trade workers with a higher fall risk (such as roofers and structural steel erectors). In different trades, the balance monitoring tool could be effectively used to redesign work-rest cycles to minimize fatigue and associated fall risk (Liu et al. 2012).

While many workers may have poor balance, those with poor postural controls can undergo balance training programs to enhance their static and dynamic balance skills (Distefano et al. 2009). These training programs may include muscle strengthening, agility and plyometric exercises, single and double leg stance on unstable surfaces such as wobble boards and biofeedback based balance improvement schemes systems (Distefano et al. 2009; Ma et al. 2016; Radford et al. 2006). During or by the end of the balance training program, the developed tool can be used to quantify improvements attained by the workers. Moreover, the tool can be used to assess the efficacy of any newly designed balance training program.

Although the use of this balance monitoring tool could be beneficial, the importance of other fall safety measures cannot be overlooked. Other mitigation measures (such as the use of fall protections, enforcement of safety provisions and compliance to protection plans (Dong et al. 2017), educational trainings, workshops and seminars) are regarded as useful in preventing falls, enhancing fall hazard awareness and imparting safe behaviors among the construction workers (López et al. 2008; Nadhim et al. 2016). Importantly, using a holistic systems approach is highly recommended to reduce the risk of fall and other accidents on construction sites (Haslam et al. 2005).

6.9 LIMITATIONS

Despite numerous advantages, the current study has a few limitations. First, it is important to evaluate both the static and dynamic balance of workers in order to assess the fall risk (Umer et al. 2018b). Accordingly, future studies should develop pragmatic dynamic balance assessment tools for construction workers. Second, the current study validated the use of WIMUs to detect task/fatigue induced changes in static balance using inexperienced workers in a laboratory setting and entailing a single work task (i.e. rebar tying). Future studies should validate the usefulness of WIMUs using experienced construction workers, on actual worksites and incorporating various construction trade tasks. Finally, the study used a laboratory study data to establish the thresholds for balance classification with a relatively small sample size and a few experts. Accordingly, future studies should use the data from actual construction workers with a larger sample size and should involve more experts to establish the thresholds.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

7.1 CONCLUSIONS

Among different industries, construction industry exhibits relatively poor health and safety performance (Snashall 2005). This necessitates further mitigation measures to improve occupational health of the construction workers. While the overall construction industry needs special consideration in this regard, some of the construction trades are more prone to occupational hazards as compared to the others, such as rebar tying (Albers and Hudock 2007; Dong et al. 2011; Forde et al. 2005; Hunting et al. 1999; Kang et al. 2017). Accordingly, this research work explored the use of contemporary health and safety informatics to identify and mitigate the risk factors of the two most widely prevalent occupational hazards faced by rebar workers i.e. lower back MSDs and FAs. Specifically, first, a systematic review was conducted to summarize the prevalence of musculoskeletal symptoms in the construction industry. Second, a biomechanical study was conducted to identify the risk factors of lower-back MSDs among the rebar workers, which was followed by evaluation of the effectiveness of a low-cost ergonomic intervention to mitigate the identified risk factors. Third, temporal changes in static balance induced by various rebar tying postures (i.e. squatting, stooping and stool-sitting) were explored. Finally, a tool was developed to proactively monitor the balance of construction workers.

The individual studies carried out for this research project are summarized as below:

a. The prevalence of musculoskeletal symptoms in the construction industry: A systematic review and meta-analysis

A systematic review was conducted to synthesize the prevalence of various musculoskeletal symptoms (MSS) in the construction industry. Results revealed that lumbar (low back), knee, shoulder and wrist MSS are consistently found to be the most prevalent among construction workers. Existing evidence suggests that female construction workers may be more vulnerable to work-related MSS although the relation between age and MSS prevalence among construction workers remains unclear. Collectively, further prevalence and mechanistic studies are warranted to identify the prevalence and underlying causes of different work-related MSS in various construction trades so that effective prevention and treatment strategies for these MSS can be developed/implemented.

b. Identification of biomechanical risk factors for the development of low back disorders during manual rebar tying

An experimental study was conducted to objectively quantify biomechanical characteristics of the spine during three common rebar tying postures (i.e. stooping, one-legged kneeling and squatting). Specifically, all of the postures required the participants to maintain their trunk inclination at an angle exceeding the ISO11226 standard recommended trunk flexion angle for static working posture. Stooping caused the largest decrease in sEMG activity of lumbar muscles as compared to the other examined postures. The decrease in sEMG activity indicates a transfer of load from back muscles to passive spinal tissues that can increase the risk of LBDs. Further, working in one-legged kneeling involved asymmetrical lumbar posture and pressure on the kneeling knee, which can increase the risk of back and knee pain in rebar workers. Importantly, the study highlighted that construction/project managers can play a crucial role in enhancing the health and productivity of rebar workers. By understanding the influences of different rebar tying postures on the muscle activity and kinematics of the trunk, construction/project managers can redesign the work schedule to ensure that workers regularly change their tasks in order to avoid working in a prolonged static posture. The managers can also introduce remedial measures (e.g. educational pamphlets on the importance of postural variation and occupational safety, on-site stretching/exercise program, and ergonomic equipment) to reduce biomechanical risk factors for work-related musculoskeletal disorders and to improve the productivity of rebar workers.

c. A low cost ergonomic intervention for mitigating physical and subjective discomfort during manual rebar tying

A study was conducted to investigate the effectiveness of using a squatting-stool for manual rebar tying against squatting in Asian workers. While the results revealed similar trunk and leg muscle activity and no significant difference in neuromuscular fatigue level of trunk and leg muscles between both rebar tying postures, stool-squatting rebar tying demonstrated significantly better: (1) lower extremity blood circulation; (2) trunk flexion angle (within the ISO recommended limits for static working postures); and (3) self-perceived discomfort ratings. These encouraging findings highlight the potential prospects of such a simple and low cost intervention for Asian workers in various construction trades (including rebar tying).. Importantly, this study highlighted that it is essential to consider both the characteristics of individual construction trades and cultures of workers in order to derive proper task-specific ergonomic interventions for the construction industry. Given the high physical demands of construction workers, more ergonomic studies should be conducted in the construction industry to help construction managers and policy makers design effective mitigation strategies to reduce work-related MSDs.

d. Proactive safety measures: Quantifying the upright standing stability after sustained rebar tying postures

This study highlighted that conducting rebar tying in conventional work postures (squatting and stooping) significantly impaired static standing balance, which might be attributed to prolonged recruitment of back and leg muscles in the stooping and reduced blood circulation to legs in the squatting posture. Compared to stooping or squatting, the adoption of an ergonomic intervention (stool-sitting) significantly improves lower limb circulation, reduces back and leg muscle activities during rebar tying, and improves post-rebar tying standing balance. Since different individuals have different balance recovery time after sustained work postures, future research should investigate optimal resting time before taking part in other risky tasks to avoid the risk of FAs. Importantly, given high interpersonal variability in both pre- and post-task standing stability, future works should focus on the development of individualized balance monitoring systems to proactively identify workers with poor pre- and post-task standing balance so as to provide tailor-make preventive measures. Meanwhile, simple validated functional balance tests (e.g. Start Excursion Balance Test) can be used to identify workers with balance deficits. Regular balance training exercises and biofeedback based devices can be adopted to improve rebar workers’ balance ability.

e. Development of a tool to monitor balance of construction workers for proactive fall safety management

A three-step study was directed to develop a tool for onsite balance monitoring of construction workers. First, a validation study was conducted to investigate the suitability of the wearable inertial measurement units (WIMUs) to detect task/fatigue induced faint changes in the static balance by validating various WIMU metrics against the metric from a forceplate. The study found that WIMU based anterior-posterior (AP) displacement metric was an adequate alternative for the forceplate based static balance assessment. Second, five experts were contacted to help determine AP displacement based thresholds for categorizing static balance performance of individuals. Last, a mobile application was developed to link data collected by WIMU during 20-second balance trials to the mobile phone application. The developed tool will have a great potential to enhance proactive identification of the workers with a higher risk of falls so that proper balance training can be provided. It can also be used to assess the effect of various tasks and environmental risk factors on the ensuing balance. Collectively, the tool can help informed decision making to alleviate the risk of falls in the construction industry.

7.2 IMPLICATIONS FOR FUTURE RESEARCH

Overall, this research project highlights that the use of health and safety informatics is highly beneficial to identify and quantify the risk factors for occupational health and safety hazards of construction trades. Once identified, these risks could be mitigated using appropriate ergonomic interventions or management methods (e.g. introducing frequent rest breaks). Although this project has advanced our understanding related to occupational health and safety hazards posed to manual rebar tying, there is a need for further studies to enhance the practice of rebar workers, in particular and all construction workers in general, elaborated as follows:

1. The studies conducted for this project employed a small number of students for data collection and analysis. It remains unknown whether the results would be same for actual construction workers or not. Therefore these experiments should be validated with a large number of actual construction workers to confirm the findings and derive useful practices and policies for better occupational health of the construction workers.
2. The studies of this project were limited by a short duration of data collection i.e. 5 to 15 minutes of rebar tying as compared to actual prolonged working duration. Future studies should evaluate how the monitored risk factors vary longitudinally, both within a day and also on day-to-day basis.
3. The experiments conducted in this research project were performed in a laboratory environment to exclude the external factors that may affect the experiments and to keep the conditions consistent within experiments (e.g. temperature and humidity). Future experiments should explore the varying effects of these weather related factors on the risk factors` development.

4. In this research project, the risk factors were evaluated individually and their interaction was not studied. Generally on the construction sites, multiple risk factors could be present (task related, personal or environment related). Accordingly, it is important to explore their interaction from a system`s perspective to better synthesize guidelines for occupational safety of construction workers.
5. While the current project has highlighted the potential of using health and safety informatics for risk factors` identification and mitigation, the economic benefits reaped by such endeavors for the construction industry remains unknown. The researchers should conduct studies to unveil the economic aspects of their short-term and long-term applications.
6. The current project proposed a simple ergonomic intervention (i.e. stool-sitting) for rebar tying to alleviate the risk of MSDs development and ensuing imbalance after rebar tying. Currently, the intervention has not been tested in actual workers that could reveal the construction workers` perspective. This is necessary to gauge the wearability and comfortability of the stool, and to solicit suggestions to improve it. Accordingly, the intervention should be optimized in terms of its mechanical design, size and material to make full use of it. Besides, it is also suggested to carry out economical analysis of the stool for construction sites to comprehend its economic viability.

APPENDICES

Appendix A. The search strategy used in the current review

Academic Search Premier (EbscoHost) search strategies:

1. (Prevalen* OR inciden* OR cross-sectional OR cohort OR perspective OR retrospective OR longitudinal OR follow up OR follow-up*).mp.[mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier]
2. (Upper trapezius OR shoulder OR arm OR elbow OR forearm OR wrist OR hand* OR fingers OR thumb).mp.[mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier]
3. (Neck OR cervical OR thoracic OR back OR thoracolumbar OR low back OR lumbar OR spinal OR spine OR vertebra* OR sacroiliac OR sacrum OR sacral).mp.[mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier]
4. (Coccyx OR hip OR buttocks OR leg OR thigh OR knee OR calf OR shin OR ankle OR foot OR heel OR sole OR toes).mp.[mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier]

5. (Ache OR pain* OR disorder*).mp.[mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier]
6. 2 AND 5
7. 3 AND 5
8. 4 AND 5
9. Musculoskeletal pain OR Musculoskeletal abnormalities OR Musculoskeletal system OR Musculoskeletal OR musculoskeletal diseases
10. 6 OR 7 OR 8 OR 9
11. (Construction OR carpenter* OR floorlayer* OR bricklayer* OR painter* OR electrician* OR plumber* OR scaffolder* OR roofer* OR mason* OR sheet metal worker* OR floor installer* iron worker* OR rebar worker* OR rodbuster* OR reinforcement worker* OR construction laborer* OR drywall installer* OR insulator*).mp.[mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier]
12. 1 AND 10 AND 11

Note: The same search strategy was used on other databases (i.e. CINAHL, Health and Safety Science Abstract, Medline, PsycINFO, Science Direct, Scopus, SportDiscus and Web of Science)

Appendix B. A quality assessment tool

Guidelines for the critical appraisal and methodological scoring system of the prevalence studies:

A. ARE THE STUDY METHODS VALID?

1. Is the study design appropriate for the research question? (1 point)

2. Is the sampling frame appropriate for prevalence studies? (1 point)

3. Is the sample size adequate (> 300 participants)? (1 point)

4. Are and standard criteria used for measurement outcome (e.g. Nordic Musculoskeletal Questionnaire)? (1 point)

5. Is the health outcome measured in an unbiased fashion? Were the results validated via medical checkup? (1 point)

6. Is the response rate adequate (70%)? Are the refusers described? (0.5 point each)

B. WHAT IS THE INTERPRETATION OF THE RESULTS?

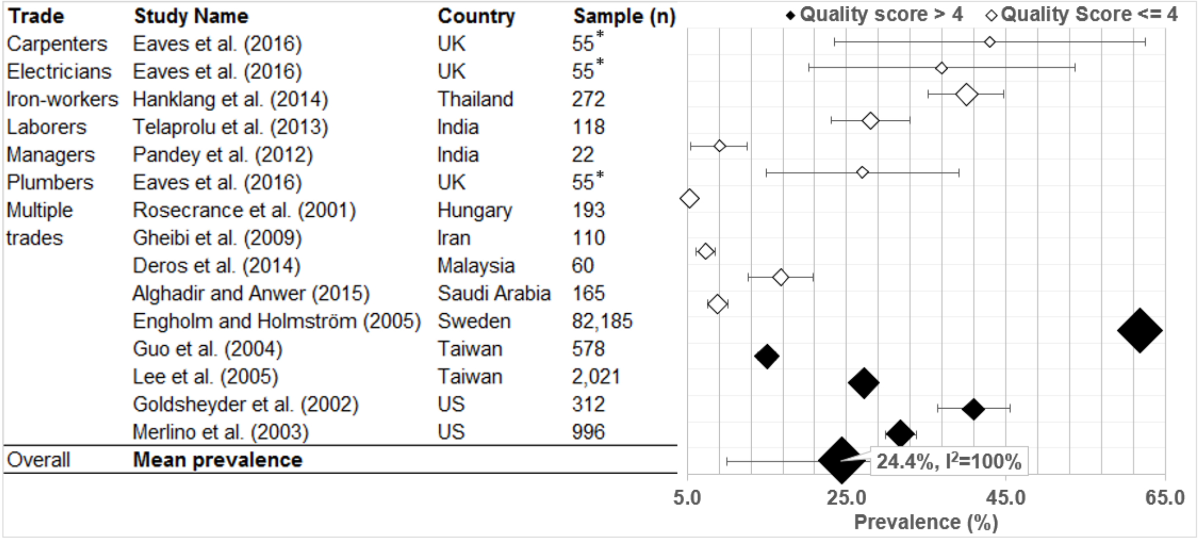
7. Are the estimates of prevalence given with confidence intervals? Is sub-group analysis done? (0.5 point each)

C. WHAT IS THE APPLICABILITY OF THE RESULTS?

8. Are the sociodemographic characteristics and the setting described in detail? (1 point)

Appendix C. 1-year prevalence of different anatomical MSS in construction industry

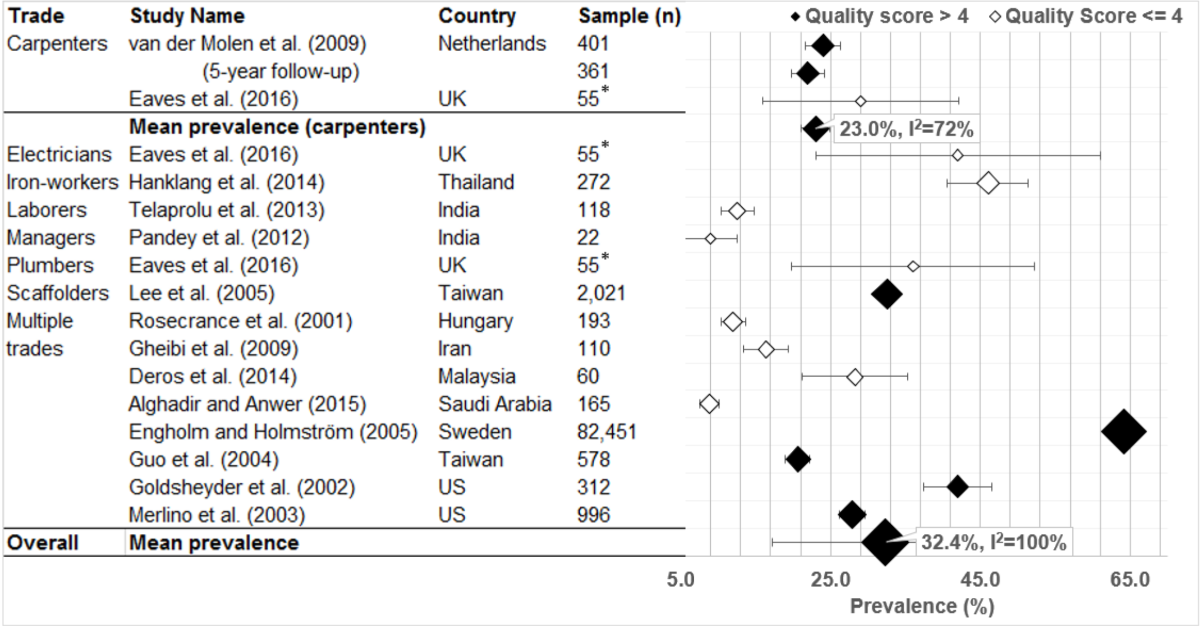
1-year prevalence of neck MSS in different construction trades



Trade	Study Name	Country	Sample (n)
Carpenters	Eaves et al. (2016)	UK	55*
Electricians	Eaves et al. (2016)	UK	55*
Iron-workers	Hanklang et al. (2014)	Thailand	272
Laborers	Telaprolu et al. (2013)	India	118
Managers	Pandey et al. (2012)	India	22
Plumbers	Eaves et al. (2016)	UK	55*
Multiple trades	Rosecrance et al. (2001)	Hungary	193
	Gheibi et al. (2009)	Iran	110
	Deros et al. (2014)	Malaysia	60
	Alghadir and Anwer (2015)	Saudi Arabia	165
	Engholm and Holmström (2005)	Sweden	82,185
	Guo et al. (2004)	Taiwan	578
	Lee et al. (2005)	Taiwan	2,021
	Goldsheyder et al. (2002)	US	312
	Merlino et al. (2003)	US	996
Overall	**Mean prevalence**		

Note: MSS = Musculoskeletal symptoms, the size of ◆ is proportional to the log of the sample size, the bars indicate 95% confidence interval, * indicates that the sample sizes of individual trades were not available. Therefore, the study was not used in the meta-analysis. The quality scores ranged from 0 to 8. Studies scored < 4 were classified as low quality, while those scored higher than 4 were classified as high quality. Some data points do not show the confidence intervals because the sample sizes are so large that they conceal their respective confidence intervals. Mean prevalence was calculated using data from all relevant studies, excluding the outliers originated from the low-quality studies.

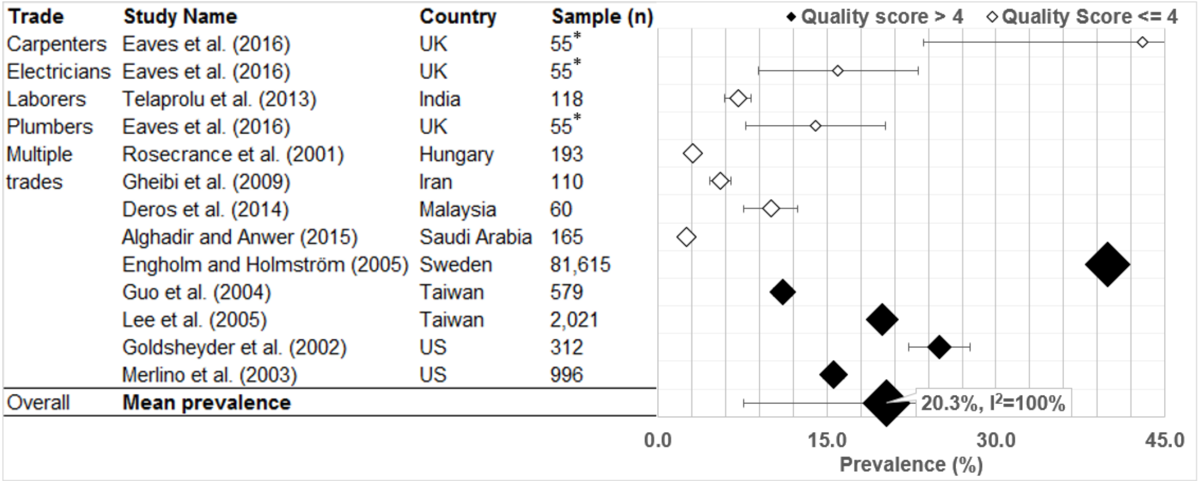
1-year prevalence of shoulder MSS in different construction trades



Trade	Study Name	Country	Sample (n)
Carpenters	van der Molen et al. (2009)	Netherlands	401
	(5-year follow-up)		361
	Eaves et al. (2016)	UK	55*
	Mean prevalence (carpenters)		
Electricians	Eaves et al. (2016)	UK	55*
Iron-workers	Hanklang et al. (2014)	Thailand	272
Laborers	Telaprolu et al. (2013)	India	118
Managers	Pandey et al. (2012)	India	22
Plumbers	Eaves et al. (2016)	UK	55*
Scaffolders	Lee et al. (2005)	Taiwan	2,021
Multiple trades	Rosecrance et al. (2001)	Hungary	193
	Gheibi et al. (2009)	Iran	110
	Deros et al. (2014)	Malaysia	60
	Alghadir and Anwer (2015)	Saudi Arabia	165
	Engholm and Holmström (2005)	Sweden	82,451
	Guo et al. (2004)	Taiwan	578
	Goldsheyder et al. (2002)	US	312
	Merlino et al. (2003)	US	996
Overall	**Mean prevalence**		

Note: MSS = Musculoskeletal symptoms, the size of ◆ is proportional to the log of the sample size, the bars indicate 95% confidence interval, * indicates that the sample sizes of individual trades were not available. Therefore, the study was not used in the meta-analysis. The quality scores ranged from 0 to 8. Studies scored < 4 were classified as low quality, while those scored higher than 4 were classified as high quality. Some data points do not show the confidence intervals because the sample sizes are so large that they conceal their respective confidence intervals. Mean prevalence was calculated using data from all relevant studies, excluding the outliers originated from the low-quality studies.

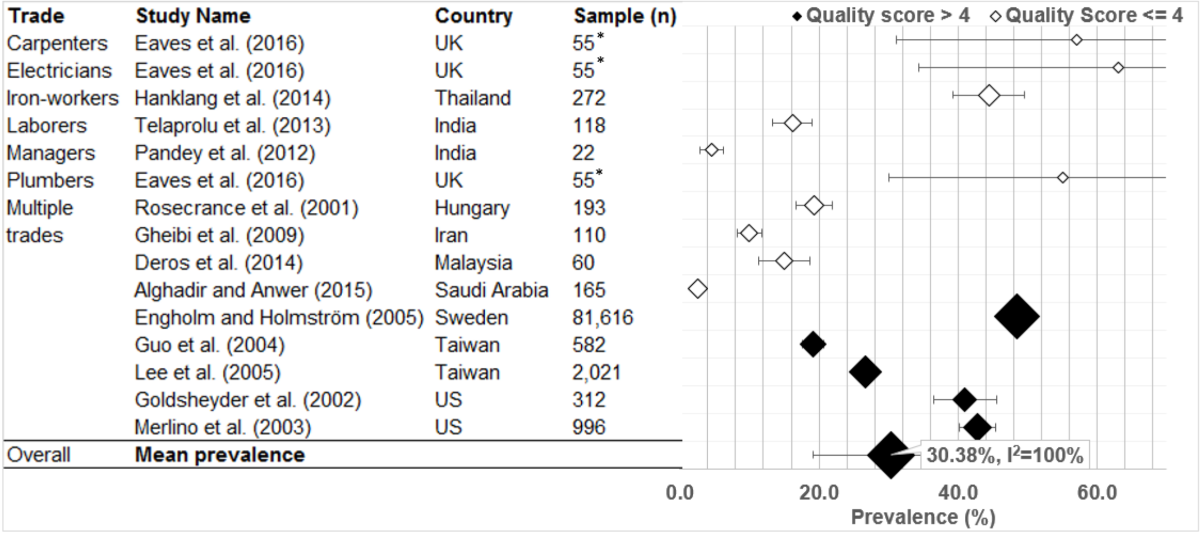
1-year prevalence of elbow MSS in different construction trades



Trade	Study Name	Country	Sample (n)
Carpenters	Eaves et al. (2016)	UK	55*
Electricians	Eaves et al. (2016)	UK	55*
Laborers	Telaprolu et al. (2013)	India	118
Plumbers	Eaves et al. (2016)	UK	55*
Multiple trades	Rosecrance et al. (2001)	Hungary	193
	Gheibi et al. (2009)	Iran	110
	Deros et al. (2014)	Malaysia	60
	Alghadir and Anwer (2015)	Saudi Arabia	165
	Engholm and Holmström (2005)	Sweden	81,615
	Guo et al. (2004)	Taiwan	579
	Lee et al. (2005)	Taiwan	2,021
	Goldsheyder et al. (2002)	US	312
	Merlino et al. (2003)	US	996
Overall	**Mean prevalence**		

Note: MSS = Musculoskeletal symptoms, the size of ◆ is proportional to the log of the sample size, the bars indicate 95% confidence interval, * indicates that the sample sizes of individual trades were not available. Therefore, the study was not used in the meta-analysis. The quality scores ranged from 0 to 8. Studies scored < 4 were classified as low quality, while those scored higher than 4 were classified as high quality. Some data points do not show the confidence intervals because the sample sizes are so large that they conceal their respective confidence intervals. Mean prevalence was calculated using data from all relevant studies, excluding the outliers originated from the low-quality studies.

