Centre for
Construction Work Health and Safety Research

MSD research report

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Centre for Construction Work Health and Safety Research

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Executive summary

A whole body system of miniature wearable sensors was used to measure biomechanical risk factors inherent in five manual rail construction work tasks. These sensors measured key joint angular motion (e.g. back motion) and muscle activity (using electromyography) while workers performed these tasks.

The tasks were identified on the basis that they present a high risk of work-related musculoskeletal disorder (MSD). Tasks were identified in consultation with supply chain participants, contractors and subcontractors.

The tasks assessed were:

- steel fixing,
- shotcreting,
- cable pulling,
- jackhammering, and
- shovelling.

Data were collected at Major Transport Infrastructure Program construction project sites and involved twelve participants who ranged in age from 18 to 60 years.

For three tasks (steelfixing, cable-pulling and shovelling) data were collected using a conventional way of performing the task, as well as a modified method. The data collected using conventional and modified methods were then compared to ascertain whether there were any significant changes in biomechanical risk factors.

For two tasks (shotcreting and jackhammering), alternative methods could not be trialled due to the inherent nature of the task and the equipment in use. However, risk factors inherent in these tasks and opportunities for the deployment of alternative methods and technologies were identified in the literature.

The risk factors for MSD differed between tasks, and differed within tasks depending on the work height (from ground level to above shoulder height) at which they were performed.

This highlights the need for task and context-specific analysis of work-related MSD risks in rail construction work.

Summary findings for each task are presented below.

Steelfixing

Assessment of steelfixing revealed that, using a conventional pincer/cutter tool, tying steel reinforcement bars together requires repeated use of the left (non-dominant) hand to supply the wire, while the right hand repeatedly clamps, twists and cuts the wire to complete a tie. The pincer/cutter tool exhibited the highest range of wrist flexion/extension and radial/ulnar deviation movement reaching values of 40 and 57 degrees respectively. The pincer/cutter method was also assessed as presenting a high risk of MSD because of the range of trunk and lumbar spine (L5S1) movement used to access low heights, and the range and repetitive hand and wrist actions used.

The steelfixing task was also assessed using a hand-held power tying tool and a long-handled stapler tool.

The two new tools assessed (a power tying tool and a long-handled stapler tool) and demonstrated some features that could, in part, overcome the limitations of the pincer/cutter tool. However, neither of the new tools was found to be sufficiently advanced in design to overcome all limitations.

The long handle of the stapler tool significantly reduced back movement for work at low height and shoulder abduction when working overhead. It also significantly reduced the time period over which forward trunk flexion fell above 40 degrees, suggesting the potential to reduce low back injury. However, the need to be able to apply the tool at a right angle to bars being fixed at ankle-to-knee and above-the-shoulder heights introduced awkward back, shoulder and wrist movements. Use of the long-handled stapler tool also generated greater shoulder abduction at working heights from the floor to the shoulder with each tool showing excessive shoulder abduction (above 90 degrees) when working above shoulder height (but not overhead). Again, this is an important finding since shoulder abduction above 90 degrees has been associated with injuries such as shoulder impingement. The electromyography (EMG) data revealed that the long-handled stapler tool required forceful manual application. Thus, using this tool required very high levels of muscle activity across the upper limbs and back. The stapler tool presents new MSD hazards not present in the conventional pincer/cutter and power tying tool.

The power tying tool required limited right shoulder and wrist movements, and the lowest levels of EMG for steel fixing (when operating at ground level). However, this tool offered no advantage to the user when working at very low and high levels where awkward trunk, lumbar, shoulder and wrist postures and movements were observed.

The results highlight the need to carefully evaluate tools for their ergonomic and functional performance, and use information in such assessments to inform the ergonomic design and improvement of tools that are currently available. The wearable sensor system used in the research can provide objective measurement of the benefits and disadvantages of different tool design and selection options.

The results also show that MSD risks vary significantly depending on the height at which work is to be conducted. Thus the size, dimensions and shape of the steel frame structure to be constructed should be considered when selecting the best method of fixing steel.

Off-site manufacturing of steel frames can permit greater control over the design of work processes and can potentially reduce the need to work in awkward postures that may be required while undertaking steelfixing in situ. However, it is possible that closer attention to the design of work in steelfixing pre-fabrication environments could reduce MSD risk further by paying attention to tool selection and/or the height at which work is carried out.

Shotcreting

The assessment showed that the variation in movement during shotcreting was relatively limited, however, the EMG data revealed high levels of bilateral lumbar, and right mid thoracic back muscle activity used by the worker to maintain balance in a relatively static posture while supporting the shotcreting equipment.

The high level of physical exertion to maintain the hose on the shoulder is considered to present a high risk of MSD. Consideration of alternative methods for manually handling and holding shotcreting hoses was made but no obvious improvements for reducing the force exertion while manually performing this task were identified.

Options to mechanise shotcreting tasks were explored and various mechanical methods were identified in the extant literature. Evidence was also found that mechanised methods for spraying concrete linings are in use in the mining sector.

Initial design considerations and criteria were proposed for a portable, mobile device that supports the hose and enables it to be directed with the same level of accuracy afforded by currently used manual methods. This design considers the environment in which shotcreting occurs and incorporates feedback from discussions with research participants and contractors engaged in shotcreting work.

Cable pulling

The analysis also provided preliminary evidence that the use of a trestle device to raise the cable when pulling it close to a pit can significantly improve operator back postures and movements. Trunk and lumbar forward flexion and the muscle activity of the back musculature were measured during two methods of cable pulling: using a conventional method and using a specially constructed trestle to elevate the cable above ground level. Peak trunk forward flexion exceeded 40 degrees for 50 per cent of work time using the conventional cable pulling technique but did not exceed 40 degrees at any time when the trestle was used. Mean trunk inclination was also high in the conventional cable pulling technique was used but reduced by approximately 50 per cent when the trestle was used. The analysis showed that the conventional method of cable pulling places the trunk and lumbar regions of the back in greater forward flexion increasing the risk of injury, and the use of a trestle device to elevate the cable can substantially reduce this risk.

The analysis also provided preliminary evidence that the use of a trestle device to raise the cable when pulling it close to a pit can significantly improve operator back postures and movements. However, the design and use of mechanical cable pulling devices should also be prioritised in order to eliminate or substantially reduce manual cable pulling, particularly in situations in which access to the site is limited or where cable pulling over longer distances is required.

Jackhammering

The specific jackhammering task assessed in the research involved the use of a jackhammer to break the tops of concrete piles. Jackhammering tools are primarily designed to be used in a vertical/downward motion to break up concrete or rock at ground or floor surfaces. The lifting, handling and use of a jackhammer above ground level, as was observed in the pile breaking work, exposed workers to peak trunk forward flexion magnitudes above 40 degrees. In particular, when bending down to lift the jackhammer to an elevated position, a worker's trunk inclination peaks at 54.2 degrees.

The EMG data also indicated that, when workers lift the jackhammer from a vertical position, with the chisel end resting on the ground, very high levels of force are exerted within the middle and lower back, right shoulder and right wrist. These values ranged from 134% of maximum voluntary contraction (MVC) for the left lumbar and mid thoracic right EMG, to 138% of MVC for the right shoulder, 210% for the right forearm, and 334% for the mid thoracic left EMG.

Once the jackhammer is in place, a high level of activation for the right upper limb to control the weight of the tool and stabilise it was found. The EMG values indicate high to very high levels for muscle activation and force exertion and the pattern of muscle activity for the right forearm wrist flexors indicates the rhythmical nature of muscle use relative to the tool's vibration. This highlights the regular, very high peaks that consistently exceed the MVC for these muscles.