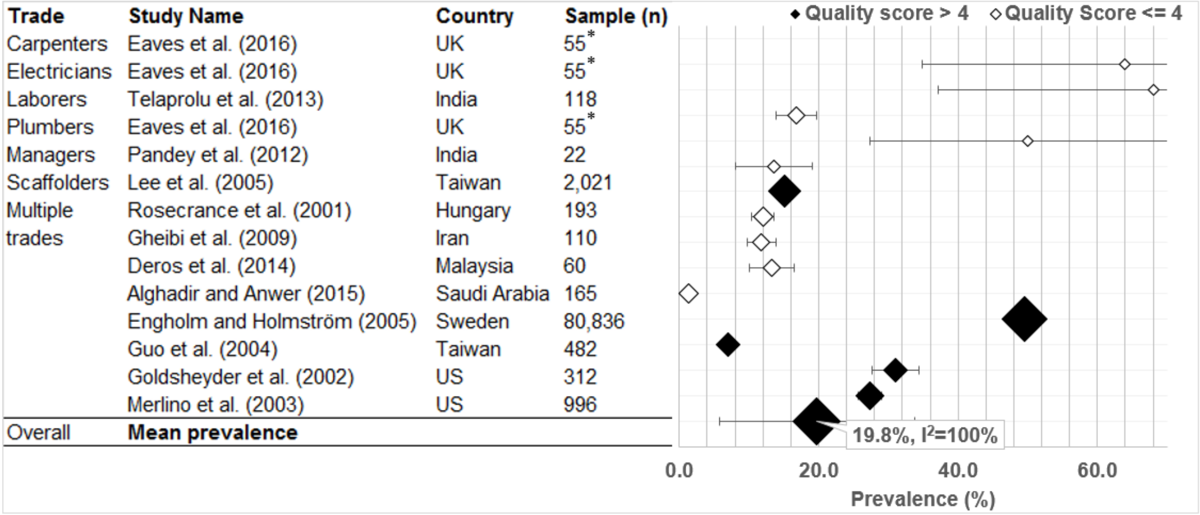
1-year prevalence of wrist MSS in different construction trades



Trade	Study Name	Country	Sample (n)
Carpenters	Eaves et al. (2016)	UK	55*
Electricians	Eaves et al. (2016)	UK	55*
Iron-workers	Hanklang et al. (2014)	Thailand	272
Laborers	Telaprolu et al. (2013)	India	118
Managers	Pandey et al. (2012)	India	22
Plumbers	Eaves et al. (2016)	UK	55*
Multiple trades	Rosecrance et al. (2001)	Hungary	193
	Gheibi et al. (2009)	Iran	110
	Deros et al. (2014)	Malaysia	60
	Alghadir and Anwer (2015)	Saudi Arabia	165
	Engholm and Holmström (2005)	Sweden	81,616
	Guo et al. (2004)	Taiwan	582
	Lee et al. (2005)	Taiwan	2,021
	Goldsheyder et al. (2002)	US	312
	Merlino et al. (2003)	US	996
Overall	**Mean prevalence**		

Note: MSS = Musculoskeletal symptoms, the size of ◆ is proportional to the log of the sample size, the bars indicate 95% confidence interval, * indicates that the sample sizes of individual trades were not available. Therefore, the study was not used in the meta-analysis. The quality scores ranged from 0 to 8. Studies scored < 4 were classified as low quality, while those scored higher than 4 were classified as high quality. Some data points do not show the confidence intervals because the sample sizes are so large that they conceal their respective confidence intervals. Mean prevalence was calculated using data from all relevant studies, excluding the outliers originated from the low-quality studies.

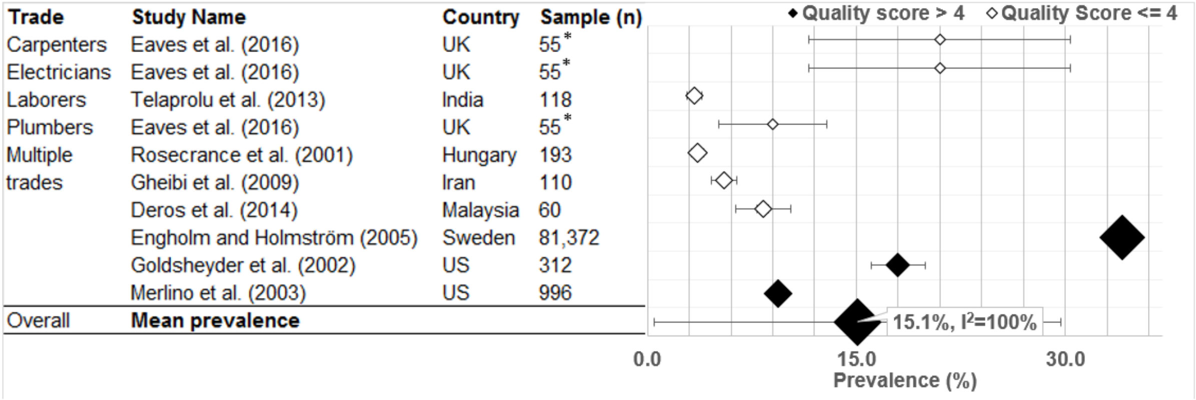
1-year prevalence of upper back MSS in different construction trades



Trade	Study Name	Country	Sample (n)
Carpenters	Eaves et al. (2016)	UK	55*
Electricians	Eaves et al. (2016)	UK	55*
Laborers	Telaprolu et al. (2013)	India	118
Plumbers	Eaves et al. (2016)	UK	55*
Managers	Pandey et al. (2012)	India	22
Scaffolders	Lee et al. (2005)	Taiwan	2,021
Multiple trades	Rosecrance et al. (2001)	Hungary	193
	Gheibi et al. (2009)	Iran	110
	Deros et al. (2014)	Malaysia	60
	Alghadir and Anwer (2015)	Saudi Arabia	165
	Engholm and Holmström (2005)	Sweden	80,836
	Guo et al. (2004)	Taiwan	482
	Goldsheyder et al. (2002)	US	312
	Merlino et al. (2003)	US	996
Overall	**Mean prevalence**		

Note: MSS = Musculoskeletal symptoms, the size of ◆ is proportional to the log of the sample size, the bars indicate 95% confidence interval, * indicates that the sample sizes of individual trades were not available. Therefore, the study was not used in the meta-analysis. The quality scores ranged from 0 to 8. Studies scored < 4 were classified as low quality, while those scored higher than 4 were classified as high quality. Some data points do not show the confidence intervals because the sample sizes are so large that they conceal their respective confidence intervals. Mean prevalence was calculated using data from all relevant studies, excluding the outliers originated from the low-quality studies.

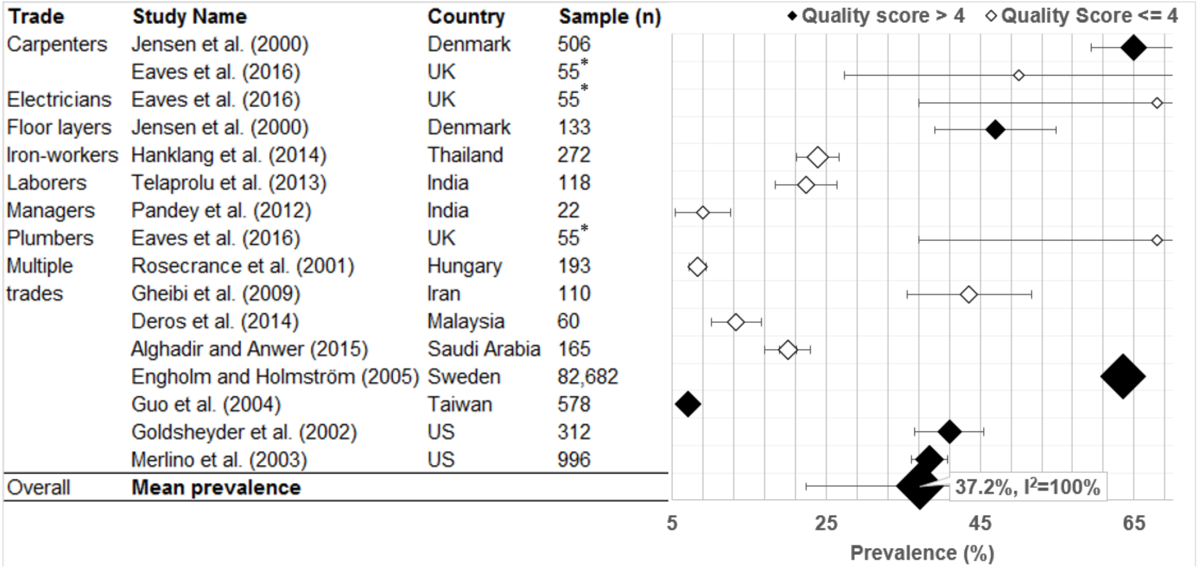
1-year prevalence of hip/thigh MSS in different construction trades



Trade	Study Name	Country	Sample (n)
Carpenters	Eaves et al. (2016)	UK	55*
Electricians	Eaves et al. (2016)	UK	55*
Laborers	Telaprolu et al. (2013)	India	118
Plumbers	Eaves et al. (2016)	UK	55*
Multiple trades	Rosecrance et al. (2001)	Hungary	193
	Gheibi et al. (2009)	Iran	110
	Deros et al. (2014)	Malaysia	60
	Engholm and Holmström (2005)	Sweden	81,372
	Goldsheyder et al. (2002)	US	312
	Merlino et al. (2003)	US	996
Overall	**Mean prevalence**		

Note: MSS = Musculoskeletal symptoms, the size of ◆ is proportional to the log of the sample size, the bars indicate 95% confidence interval, * indicates that the sample sizes of individual trades were not available. Therefore, the study was not used in the meta-analysis. The quality scores ranged from 0 to 8. Studies scored < 4 were classified as low quality, while those scored higher than 4 were classified as high quality. Some data points do not show the confidence intervals because the sample sizes are so large that they conceal their respective confidence intervals. Mean prevalence was calculated using data from all relevant studies, excluding the outliers originated from the low-quality studies.