The duration of the jackhammering activity can be reduced through the installation of lagging that enables the top of concrete columns to be broken more easily. However, this requires careful installation and quality control for it to be effective. The use of lagging also requires the use of a jackhammer.

The extant literature revealed that alternative technologies and methods of breaking concrete piles have been developed, for example using a hydraulic breaking technique. These techniques may be usefully investigated for their viability and potential adoption in Australia.

Shovelling

In the assessment of the shovelling task, trunk inclination varied between participants, but, in most cases, measurements were above the 20 degree threshold value in both participants.

The potential for a supplementary handle design to reduce back and upper limb movements for the operator was assessed. For one participant the results were inconclusive but for another participant the supplementary handle consistently reduced peak, mean and minimum trunk inclination values when the shovel was being used to:

- dig and toss material to the side,
- dig and toss material into a wheelbarrow, and
- scrape and toss material to the side.

The supplementary handle was also found to significantly reduce peak L5S1 forward flexion when material is being dug and tossed into a wheelbarrow of scraped and tossed to the side and significantly reduce the lumbar forward flexion range of movement when material was being dug and tossed into a wheelbarrow. Shoulder abduction was also reduced by the supplementary handle and the rotational movement of the forearm and wrist were significantly improved when using the supplementary handle (in terms of being more neutral). The results for wrist adduction and extension comparisons between shovel handle types were mixed.

These results suggest that the redesign of a traditional tool, in this case a shovel handle, has the potential to reduce some (but not necessarily all) MSD risk factors in shovelling. Further, using objective measurement of movement and muscle activity can help to inform and evaluate design alternatives.

Overall findings

The study demonstrated the feasibility and potential benefits of direct measurement of biomechanical risk factors for work-related MDS in construction work. In particular, this measurement provides a reliable and valid way to:

- identify risk factors inherent in manual construction activities,
- identify opportunities for the elimination or reduction of risk exposures for work-related MSD,
- compare and evaluate the risk inherent in different ways of working, and
- inform the development and improvement of ergonomic tools and equipment for the construction industry.

The findings also identified several macro-level factors related to the systems of work in the Australian rail construction context that could impact the reduction of work-related MSD. These included the management and coordination of the work of different supply chain participants and the adoption of new technologies for performing particular tasks such as concrete pile head breaking and shotcreting.

The research also provides preliminary evidence for the benefits and importance of engaging suppliers and manufacturers and investing in the ergonomic design of commonly used tools and equipment to reduce work-related MSD risk in the Australian construction industry.

Part 1: Introduction

Musculoskeletal disorders (MSDs) are the most common work-related conditions in Australia. They are associated with hazardous manual tasks and poorly designed work. In 2014-15, 43,555 serious workers' compensation claims were lodged for body stressing in Australia. Of these, 10 per cent were lodged by labourers (Safe Work Australia, 2017).

The *Australian Work Health and Safety Strategy 2012-2022* (Safe Work Australia, 2012) targets a reduction of at least 30 per cent, to be achieved by 2022, in the incidence rate of claims for musculoskeletal disorders resulting in one or more weeks off work.

The *Strategy* also identifies construction as a Priority Industry.

International research identifies construction as a particularly high risk industry for work-related MSDs (Hartmann & Fleischer, 2005; Latza et al., 2000). Construction work involves a variety of ergonomic hazards; for example, heavy lifting, repetitive movements, awkward postures, vibration and forceful exertions.

Body stressing is the most frequently cited cause of injury in the Australian construction industry, accounting for 37 per cent of occurrences (Safe Work Australia, 2017). Back injuries account for 20 per cent of serious workers' compensation claims made by construction workers (Safe Work Australia, 2017). It is also estimated that MSDs made up 50 per cent of injury incidents experienced on a recent major rail construction project (Regional Rail Link). Given the unprecedented program of major transport infrastructure construction work currently underway in Victoria, understanding and addressing the causes of MSDs associated with manual rail construction work tasks is a priority.