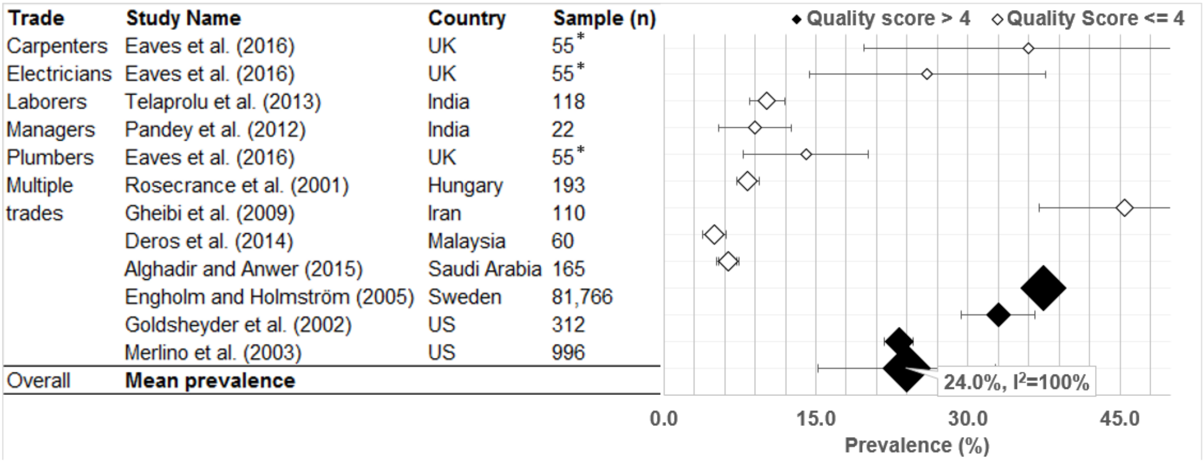
1-year prevalence of knee MSS in different construction trades



Trade	Study Name	Country	Sample (n)
Carpenters	Jensen et al. (2000)	Denmark	506
	Eaves et al. (2016)	UK	55*
Electricians	Eaves et al. (2016)	UK	55*
Floor layers	Jensen et al. (2000)	Denmark	133
Iron-workers	Hanklang et al. (2014)	Thailand	272
Laborers	Telaprolu et al. (2013)	India	118
Managers	Pandey et al. (2012)	India	22
Plumbers	Eaves et al. (2016)	UK	55*
Multiple trades	Rosecrance et al. (2001)	Hungary	193
	Gheibi et al. (2009)	Iran	110
	Deros et al. (2014)	Malaysia	60
	Alghadir and Anwer (2015)	Saudi Arabia	165
	Engholm and Holmström (2005)	Sweden	82,682
	Guo et al. (2004)	Taiwan	578
	Goldsheyder et al. (2002)	US	312
	Merlino et al. (2003)	US	996
Overall	**Mean prevalence**		

Note: MSS = Musculoskeletal symptoms, the size of ◆ is proportional to the log of the sample size, the bars indicate 95% confidence interval, * indicates that the sample sizes of individual trades were not available. Therefore, the study was not used in the meta-analysis. The quality scores ranged from 0 to 8. Studies scored < 4 were classified as low quality, while those scored higher than 4 were classified as high quality. Some data points do not show the confidence intervals because the sample sizes are so large that they conceal their respective confidence intervals. Mean prevalence was calculated using data from all relevant studies, excluding the outliers originated from the low-quality studies.

1-year prevalence of ankle/foot MSS in different construction trades



Trade	Study Name	Country	Sample (n)
Carpenters	Eaves et al. (2016)	UK	55*
Electricians	Eaves et al. (2016)	UK	55*
Laborers	Telaprolu et al. (2013)	India	118
Managers	Pandey et al. (2012)	India	22
Plumbers	Eaves et al. (2016)	UK	55*
Multiple trades	Rosecrance et al. (2001)	Hungary	193
	Gheibi et al. (2009)	Iran	110
	Deros et al. (2014)	Malaysia	60
	Alghadir and Anwer (2015)	Saudi Arabia	165
	Engholm and Holmström (2005)	Sweden	81,766
	Goldsheyder et al. (2002)	US	312
	Merlino et al. (2003)	US	996
Overall	**Mean prevalence**		

Note: MSS = Musculoskeletal symptoms, the size of ◆ is proportional to the log of the sample size, the bars indicate 95% confidence interval, * indicates that the sample sizes of individual trades were not available. Therefore, the study was not used in the meta-analysis. The quality scores ranged from 0 to 8. Studies scored < 4 were classified as low quality, while those scored higher than 4 were classified as high quality. Some data points do not show the confidence intervals because the sample sizes are so large that they conceal their respective confidence intervals. Mean prevalence was calculated using data from all relevant studies, excluding the outliers originated from the low-quality studies.

REFERENCES

ACSA (Alberta Construction Safety Association 2009), "Lost-time claims, disabling injury claims and claim rates—2004 to 2008", (http://employment.alberta.ca/documents/WHS/WHS-PUB-2009-data-analysis.pdf)

Agresti, A., and Coull, B. A. (1998). “Approximate is Better than ‘Exact’ for Interval Estimation of Binomial Proportions.” *The American Statistician*, 52(2), 119–126.

Ahern, D. K., Hannon, D. J., Goreczny, A. J., Follick, M. J., and Parziale, J. R. (1990). “Correlation of chronic low-back pain behavior and muscle function examination of the flexion-relaxation response.” *Spine*, 15, 92–95.

Albers, J. T., and Hudock, S. D. (2007). “Biomechanical assessment of three rebar tying techniques.” *International journal of occupational safety and ergonomics : JOSE*, 13(3), 279–289.

Alghadir, A., and Anwer, S. (2015). “Prevalence of musculoskeletal pain in construction workers in Saudi Arabia.” *The Scientific World Journal*, 1–5.

Alwasel, A., Elrayes, K., Abdel-Rahman, E., and Haas, C. (2013). “A HUMAN BODY POSTURE SENSOR FOR MONITORING AND DIAGNOSING MSD RISK FACTORS.” *Proceedings of the 30th ISARC, Montréal, Canada*, 531–539.

Alwasel, A., Elrayes, K., Abdel-rahman, E. M., and Haas, C. (2011). “Sensing Construction Work-related Musculoskeletal Disorders (WMSDs).” *Proceedings of the 28th ISARC, Seoul, Korea*, 164–169.

Antwi-Afari, M. F., Li, H., Edwards, D. J., Pärn, E. A., Seo, J., and Wong, A. (2017). “Effects of different weights and lifting postures on balance control following repetitive lifting tasks in construction workers.” *International Journal of Building Pathology and Adaptation*.

Armstrong, T., Buckle, P., Fine, L., Hagberg, M., Jonsson, B., Kilbom, A., Kuorinka, I., Silverstein, B., Sjogaard, G., and Viikari-Juntura, E. (1993). “A conceptual model for work-related neck and upper-limb musculoskeletal disorders.” *Scandinavian Journal of Work, Environment & Health*, 19(2), 73–84.

Arndt, V., Rothenbacher, D., Brenner, H., Fraisse, E., Zschenderlein, B., Daniel, U., Schuberth, S., and Fliedner, T. M. (1996). “Older workers in the construction industry: results of a routine health examination and a five year follow up.” *Occupational and environmental medicine*, 53, 686–691.

Arndt, V., Rothenbacher, D., Daniel, U., Zschenderlein, B., Schuberth, S., and Brenner, H. (2005). “Construction work and risk of occupational disability: a ten year follow up of 14474 male workers.” *Occupational and Environmental Medicine*, 62(8), 559–567.

Bartley, E. J., and Fillingim, R. B. (2013). “Sex differences in pain : a brief review of clinical and experimental findings.” *British Journal of Anaesthesia*, 111(1), 52–58.

Basmajian, J. V., and Deluca, C. J. (1985). *Muscles Alive: their Functions Revealed by Electromyography*. Williams and Wilkins, Baltimore.

Beaton, D. E., Cole, D. C., Manno, M., Bombardier, C., Hogg-Johnson, S., and Shannon, H. S. (2000). “Describing the Burden of Upper-Extremity Musculoskeletal Disorders in Newspaper Workers: What Difference do Case Definitions Make?” *Journal of Occupational Rehabilitation*, 10(1), 39–53.

Bedouch, P., Marra, C. A., FitzGerald, J. M., Lynd, L. D., and Sadatsafavi, M. (2012). “Trends in asthma-related direct medical costs from 2002 to 2007 in British Columbia, Canada: a population based-cohort study.” *PloS One*, 7(12), 1–8.

Benjamini, Y., and Hochberg, Y. (1995). “Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing.” *Journal of the Royal Statistical Society*, 57(1), 289–300.

Bentley, T. A., Hide, S., Tappin, D., Moore, D., Legg, S., Ashby, L., and Parker, R. (2006). “Investigating risk factors for slips, trips and falls in New Zealand residential construction using incident-centred and incident-independent methods.” *Ergonomics*, 49(1), 62–77.

Bernold, L., and AbouRizk, S. (2010). *Managing Performance in Construction*. John Wiley & Sons, New Jersey.

Biswas, A., Lemaire, E. D., and Kofman, J. (2008). “Dynamic gait stability index based on plantar pressures and fuzzy logic.” *Journal of Biomechanics*, 41, 1574–1581.

Bobick, T. G. (2004). “Falls through Roof and Floor Openings and Surfaces , Including Skylights : 1992 – 2000.” *Journal of Construction Engineering and Management*, 130(6).

Bodhare, T., Valsangkar, S., and Bele, S. (2011). “An epidemiological study of work-related musculoskeletal disorders among construction workers in Karimnagar, Andhra Pradesh.” *Indian Journal of Community Medicine*, 36(4), 304–307.

Boschman, J. S., van der Molen, H. F., Sluiter, J. K., and Frings-Dresen, M. H. W. (2012). “Musculoskeletal disorders among construction workers: a one-year follow-up study.” *BMC Musculoskeletal Disorders*, BMC Musculoskeletal Disorders, 13(1), 196–205.

Brown, L. A., Jensen, J. L., Korff, T., and Woollacott, M. H. (2001). “The translating platform paradigm: perturbation displacement waveform alters the postural response.” *Gait & Posture*, 14(3), 256–263.

Buchholz, B., Paquet, V., Punnet, L., Lee, D., and Moir, S. (1996). “PATH : A Work Sampling-Based Approach to Ergonomic Job Analysis for Construction Work PATH : A work sampling-based approach to ergonomic job analysis for construction and other nonrepetitive work." *APPLIED ERGONOMICS*, 27(3), 177–187.

Buchholz, B., Paquet, V., Wellman, H., and Forde, M. (2003). "Quantification of Ergonomic Hazards for Ironworkers Performing Concrete Reinforcement Tasks During Heavy Highway Construction." *AIHA Journal*, 64, 243–250.

Building and Construction Industry in Hong Kong. (2016). .

Burdorf, A., Govaert, G., and Elders, L. (1991). "Postural load and back pain of workers in the manufacturing of prefabricated concrete elements." *Ergonomics*, 34(7), 909–918.

Burdorf, A., and Sorock, G. (2016). "Positive and negative evidence of risk factors for back disorders." *Scand J Work Environ Health*, 23(4), 243–256.

Burström, L., Järvholm, B., Nilsson, T., and Wahlström, J. (2013). "Back and neck pain due to working in a cold environment: A cross-sectional study of male construction workers." *International Archives of Occupational and Environmental Health*, 86(7), 809–813.

Caban-Martinez, A. J., Lee, D. J., Clarke, T. C., Davila, E. P., Clark, J. D., Ocasio, M. A., and Fleming, L. E. (2010). "Self-reported joint and back pain among Hispanic construction workers: a pilot workplace musculoskeletal assessment." *Journal of Musculoskeletal Research*, 13(2), 49–55.

Cameron, I., Gillan, G., and Duff, A. R. (2007). "Issues in the selection of fall prevention and arrest equipment." *Engineering, Construction and Architectural Management*, 14(4).

Caron, O. (2003). "Effects of local fatigue of the lower limbs on postural control and postural stability in standing posture." *Neuroscience Letters*, 340(2), 83–86.

Chameau, J., and Santamarina, J. C. (1987). "Membership Functions I : Comparing Methods of Measurement." *International Journal of Approximate Reasoning*, 1(3), 287–301.

Chan, A. P. C., Wong, F. K. W., Chan, D. W. M., Yam, M. C. H., Kwok, A. W. K., Lam, E. W. M., and Cheung, E. (2008). "Work at height fatalities in the repair, maintenance, alteration, and addition works." *Journal of Construction Engineering and Management*, 134(7).

Chantawit, D., Hadikusumo, B. H. W., Charoenngam, C., and Rowlinson, S. (2005). "4DCAD-Safety: visualizing project scheduling and safety planning." *Construction Innovation*, 5, 99–114.

Chen, J., Ahn, C. R., and Han, S. (2014). "Detecting the Hazards of Lifting and Carrying in Construction through a Coupled 3D Sensing and IMUs Sensing System." *Computing in Civil and Building Engineering*, 1110–1117.

Cheng, T., Migliaccio, G. C., Ph, D., Teizer, J., and Gatti, U. C. (2013). "Data Fusion of Real-Time Location Sensing and Physiological Status Monitoring for Ergonomics Analysis of Construction Workers." *JOURNAL OF COMPUTING IN CIVIL ENGINEERING*, (JUNE), 320–335.

Cheung, J. (2016). *Legislative Council Panel on Housing Meeting on 1 February 2016*.

Chi, C.-F. (2016). "Accident Causes and Prevention Measures for Fatal Occupational Falls in the Construction Industry." *Fall Prevention and Protection*, H. Hsiao, ed., Taylor & Francis, Boca Raton, FL.

Chi, C.-F., Chang, T.-C., and Ting, H.-I. (2005). "Accident patterns and prevention measures for fatal occupational falls in the construction industry." *Applied Ergonomics*, 36(4), 391–400.

Choi, S. D. (2008). "Postural Balance and Adaptations in Transitioning Sloped Surfaces Postural Balance and Adaptations in Transitioning Sloped Surfaces." *International Journal of Construction Education and Research*, 4, 189–199.

Choi, S. D. (2012). "A study of trade-specific occupational ergonomics considerations in the U.S. construction industry." *Work*, 42(2), 215–222.

Choi, S. D., Yuan, L., and Borchardt, J. G. (2014). "Critical Analyses of Work-related Musculoskeletal Disorders and practical solutions in construction." *Proceedings of the Human Factors and Ergonomics Society 58th Annual Meeting*, 1633–1637.

Chou, S.-Y., and Chang, Y.-H. (2008). "A decision support system for supplier selection based on a strategy-aligned fuzzy SMART approach." *Expert Systems with Applications*, 34(4), 2241–2253.

Chung, M. K., Lee, I., and Kee, D. (2003). "Effect of stool height and holding time on postural load of squatting postures." *International Journal of Industrial Ergonomics*, 32(5), 309–317.

Cioffi, D. F. (2006). "Designing project management: A scientific notation and an improved formalism for earned value calculations." *International Journal of Project Management*, 24(2), 136–144.

Civilian occupations with high fatal injury counts by leading event, 2015. (2016). .

Coenen, P., Kingma, I., Boot, C. R. L., Twisk, J. W. R., Bongers, P. M., and van Dieën, J. H. (2013). "Cumulative low back load at work as a risk factor of low back pain: a prospective cohort study." *Journal of occupational rehabilitation*, 23, 11–18.

Construction in Hong Kong, Key Trends and Opportunities to 2021. (2017). .

Construction Sector Action Plan 2010–2013. (2011). .

Coorevits, P., Danneels, L., Cambier, D., Ramon, H., and Vanderstraeten, G. (2008). "Assessment of the validity of the Biering-Sorensen test for measuring back muscle fatigue based on EMG median frequency characteristics of back and hip muscles." *Journal* *of Electromyography and Kinesiology*, 18, 997–1005.

Cymerman, A., Reeves, J. T., Sutton, J. R., Rock, P. B., Groves, B. M., Malconian, M. K., Young, P. M., Wagner, P. D., and Houston, C. S. (1989). “Operation Everest II : maximal oxygen uptake at extreme altitude.” *Journal of Applied Physiology*, 66(5), 2446–2453.

Dababneh, A. J., Waters, T. R., Schneider, S., and Editor, C. (2000). “Ergonomics of Rebar Tying.” *Applied occupational and environmental hygiene*, 15(10), 721–727.

Davidson, B. S., Madigan, M. L., Nussbaum, M. A., and Wojcik, L. A. (2009). “Effects of localized muscle fatigue on recovery from a postural perturbation without stepping.” *Gait and Posture*, 29(4), 552–557.

Dekker, S., Cilliers, P., and Hofmeyr, J.-H. (2011). “The complexity of failure: Implications of complexity theory for safety investigations.” *Journal of Safety Research*, 49(6), 939–945.

Delleman, N. J., and Dul, J. (2007). “International standards on working postures and movements ISO 11226 and EN 1005-4.” *Ergonomics*, 50(11), 1809–1819.

Denis, D., St-Vincent, M., Imbeau, D., Jette´, C., and Nastasia, I. (2008). “Intervention practices in musculoskeletal disorder prevention : A critical literature review.” *Applied Ergonomics*, 39(1), 1–14.

Dewlaney, K. S., and Hallowell, M. (2012). “Prevention through design and construction safety management strategies for high performance sustainable building construction.” *Construction Management and Economics*, 30(2), 165–177.

DiDomenico, A., Gielo-Perczak, K., McGorry, R. W., and Chang, C. C. (2010a). “Effects of simulated occupational task parameters on balance.” *Applied Ergonomics*, 41(3), 484–489.

DiDomenico, A., McGorry, R. W., and Banks, J. J. (2011). “Effects of common working postures on balance control during the stabilisation phase of transitioning to standing.” *Ergonomics*, 54(11), 1053–1059.

DiDomenico, A., McGorry, R. W., and Banks, J. J. (2016). “Stabilisation times after transitions to standing from different working postures.” *Ergonomics*, 59(10), 1288–1293.

DiDomenico, A., McGorry, R. W., Huang, Y. H., and Blair, M. F. (2010b). “Perceptions of postural stability after transitioning to standing among construction workers.” *Safety Science*, 48(2), 166–172.

Dikmen, I., Birgonul, M. T., and Han, S. (2007). “Using fuzzy risk assessment to rate cost overrun risk in international construction projects.” *International Journal of Project Management*, 25(5), 494–505.

Distefano, L. J., Clark, M. A., and Padua, D. A. (2009). “Evidence Supporting Balance Training in Healthy Individuals: A Systemic Review.” *Journal of Strength & Conditioning*

Research, 23(9), 2718–2731.

Dong, X. S., Largay, J. A., Choi, S. D., Wang, X., Cain, C. T., and Romano, N. (2017). "Fatal falls and PFAS use in the construction industry: Findings from the NIOSH FACE reports." *Accident Analysis & Prevention*, Elsevier Ltd, 102, 136–143.

Dong, X. S., and Wang, X. (2011). "Fatal Falls in the U.S. Construction Industry, 1992-2008." *The international conference on Fall Prevention and Protection*, NIOSH, Morgantown WV.

Dong, X. S., Wang, X., and Daw, C. (2011). "Fatal Falls Among Older Construction Workers." *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 54(3).

Dong, X. S., Wang, X., Fujimoto, A., and Dobbin, R. (2012). "Chronic back pain among older construction workers in the United States: a longitudinal study." *International journal of occupational and environmental health*, 18(2), 99–109.

Duarte, M., Harvey, W., and Zatsiorsky, V. . (2000). "Stabilographic analysis of unconstrained standing." *Ergonomics*, 43(11), 1824–1839.

Dzeng, R. J., Fang, Y. C., and Chen, I. C. (2014). "A feasibility study of using smartphone built-in accelerometers to detect fall portents." *Automation in Construction*, Elsevier B.V., 38, 74–86.

Earnest, G. S., and Branche, C. M. (2016). "Knowledge Gaps and Emerging Issues for Fall Control in Construction." *Fall Prevention and Protection*, H. Hsiao, ed., Taylor & Francis, Boca Raton, FL.

Eaves, S., Gyi, D. E., and Gibb, A. G. F. (2016). "Building healthy construction workers: Their views on health, wellbeing and better workplace design." *Applied Ergonomics*, Elsevier Ltd, 54, 10–18.

Ekpenyong, C. E., and Inyang, U. C. (2014). "Associations between worker characteristics, workplace factors, and work-related musculoskeletal disorders: A cross-sectional study of male construction workers in Nigeria." *International Journal of Occupational Safety and Ergonomics*, 20(3), 447–462.

Elders, L. A. M., and Burdorf, A. (2004). "Prevalence, incidence, and recurrence of low back pain in scaffolders during a 3-year follow-up study." *Spine*, 29(6), E101–E106.

Engholm, G., and Holmström, E. (2005). "Dose – response associations between musculoskeletal construction workers Dose – response associations between musculoskeletal disorders and physical and psychosocial factors among construction workers." *Scand J Work Environ Health*, 31(2), 57–67.

Fejer, R., Kyvik, K. O., and Hartvigsen, J. (2006). "The prevalence of neck pain in the world population: A systematic critical review of the literature." *European Spine Journal*, 15, 834–848.

Fitzgerald, M. D., Tanaka, H., Tran, Z. V, Seals, D. R., Margaret, D., Tanaka, H., Zung, V., and Seals, D. R. (1985). “Age-related declines in maximal aerobic capacity in regularly exercising vs . sedentary women : a meta-analysis.” *journal of applied physiology*, 83(1), 160–165.

Forde, M. S., and Buchholz, B. (2004). “Task content and physical ergonomic risk factors in construction ironwork.” *International Journal of Industrial Ergonomics*, 34(4), 319–333.

Forde, M. S., Punnett, L., and Wegman, D. H. (2005). “Prevalence of musculoskeletal disorders in union ironworkers.” *Journal of occupational and environmental hygiene*, 2(4), 203–212.

Forecast of manpower situation of skilled construction workers. (2016). .

Gambatese, J. A., Behm, M., and Hinze, J. W. (2005). “Viability of Designing for Construction Worker Safety.” *Journal of Construction Engineering and Management*, 131(9).

Gambatese, J. A., Behm, M., and Rajendran, S. (2008). “Design’s role in construction accident causality and prevention: Perspectives from an expert panel.” *Safety Science*, 46(4), 675–691.

Garg, A. (1992). “Occupational biomechanics and low-back pain.” *Occupational Medicine (Philadelphia, Pa.)*, 7(4), 609–628.

Gatti, U. C., Migliaccio, G. C., Schneider, S., and Fierro, R. (2010). “Assessing physical strain in construction workforce: a first step for improving safety and productivity management.” *27th International Symposium on Automation and Robotics in Construction (ISARC 2010)*, 255–264.

Gauchard, G., Chau, N., Mur, J. M., and Perrin, P. (2001). “Falls and working individuals: role of extrinsic and intrinsic factors.” *Ergonomics*, 44(14), 1330–1339.

Genaidy, A. M., Al-Shedi, A. A., and Karwowski, W. (1994). “Postural stress analysis in industry.” *Applied Ergonomics*, 25(2), 77–87.

Gescheider, G. A. (1985). *Psychophysics: Method, Theory, and Application*. Lawrence Erlbaum Associates, Hillsdale, NJ.

Gheibi, L., Nasl Saraji, J., Zeraati, H., and Pouryaghub, G. (2009). “Assessment of ergonomic situation of workers in a dam construction workshops using the NIOSH-CPWR Checklist.” *Journal of School of Public Health and Institute of Public Health Research*, 7(3), 13–24.

Gilkey, D. P., Keefe, T. J., Bigelow, P. L., Herron, R. E., Duvall, K., Hautaluoma, J. E., Rosecrance, J. S., and Sesek, R. (2007). “Low back pain among residential carpenters: ergonomic evaluation using OWAS and 2D compression estimation.” *International journal of occupational safety and ergonomics*, 13(3), 305–321.

Gillen, M., Faucett, J. A., Beaumont, J. J., and McLoughlin, E. (1997). “Injury severity associated with nonfatal construction falls.” *American Journal of Industrial Medicine*, 32(6), 647–655.

Goldsheyder, D., Nordin, Ã. M., Weiner, S. S., and Hiebert, R. (2002). “Musculoskeletal symptom survey among mason tenders.” *American Journal of Industrial Medicine*, 42, 384–396.

Graham, I. D., Harrison, M. B., Nelson, E. A., Lorimer, K., and Fisher, A. (2003). “Prevalence of lower-limb ulceration: a systematic review of prevalence studies.” *Advances in skin & wound care*, 16(November), 305–316.

“Gross Domestic Product (GDP) by economic activity - percentage contribution to GDP at basic prices.” (n.d.). *Census and Statistics Department, The Government of the Hong Kong Special Administrative Region*, <https://www.censtatd.gov.hk/hkstat/sub/sp250.jsp?tableID=036&ID=0&productType=8> (Aug. 29, 2017).

Guo, H. R., Chang, Y. C., Yeh, W. Y., Chen, C. W., and Guo, Y. L. (2004). “Prevalence of musculoskeletal disorder among workers in Taiwan: A nationwide study.” *Journal of Occupational Health*, 46, 26–36.

Gupta, S. (2011). “Ergonomic applications to dental practice.” *Indian Journal of Dental Research*, 22(6), 816–822.

Hadikusumo, B. H. W., and Rowlinson, S. (2004). “Capturing safety knowledge using design-for-safety- process tool.” *Journal of Construction Engineering and Management*, 130(2), 281–289.

Hägg, G. M., and Åström, A. (1997). “Load pattern and pressure pain threshold in the upper trapezius muscle and psychosocial factors in medical secretaries with and without shoulder/neck disorders.” *International Archives of Occupational and Environmental Health*, 69(6), 423–432.

Hajaghazadeh, M., Mohammadian, Y., Normohammadi, M., and Zare, M. (2012). “An ergonomic study in building demolition: Assessment of musculoskeletal disorders risk factors by PATH method.” *International Journal of Environmental Health Engineering*, 1(43), 1–5.

Hallowell, M. R., and Gambatese, J. A. (2009). “Activity-Based Safety Risk Quantification for Concrete Formwork Construction.” *Journal of Construction Engineering and Management*, 135(10).

Han, S. H., Song, M., and Kwahk, J. (1999). “A systematic method for analyzing magnitude estimation data.” *International Journal of Industrial Ergonomics*, 23, 513–524.

Han, S., and Lee, S. (2013). “A vision-based motion capture and recognition framework for behavior-based safety management." *Automation in Construction*, Elsevier B.V., 35, 131–141.

Han, S., Lee, S., and Peña-mora, F. (2013). "Vision-Based Detection of Unsafe Actions of a Construction Worker : Case Study of Ladder Climbing." *JOURNAL OF COMPUTING IN CIVIL ENGINEERING*, 27, 635–644.

Hanapi, N. M., Kamal, M. M. M., Ismail, M. I., and Abdullah, I. A. P. (2013). "Identifying Root Causes and Mitigation Measures of Construction Fall Accidents." *Gading Business and Management Journal*, 17(1), 65–79.

Hanklang, S., Kaewboonchoo, O., Silpasuwan, P., and Mungarndee, S. S. (2014). "Musculoskeletal disorders among Thai women in construction-related work." *Asia-Pacific Journal of Public Health*, 26(2), 196–202.

"Happyback." (n.d.). .

Hapsari, V. D., and Xiong, S. (2016). "Effects of high heeled shoes wearing experience and heel height on human standing balance and functional mobility." *Ergonomics*, 59(2).

Haslam, R. A., Hide, S. A., Gibb, A. G. F., Gyi, D. E., Pavitt, T., Atkinson, S., and Duff, A. R. (2005). "Contributing factors in construction accidents." *Applied Ergonomics*, 36(4), 401–415.

Hegmann, K. T., Thiese, M. S., Garg, E. M. W. A., Kapellusch, J. M., Foster, J., Biggs, J., Edwards, H., Wertsch, J., and Kendall, R. (2014). "Impacts of differences in epidemiological case definitions on prevalence for upper-extremity musculoskeletal disorders." *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 56(1), 191–202.

Helander, M. G. (1991). "Safety hazards and motivation for safe work in the construction industry." *International Journal of Industrial Ergonomics*, 8(3), 205–223.

Hepple, R. T. (2002). "The Role of O2 supply in Muscle Fatigue." *Canadian Journal of Applied Physiology*, 27(1), 56–69.

Van Herp, G., Rowe, P., Salter, P., and Paul, J. P. (2000). "Three-dimensional lumbar spinal kinematics: a study of range of movement in 100 healthy subjects aged 20 to 60+ years." *Rheumatology*, 39, 1337–1340.

HONG, S. L., BROWN, A. J., and NEWELL, K. M. (2008). "Compensatory properties of visual information in the control of isometric force." *Perception & psychophysics*, 70(2), 306–313.

Hoonakker, P., and van Duivenbooden, C. (2010). "Monitoring working conditions and health of older rorkers in Dutch construction industry." *Am J Ind Med*, 53, 641–653.

Horta, M., Camanho, A. S., Johnes, J., and Johnes, G. (2013). “Performance trends in the construction industry worldwide : an overview of the turn of the century.” *Journal of Productivity Analysis,* 39(1), 89–99.

Hoy, D., Bain, C., Williams, G., March, L., Brooks, P., Blyth, F., Woolf, A., Vos, T., and Buchbinder, R. (2012). “A systematic review of the global prevalence of low back pain.” *Arthritis and Rheumatism,* 64(6), 2028–2037.

Hsiao, H., and Simeonov, P. (2001). “Preventing falls from roofs: A critical review.” *Ergonomics,* 44(5), 537–561.

Hsiao, H., Simeonov, P., Pizatella, T., Stout, N., McDougall, V., and Weeks, J. (2008). “Extension-ladder safety: Solutions and knowledge gaps.” *International Journal of Industrial Ergonomics,* 38(11–12).

Hsieh, T. Y., Lu, S. T., and Tzeng, G. H. (2004). “Fuzzy MCDM approach for planning and design tenders selection in public office buildings.” *International Journal of Project Management,* 22(7), 573–584.

Hu, K., Rahmandad, H., Smith-Jackson, T., and Winchester, W. (2011). “Factors influencing the risk of falls in the construction industry: a review of the evidence.” *Construction Management and Economics,* 29(4), 397–416.

Huang, X., and Hinze, J. (2003). “Analysis of Construction Worker Fall Accidents.” *Journal of Construction Engineering and Management*, 129(3).

Hunting, K. L., Welch, L. S., Nessel-Stephens, L., Anderson, J., and Mawudeku, A. (1999). “Surveillance of Construction Worker Injuries: The Utility of Trade-Specific Analysis.” *Applied Occupational and Environmental Hygiene,* 14, 459–470.

Hyunsoo Kim, R.Ahn, C., L.Stentz, T., and Jebelli, H. (2018). “Assessing the effects of slippery steel beam coatings to ironworkers’ gait stability.” *Applied Ergonomics,* 68, 72–79.

Inyang, N., and Al-Hussein, M. (2011). “Ergonomic Hazard Quantification and Rating of Residential Construction Tasks.” *CSCE 2011 General Conference - Congrès générale 2011 de la SCGC.*

Inyang, N., Al-hussein, M., El-rich, M., and Al-jibouri, S. (2012). “Ergonomic Analysis and the Need for Its Integration for Planning and Assessing Construction Tasks.” *Journal of Construction Engineering and Management,* 138(December), 1370–1376.

ISO 11226: Ergonomics-Evaluation of static working postures. (2006). .

Jebelli, H. (2015). “ASSESSING GAIT AND POSTURAL STABILITY OF CONSTRUCTION WORKERS USING WEARABLE WIRELESS sensor networks.” University of Nebraska, Lincoln.

Jebelli, H., Ahn, C. R., and Stentz, T. L. (2012). “Comprehensive Fall-Risk Assessment of Construction Workers Using Inertial Measurement Units : Validation of the Gait-Stability Metric to Assess the Fall Risk of Iron Workers.” *Journal of Computing in Civil Engineering*.

Jebelli, H., Ahn, C. R., and Stentz, T. L. (2014). “The validation of gait-stability metrics to assess construction workers’ fall risk.” *International Conference on Computing in Civil and Building Engineering*, Orlando, Florida.

Jebelli, H., Ahn, C. R., and Stentz, T. L. (2016). “Fall risk analysis of construction workers using inertial measurement units: Validating the usefulness of the postural stability metrics in construction.” *Safety Science*, Elsevier Ltd, 84, 161–170.

Jensen, L. K., Mikkelsen, S., Loft, I. P., and Eenberg, W. (2000). “Work-Related knee disorders in floor layers and carpenters.” *Journal of Occupational and Environmental Medicine*, 42(8), 835–842.

Jin, S., McCulloch, R., and Mirka, G. a. (2009). “Biomechanical evaluation of postures assumed when harvesting from bush crops.” *International Journal of Industrial Ergonomics*, 39, 347–352.

Johnson, C. B., Mihalko, S. L., and Newell, K. M. (2003). “Aging and the Time Needed to Reacquire Postural Stability.” *Journal of Aging and Physical Activity*, 11(4).

Jonsson, B. (1982). “Measurement and evaluation of local muscular strain in the shoulder during contrained work.” *J Human Ergol*, 11, 73–88.

Jung, H. S., and Jung, H.-S. (2008). “Evaluation of proper height for squatting stool.” *Ergonomics*, 51(5), 671–90.

Kang, Y., Siddiqui, S., Suk, S. J., Chi, S., and Kim, C. (2017). “Trends of Fall Accidents in the U.S. Construction Industry.” *Journal of Construction Engineering and Management*, 143(8), 4017043.

Kasahara, S., Ebata, J., and Takahashi, M. (2007). “Analysis of the Repeated One-Leg Heel-Rise Test of Ankle Plantar Flexors in Manual Muscle Testing.” *Journal of Physical Therapy Science*, 19, 251–256.

Kaskutas, V., Dale, A. M., Nolan, J., Patterson, D., Lipscomb, H. J., and Evanoff, B. (2009). “Fall hazard control observed on residential construction sites.” *American Journal of Industrial Medicine*, 52(6), 491–499.

Kenny, G. P., Yardley, J. E., Martineau, L., and Jay, O. (2008). “Physical Work Capacity in Older Adults : Implications for the Aging Worker.” *American Journal of Industrial Medicine*, 51(8), 610–625.

Kent, M. (2006). *The Oxford Dictionary of Sports Science & Medicine*. Oxford University Press.

Kim, H., Ahn, C. R., and Yang, K. (2017). “Identifying Safety Hazards Using Collective Bodily Responses of Workers.” *Journal of Construction Engineering and Management*, 143(2).

Kim, S., Dutra, L. M., and Okechukwu, C. A. (2014). “Contractor-, steward-, and coworker-safety practice: associations with musculoskeletal pain and injury-related absence among construction apprentices.” *Int Arch Occup Environ Health*, 87(5), 493–500.

King, S., Chambers, C. T., Huguet, A., MacNevin, R. C., McGrath, P. J., Parker, L., and MacDonald, A. J. (2011). “The epidemiology of chronic pain in children and adolescents revisited: A systematic review.” *Pain*, International Association for the Study of Pain, 152(12), 2729–2738.

Kinoshita, Y., and Guo, F. (2015). *What Can Boost Female Labor Force Participation in Asia?*

Kivimäki, J., Riihimäki, H., and Hänninen, K. (1992). “Knee disorders in carpet and floor layers and painters.” *Scand J Work Environ Health*, 18(5), 310–316.

Kok, L. M., Huisstede, B. M. A., Voorn, V. M. A., Schoones, J. W., and Nelissen, R. G. H. H. (2015). “The occurrence of musculoskeletal complaints among professional musicians: a systematic review.” *International Archives of Occupational and Environmental Health*.

Konrad, P. (2005). *“The abc of emg.” A practical introduction to kinesiological electromyography*.

Lam, K.-C., Tao, R., and Lam, M. C.-K. (2010). “A material supplier selection model for property developers using Fuzzy Principal Component Analysis.” *Automation in Construction*, 19(5), 608–618.

Lee, D., Pietrucha, M., and Sinha, S. (2005). “Use of Fuzzy Sets to Evaluate Driver Perception of Variable Message Signs.” *Transportation Research Record*, 1937, 96–104.

Lee, T.-H., and Han, C.-S. (2013). “Analysis of Working Postures at a Construction Site Using the OWAS Method.” *International Journal of Occupational Safety and Ergonomics*, 19(2), 245–250.

Lehtola, M. M., Molen, H. F. Van Der, Lappalainen, J., Hoonakker, P. L. T., Hsiao, H., Haslam, R. A., Hale, A. R., and Verbeek, J. H. (2008). “The Effectiveness of Interventions for Preventing Injuries in the construction industry, A Systematic Review.” *american journal of preventive medicine*, 35(1), 77–85.

Lemasters, G. K., Atterbury, M. R., Booth-Jones, A. D., Bhattacharya, A., Ollila-Glenn, N., Forrester, C., and Forst, L. (1998). “Prevalence of work related musculoskeletal disorders in active union carpenters.” *Occupational and environmental medicine*, 55, 421–427.

Li, K. W., and Lee, C. (1999). “Postural Analysis of Four Jobs on Two Building Construction Sites : an Experience of Using the OWAS Method in Taiwan.” *Journal of Occupational Health*, 183–190.

Li, R. Y. M. (2009). “Workers ’ Compensation for Non-fatal Construction Accidents : Review of Hong Kong Court Cases.” *Asian Social Science*, 5(11).

Lin, D., Nussbaum, M. A., Seol, H., Singh, N. B., Madigan, M. L., and Wojcik, L. A. (2009). “Acute effects of localized muscle fatigue on postural control and patterns of recovery during upright stance: influence of fatigue location and age.” *European Journal of Applied Physiology*, 106(3), 425–434.

Lindemann, U., Moe-nilssen, R., Nicolai, S. E., Becker, C., and Chiari, L. (2011). “Assessment of balance in unsupported standing with elderly inpatients by force plate and accelerometers.” *Aging Clinical and Experimental Research*, 24(1), 37–41.

Liu, J., Zhang, X., and Lockhart, T. E. (2012). “Fall Risk Assessments Based on Postural and Dynamic Stability Using Inertial Measurement Unit.” *Safety and Health at Work*, 3(3), 192–198.

Loney, P. L., Chambers, L. W., Bennett, K. J., Roberts, J. G., and Stratford, P. W. (1998). “Critical appraisal of the health research literature: prevalence or incidence of a health problem.” *Chronic diseases in Canada*, 19(4), 170–176.

Longpré, H. S., Acker, S. M., and Maly, M. R. (2015). “Muscle activation and knee biomechanics during squatting and lunging after lower extremity fatigue in healthy young women.” *Journal of Electromyography and Kinesiology*, 25, 40–46.

López, M. A. C., Ritzel, D. O., Fontaneda, I., and Alcantara, O. J. G. (2008). “Construction industry accidents in Spain.” *Journal of Safety Research*, 39(5), 497–507.

Lost-time claims, disabling injury claims and claim rates—2004 to 2008. (2009). .

Lotz, C. A., Agnew, M. J., Godwin, A. A., and Stevenson, J. M. (2009). “The effect of an on-body personal lift assist device (PLAD) on fatigue during a repetitive lifting task.” *Journal of Electromyography and Kinesiology*, 19, 331–340.

Ma, C. Z. H., Wong, D. W. C., Lam, W. K., Wan, A. H. P., and Lee, W. C. C. (2016). “Balance improvement effects of biofeedback systems with state-of-the-art wearable sensors: A systematic review.” *Sensors*, 16(4).

Madigan, M. L., Davidson, B. S., and Nussbaum, M. A. (2006). “Postural sway and joint kinematics during quiet standing are affected by lumbar extensor fatigue.” *Human Movement Science*, 25, 788–799.

Maki, B. E., Holliday, P. J., and Fernie, G. R. (1990). “Aging and Postural Control: A Comparison of Spontaneous- and Induced-Sway Balance Tests.” *J Am Geriatr Soc*, 38, 1–9.

Mancini, M., Salarian, A., Carlson-Kuhta, P., Zampieri, C., King, L., Chiari, L., and Horak, F. B. (2012). “ISway: a sensitive, valid and reliable measure of postural control.” *Journal of*

NeuroEngineering and Rehabilitation, 9(1), 59.

Mannion, A. F., and Dolan, P. (1994). “Electromyographic median frequency changes during isometric contraction of the back extensors to fatigue.” *Spine*.

Marras, W. S., Lavender, S. a, Ferguson, S. a, Splittstoesser, R. E., and Yang, G. (2010). “Quantitative dynamic measures of physical exposure predict low back functional impairment.” *Spine*, 35(8), 914–923.

Mcgill, S. M., Hughson, R. L., Parks, K., Mcgill, S. M., Hughson, R. L., and Lumbar, K. P. (2000). “Lumbar erector spinae oxygenation during prolonged contractions : implications for prolonged work.” *Ergonomics*, 43(4), 486–493.

McGill, S. M., and Kippers, V. (1994). “Transfer of loads between lumbar tissues during the flexion-relaxation phenomenon.” *Spine*, 19(19), 2190–2196.

McGuine, T. A., Greene, J. J., Best, T., and Leverson, G. (2000). “Balance as a predictor of ankle injuries in high school basketball players.” *Clinical Journal of Sport Medicine*, 10(4), 239–244.

Mebarki, B., Argoub, M., and Tebboune, B. (2015). “Assessment of postural stress among bricklayers in a construction company.” *19th Triennial Congress of the IEA, Melbourne*, 1–6.

Meo, S. A., Alsaaran, Z. F., Alshehri, M. K., Khashougji, M. A., Almeterk, A. A. Z., Almutairi, S. F., and Alsaeed, S. F. (2013). “Work-related musculoskeletal symptoms among building construction workers in Riyadh, Saudi Arabia.” *Pak J Med Sci*, 29(6), 1394–1399.

Merlino, L. A., Rosecrance, J. C., Anton, D. C., and Cook, T. M. (2003). “Symptoms of musculoskeletal disorders among apprentice construction workers.” *Applied occupational and environmental hygiene*, 18(1), 57–64.

Miller, A. E. J., Macdougall, J. D., Tarnopolsky, M. A., and Sale, D. G. (1993). “Gender differences in strength and muscle fiber characteristics.” *European Journal of Applied Physiology and Occupational Physiology*, 66(3), 254–262.

Moher, D., Liberati, A., Tetzlaff, J., and Altman, D. G. (2009). “Reprint--preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement.” *Physical therapy*, 89(9), 873–880.

Molano, S. M., Burdorf, A., and Elders, L. A. M. (2001). “Factors associated with medical care-seeking due to low-back pain in scaffolders.” *American Journal of Industrial Medicine*, 40, 275–281.

van der Molen, H. F., Sluiter, J. K., and Frings-Dresen, M. H. W. (2009). “The use of ergonomic measures and musculoskeletal complaints among carpenters and pavers in a 4.5-year follow-up study.” *Ergonomics*, 52(8), 954–963.

Nadhim, E. A., Hon, C., Xia, B., Stewart, I., and Fang, D. (2016). “Falls from height in the construction industry: A critical review of the scientific literature.” *International Journal of Environmental Research and Public Health*, 13(7).

NATIONAL CENSUS OF FATAL OCCUPATIONAL INJURIES IN 2015. (2016). .

Neumann, W. P., Wells, R. P., Norman, R. W., Andrews, D. M., Frank, J. W., Shannon, H. S., and Kerr, M. S. (1999). “Comparison of four peak spinal loading exposure measurement methods and their association with low-back pain.” *Scand J Work Environ Health*, 25(5), 404–409.

Nguyen, L. D., Tran, D. Q., and Chandrawinata, M. P. (2016). “Predicting Safety Risk of Working at Heights Using Bayesian Networks.” *Journal of Construction Engineering and Management*, 142(9).

Non-traumatic musculoskeletal injury by construction rate group. (n.d.). .

Nonfatal Occupational Injuries and Illnesses Requiring Days Away from Work, 2014. (2015). .

Nordander, C., Hansson, G.-Å., Rylander, L., Asterland, P., BystrÖm, J. U., Ohlsson, K., Balogh, I., and Skerfving, S. (2000). “Muscular rest and gap frequency as EMG measures of physical exposure: the impact of work tasks and individual related.” *Ergonomics*, 43(11), 1904–1919.

Nussbaum, M. A. (2003). “Postural stability is compromised by fatiguing overhead work.” *AIHA Journal*, 64(1), 56–61.

Oatis, C. A. (2004). *Kinesiology: The Mechanics and Pathomechanics of Human Movement*. Lippincott Williams & Wilkins, Philadelphia.

Occupational Safety and Health Statistics Bulletin. (2017). .

Ogata, K., and Whiteside, L. A. (1982). “Effects of external compression on blood flow to muscle and skin.” *Clinical orthopaedics and related research*, (168), 105–107.

Paillard, T., and Noé, F. (2015). “Techniques and Methods for Testing the Postural Function in Healthy and Pathological Subjects.” *BioMed Research International*.

Paloski, W. H., Wood, S. J., Feiveson, A. H., Black, F. O., Hwang, E. Y., and Reschke, M. F. (2006). “Destabilization of human balance control by static and dynamic head tilts.” *Gait & Posture*, 23(3), 315–323.

Pan, C. S., and Chiou, S. S. (1999). “Analysis of biomechanical stresses during drywall lifting.” *International Journal of Industrial Ergonomics*, 23(5–6), 505–511.

Pandey, V., Chakraborty, T., and Mukhopadhyay, S. (2012). “Prevalence of musculoskeletal disorders, levels of physical activity and perceived quality of life amongst construction site managers in Mumbai: A case study.” *Work*, 43(4), 447–451.

Parker, T., and Worringham, C. (2004). *FITNESS FOR WORK IN MINING: NOT A "one size fits all" APPROACH*.

Peppas, G., Alexiou, V. G., Mourtzoukou, E., and Falagas, M. E. (2008). "Epidemiology of constipation in Europe and Oceania: a systematic review." *BMC gastroenterology*, 8, 5.

Pheasant, S. (1996). *Bodyspace: Anthropometry, Ergonomics and the Design of Work*. Taylor & Francis, London.

Piirtola, M., and Era, P. (2006). "Force Platform Measurements as Predictors of Falls among Older People – A Review." *Gerontology*, 52, 1–16.

Pincivero, D. M., Aldworth, C., Dickerson, T., Petry, C., and Shultz, T. (2000). "Quadriceps-hamstring EMG activity during functional, closed kinetic chain exercise to fatigue." *European journal of applied physiology*, 81, 504–509.

Pline, K. M., Madigan, M. L., and Nussbaum, M. A. (2006). "Influence of fatigue time and level on increases in postural sway." *Ergonomics*, 49(15), 1639–1648.

Plouvier, S., François, J., Cyr, D., Bonenfant, S., Descatha, A., Goldberg, M., and Leclerc, A. (2015). "Occupational biomechanical exposure predicts low back pain in older age among men in the Gazel Cohort." *Int Arch Occup Environ Health*, 88, 501–510.

Poon, S. W., Tang, S. L., and Wong, F. K. W. (2008). *Management and Economics of Construction Safety in Hong Kong*. Hong Kong University Press, Hong Kong.

Potvin, J. R., and Norman, R. W. (1993). "Quantification of erector spinae muscle fatigue during prolonged, dynamic lifting tasks." *European Journal of Applied Physiology and Occupational Physiology*, 67, 554–562.

Prieto, T. E., Myklebust, J. B., Hoffmann, R. G., Lovett, E. G., and Myklebust, B. M. (1996). "Measures of postural steadiness differences between healthy young and elderly adults." *Transactions of Biomedical Engineering*, 43(9), 965–966.

Punnett, L., Fine, L. J., Keyserling, W. M., Herrin, G. D., and Chaffin, D. B. (1991). "Back disorders and nonneutral trunk postures of automobile assembly workers." *Scandinavian Journal of Work, Environment & Health*, 17(5), 337–346.

Radford, J. A., Burns, J., Buchbinder, R., Landorf, K. B., and Cook, C. (2006). "Does stretching increase ankle dorsiflexion range of motion? A systematic review." *British Journal of Sports Medicine*, 40(10), 870–875.

Ray, S. J., and Teizer, J. (2012). "Real-time construction worker posture analysis for ergonomics training." *Advanced Engineering Informatics*, Elsevier Ltd, 26, 439–455.

Report of Manpower Forecasting 2015 Construction Workers. (n.d.). .

Rinder, M. M., Genaidy, A., Salem, S., Shell, R., and Karwowski, W. (2008). "Interventions in the Construction Industry : A Systematic Review and Critical Appraisal." *Human Factors and Ergonomics in Manufacturing*, 18(2), 212–229.

Robinovitch, S. N. (2003). "Fall-related Occupational Injuries." *Occupational Ergonomics*, W. Karwowski and W. S. Marras, eds., CRC Press, Boca Raton, FL.

Rosecrance, J., Pórszász, J., Cook, T. M., Fekecs, É., Karácsony, T., Merlino, L. A., and Anton, D. C. (2001). "Musculoskeletal disorders among construction apprentices in Hungary." *Central European Journal of Public Health*, 9(4), 183–187.

Rothenbacher, D., Brenner, H., Arndt, V., Fraisse, E., Zschenderlein, B., and Fliedner, T. M. (1997). "Disorders of the back and spine in construction workers." *Spine*, 22(13), 1481–1486.

Rozenfeld, O., Sacks, R., Rosenfeld, Y., and Baum, H. (2010). "Construction Job Safety Analysis." *Safety Science*, 48(4), 491–498.

Saari, J., Wickström, G., Saari, J., and Wickstrom, G. (1978). "Load on back in concrete reinforcement work." *Scand J Work Environ Health*, 4(1).

Samorodov, A. (1999). *Ageing and labour markets for older workers*.

Saurin, T. A., Formoso, C. T., and Guimares, L. B. M. (2003). "Safety and production: an integrated planning and control model." *Construction Management and Economics*, 21.

Schieppati, M., Nardone, A., and Schmid, M. (2003). "Neck muscle fatigue affects postural control in man." *Neuroscience*, 121(2), 277–285.

Schiffman, J. M., Bensel, C. K., Hasselquist, L., Gregorczyk, K. N., and Piscitelle, L. (2006). "Effects of carried weight on random motion and traditional measures of postural sway." *Applied Ergonomics*, 37, 607–614.

Schneider, S., and Susi, P. (1994). "Ergonomics and construction: a review of potential hazards in new construction." *American industrial hygiene association journal*, 55(7), 635–649.

Schubert, P., and Kirchner, M. (2014). "Ellipse area calculations and their applicability in posturography." *Gait & Posture*, Elsevier B.V., 39(1), 518–522.

Schwatka, N. V, Butler, L. M., and Rosecrance, J. R. (2012). "An Aging Workforce and Injury in the Construction Industry." *Epidemiologic Reviews*, 34(2011), 156–167.

Seidler, A., Heiskel, H., Henkel, N., Kaiser, U., Bickeböller, R., Willingstorfer, W. J., Beck, W., and Elsner, G. (2001). "The role of cumulative physical work load in lumbar spine disease : risk factors for lumbar osteochondrosis and spondylosis associated with chronic complaints." *Occupational and Environmental Medicine*, 58, 735–746.

Seo, J. (2016). "Evaluation of construction workers` physical demands through computer vision-based kinematic data collection and analysis." Univeristy of Michigan.

Seo, J., Starbuck, R., Han, S., Asce, A. M., Lee, S., and Armstrong, T. J. (2014). "Motion Data-Driven Biomechanical Analysis during Construction Tasks on Sites." *Journal of Computing in Civil Engineering*.

Shirado, O., Ito, T., Kaneda, K., and Strax, T. E. (1995). "Flexion-relaxation phenomenon in the back muscles." *American Journal of Physical Medicine Rehabilitation*.

Silverstein, B., and Kalat, J. (1999). *Non-Traumatic SoftTissueMSDs, 1990–1997. Safety and Health Assessment and Research for Prevention (SHARP) Program Report #40- 3-99*.

Skobelkin, O. K., Kozlov, V. I., Litwin, G. D., Builin, V. A., Gurovo, O. A., and Azizov, G. A. (1990). "Blood microcirculation under laser physio-and reflexotherapy in patients with lesions in vessels of low extremities." *Laser Therapy*, 2(2), 69–77.

Snashall, D. (2005). "Occupational health in the construction industry." *Scandinavian Journal of Work, Environment & Health*, 31, 5–10.

Solomonow, M., Baratta, R. V, Banks, A., Freudenberger, C., and Zhou, B. H. (2003). "Flexion – relaxation response to static lumbar flexion in males and females." *Clinical Biomechanics*, 18, 273–279.

Sousa, V., Almeida, N. M., and Dias, L. A. (2014). "Risk-based management of occupational safety and health in the construction industry – Part 1: Background knowledge." *Safety Science*, 66, 75–86.

Springer, B. K., and Pincivero, D. M. (2009). "The effects of localized muscle and whole-body fatigue on single-leg balance between healthy men and women." *Gait & Posture*, 30(1), 50–54.

Sriwarno, A. B., Shimomura, Y., Iwanaga, K., and Katsuura, T. (2007). "The influence of different lower seat height on the muscular stress during squatting for a ground level job." *Journal of Human Ergology*, 36(1), 25–33.

Starbuck, R., Seo, J., Han, S., and Lee, S. (2014). "A Stereo Vision-based Approach to Marker-less Motion Capture for On-Site Kinematic Modeling of Construction Worker Tasks." *Computing in civil and building engineering*, 1094–1101.

Statistics), B. (Bureau of L. (2013). *Nonfatal occupational injuries and illnesses requiring days away from work, 2012*.

Sullivan, P. B. O., Grahamslaw, K. M., Kendell, M., Lapenskie, S. C., Moller, N. E., and Richards, K. V. (2002). "The Effect of Different Standing and Sitting Postures on Trunk Muscle Activity in a Pain-Free Population." *Spine*, 27(11), 1238–1244.

Sullivan, P. O., Dankaerts, W., Burnett, A., Chen, D., Booth, R., Carlsen, C., and Schultz, A. (2006). "Evaluation of the Flexion Relaxation Phenomenon of the Trunk Muscles in Sitting." *Spine*, 31(17), 2009–2016.

Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM). (2005). Netherlands.

Szeto, G. P. Y., Wong, K. T., Law, K. Y., and Lee, E. W. C. (2013). “A study of spinal kinematics in community nurses performing nursing tasks.” *International Journal of Industrial Ergonomics*, Elsevier Ltd, 43, 203–209.

Szeto, G. P. Y. Y., Straker, L. M., O’Sullivan, P. B., and O’Sullivan, P. B. (2005). “A comparison of symptomatic and asymptomatic office workers performing monotonous keyboard work—2: Neck and shoulder kinematics.” *Manual Therapy*, 10, 281–291.

Tah, J. H. M., and Carr, V. (2010). “A proposal for construction project risk assessment using fuzzy logic.” *Construction Management and Economics*, 18(4), 491–500.

Telaprolu, N., Lal, B., and Chekuri, S. (2013). “Work related musculoskeletal disorders among unskilled Indian women construction workers.” *National Journal of Community Medicine*, 4(4), 658–661.

The Construction Chart Book. (2013). The Center for Construction Research and Training, CPWR, Maryland, USA.

Thomas, D. R. (2010). “Sarcopenia.” *Clinics in Geriatric Medicine*, 26(2).

Thun, M., Tanaka, S., Smith, A. B., Halperin, W. E., Lee, S. T., Luggen, M. E., and Hess, E. V. (1987). “Morbidity from repetitive knee trauma in carpet and floor layers.” *British Journal of Industrial Medicine*, 44(9), 611–620.

Trojian, T. H., and McKeag, D. B. (2006). “Single leg balance test to identify risk of ankle sprains.” *British Journal of Sports Medicine*, 40, 610–613.

Ueno, S., Hisanaga, N., Jonai, H., Shibata, E., and Kamijima, M. (1999). “Association between musculoskeletal pain in Japanese construction workers and job, age, alcohol consumption and smoking.” *Industrial health*, 37, 449–456.

Ulrey, B. L., and Fathallah, F. A. (2013). “Effect of a personal weight transfer device on muscle activities and joint flexions in the stooped posture.” *Journal of Electromyography and Kinesiology*, 23(1), 195–205.

Umer, W., Antwi-Afari, M. F., Li, H., Szeto, G. P., and Wong, A. Y. (2018a). “The prevalence of musculoskeletal disorders in the construction industry: A systematic review and meta-analysis.” *International Archives of Occupational and Environmental Health*, 91(2), 125–144.

Umer, W., Li, H., Szeto, G. P., and Wong, A. Y. (2017a). “A low cost ergonomic intervention for mitigating physical and subjective discomfort during manual rebar tying.” *Journal of Construction Engineering and Management*, 143(10).

Umer, W., Li, H., Szeto, G. P., and Wong, A. Y. (2018b). “Proactive safety measures: Quantifying the upright standing stability after sustained rebar tying postures.” *Journal of Construction Engineering and Management,* 144(4).

Umer, W., Li, H., Szeto, G. P. Y., and Wong, A. Y. L. (2017b). “Identification of Biomechanical Risk Factors for the Development of Lower-Back Disorders during Manual Rebar Tying.” *Construction Engineering and Management,* 143(1), 1–10.

Vi, P. (2003). “Reducing Risk of Musculoskeletal Disorders Through the Use of Rebar-Tying Machines.” *Applied Occupational and Environmental Hygiene,* 18(9), 649–654.

Village, J. (2000). “A Comparison of ‘Case Definitions’ to Estimate Prevalence of Work-Related Musculoskeletal Disorders in Hospital Laundry Workers and the Influence of Psychosocial Variables.” *Proceedings of the Human Factors and Ergonomics Society Annual Meeting,* 44(30), 577–580.

Visser, S., van der Molen, H. F., Kuijer, P. P. F. M., van Holland, B. J., and Frings-Dresen, M. H. W. (2013). “Evaluation of two working methods for screed floor layers on musculoskeletal complaints, work demands and workload.” *Ergonomics,* 56(1), 69–78.

Wang, D., Dai, F., and Ning, X. (2015a). “Risk Assessment of Work-Related Musculoskeletal Disorders in Construction : State-of-the-Art Review.” *Journal of Construction Engineering and Management,* 1–15.

Wang, D., Hu, B., Dai, F., and Ning, X. (2015b). “SENSOR-BASED FACTORIAL EXPERIMENTAL STUDY ON LOW BACK DISORDER RISK FACTORS AMONG ROOFERS.” *5th International/11th Construction Specialty Conference,* 238,1-10.

Weinstein, M. G., Hecker, S. F., Hess, J. A., and Kincl, L. (2007). “A roadmap to diffuse ergonomic innovations in the construction industry: There is nothing so practical as a good theory.” *International Journal of Occupational and Environmental Health,* 13(1), 46–55.

Welch, L. S., Haile, E., Boden, L. I., and Hunting, K. L. (2008). “Age, work limitations and physical functioning among construction roofers.” *Work,* 31, 377–385.

Welch, L. S., Haile, E., Boden, L. I., and Hunting, K. L. (2009). “Musculoskeletal disorders among construction roofers—physical function and disability.” *Scand J Work Environ Health,* 35(1), 56–63.

West, G. H., Dawson, Ã. J., Teitelbaum, C., Novello, R., Hunting, K., and Welch, L. S. (2016). “An Analysis of Permanent Work Disability Among Construction Sheet Metal Workers.” *American Journal of Industrial Medicine,* 59(3), 186–195.

“What Ironworkers Do.” (2015). *Bureau of Labor Statistics,* <https://www.bls.gov/ooh/construction-and-extraction/structural-iron-and-steel-workers.htm#tab-2>.

Wilkins, J. C., McLeod, T. C. V., Perrin, D. H., and Gansneder, B. M. (2004). “Performance on the Balance Error Scoring System Decreases After Fatigue.” *Journal of Athletic Training*, 39(2), 156–161.

Wim Ament, Bonga, G. J. J., Verkerke, A. L. H., and Verkerke, G. J. (1993). “EMG median power frequency in an exhausting exercise.” *Journal of Electromyography and Kinesiology*, 3(4), 214–220.

Wong, A. Y. L., Parent, E. C., Dhillon, S. S., Prasad, N., and Kawchuk, G. N. (2015a). “Do Participants With Low Back Pain Who Respond to Spinal Manipulative Therapy Differ Biomechanically From Nonresponders, Untreated Controls or Asymptomatic Controls?” *Spine*, 40(17), 1329–1337.

Wong, A. Y. L., Parent, E. C., Funabashi, M., Stanton, T. R., and Kawchuk, G. N. (2013). “Do various baseline characteristics of transversus abdominis and lumbar multifidus predict clinical outcomes in nonspecific low back pain? A systematic review.” *Pain*, International Association for the Study of Pain, 154(12), 2589–2602.

Wong, J., Zhang, J., and Lee, J. (2015b). “A Vision of the Future Construction Industry of Hong Kong.” *Proceedings of the 32st ISARC*, Oulu, Finland.

Wong, L., Wang, Y., Law, T., and Lo, C. T. (2016). “Association of Root Causes in Fatal Fall-from-Height Construction Accidents in Hong Kong.” *Journal of Construction Engineering and Management*, 142(7).

Working at heights. (n.d.). .

Xia, B., Chan, A. P. C., and Yeung, J. F. Y. (2011). “Developing a Fuzzy Multicriteria Decision-Making Model for Selecting Design-Build Operational Variations.” *Journal of Construction Engineering and Management*, 137(12), 1176–1184.

Xie, Y., Szeto, G. P. Y., Dai, J., and Madeleine, P. (2016). “A comparison of muscle activity in using touchscreen smartphone among young people with and without chronic neck–shoulder pain.” *Ergonomics*, 59(1), 61–72.

Y.K., J., Ng, A., and Chan, H. S. (2015). “The Ageing Construction Workforce in Hong Kong: A Review.” *Proceedings of the International MultiConference of Engineers and Computer Scientists*, S. I. Ao, O. Castillo, C. Douglas, D. D. Feng, and J.-A. Lee, eds., International Association of Engineers, Hong Kong, Hong Kong, 18–21.

Yang, K., Ahn, C. R., Vuran, M. C., and Aria, S. S. (2016). “Semi-supervised near-miss fall detection for ironworkers with a wearable inertial measurement unit.” *Automation in Construction*, Elsevier B.V., 68.

Yang, K., Ahn, C., Vuran, M. C., and Kim, H. (2017a). “Analyzing Spatial Patterns of Workers’ Gait Cycles for Locating Latent Fall Hazards.” *Computing in Civil Engineering*, American Society of Civil Engineers, Seattle, Washington.

YANG, K., ARIA, S., AHN, C. R., and STENTZ, T. L. (2014). “Automated Detection of Near-miss Fall Incidents in Iron Workers Using Inertial Measurement Units.” *Construction Research Congress*, 935–944.

Yang, K., R.Ahn, C., Vuran, M. C., and Kim, H. (2017b). “Collective sensing of workers’ gait patterns to identify fall hazards in construction.” *Automation in Construction*, 82.

Yi, K.-J., and Langford, D. (2006). “Scheduling-Based Risk Estimation and Safety Planning for Construction Projects.” *Journal of Construction Engineering and Management*, 132(6).

Yi, W., and Chan, A. P. C. (2013). “Optimizing workerest schedule for construction rebar workers in hot and humid environment.” *Building and Environment*, 61, 104–113.

Yung, P. (2009). “Institutional arrangements and construction safety in China: an empirical examination.” *Construction Management and Economics*, 27(5).

Zhang, S., Teizer, J., Lee, J.-K., Eastman, C. M., and Venugopal, M. (2013). “Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules.” *Automation in Construction*, 29, 183–195.

Zurek, P., Rynkiewicz, M., Rynkiewicz, T., and Kos, H. (2010). “The ability to maintain static balance in competitors of cyclic sports at the stage of directed training.” *Studies in Physical Culture and Tourism*, 17(3), 217–222.

Zwart, B. C. H. De, Frings-Dresen, M. H. W., and Duivenbooden, J. C. van. (1999). “Senior workers in the Dutch construction industry: A search for age-related work and health issues.” *Experimental Aging Research*, 25(4), 385–391.