This report presents the results of a research project investigating the risk factors for MSD among workers engaged in five manual rail construction work tasks.

These manual rail construction tasks were identified by a research project steering group that comprised senior representatives from WorkSafe Victoria, the Major Transport Infrastructure Program, the Melbourne Metro Rail Authority, and the Level Crossing Removal Authority. Contractors engaged in delivering past and present rail construction projects were also consulted in selecting tasks. The manual rail construction tasks assessed in the research were:

- steel fixing
- shotcreting
- cable pulling
- shovelling, and
- jackhammering.

The research aimed to:

1. Improve knowledge relating to the risk factors and potential for MSD in the five targeted tasks.

2. Provide an evidence-base relating to the opportunities to reduce the risk of MSD in the tasks.

3. Measure and objectively assess the benefits of redesigning aspects of the selected tasks.

4. Use wearable sensors to enable the capture and analyse objective data to understand the risk factors, as well as identify and evaluate work redesign strategies for preventing MSD.

The results of the methods and results of the research are described in this report. In addition, research-to-practice documents and training resources will be developed to disseminate the findings to key industry stakeholders.

The remainder of this report is structured as follows:

- Part 2 presents a comprehensive review of the research literature relating to MSD risk in construction, as well as the methods of measurement previously used to understand and quantify MSD risks associated with work tasks.
- Part 3 describes the research methods we deployed in the study to measure and understand work-related MSD risk in the five tasks studied, and to analyse and understand the potential to reduce MSD risk through task or equipment redesign.
- Part 4 presents the results of the field-based assessment of work tasks.
- Part 5 presents a discussion of the major findings, draws conclusions and offers suggestions based on the research.

Part 2: Literature review

2.1 Methods used to conduct literature review

A search of online databases was undertaken to identify and source relevant scientific papers. These databases included PubMed, eMedicine, WebMD, Science Direct, Ergonomics Abstracts, Google Scholar, Ingenta, CISDOC, HESLIN, MEDLINE, AMED, Scopus, CINAHL, AMED and EBSCO.

The literature review sought to cover subject matter related to MSDs in the construction industry.

First, to identify literature relating to MSDs within the construction industry or in other blue collar occupations, we applied the following search terms: [(musculo* AND construction) OR (musculo* AND blue)].

Second, to identify literature relating to intervention practices for MSD prevention, we applied the following search terms: [(musculo* AND intervention) OR (musculo* AND redesign) OR (musculo* AND participatory)].

To identify literature concerning the characterisation and measurement of work tasks for MSD risk, we applied the following search terms: [(ambulatory* AND motion) OR (ambulatory * AND muscle) OR (ambulatory * AND heart*)].

Other keywords used to identify relevant literature included: back injury, strain, sprain, body stressing, shoulder, knee, inertial sensors, accelerometer, gyroscope, metabolic, classification, machine learning, regression, muscle-fibre, muscle-tendon, and muscle-fascicle.

The articles were then selected for their applicability to this review and referred to accordingly.

2.2 Prevalence and risk factors for MSDs in the construction industry

Following the Second World War, the organisation as a place of work underwent a dramatic transformation. Over the last 20 years in particular, due to changes brought about by globalisation and associated shifts in organisational culture, systems of manufacturing, construction and production have been revolutionised. Some scholars refer to this as ‘reactive productivism’ (Lanfranchi & Duveau, 2008) – a phenomenon which first appeared in Japan and was later adopted in countries around the world. The system is characterised by an amplified workload, an emphasis on flexibility, and productivity requirements. One of the major flaws of the system is that priority is given to productivity, often at the expense of workers’ health and safety. An inevitable consequence, especially in the construction industry, is the prevalence of MSDs which have become some of the most common forms of work-related diseases worldwide (Lanfranchi & Duveau, 2008).

Various stakeholder groups have demonstrated a determination to reach a more sustainable physical workload and reduce the level of physical wear imposed on construction workers.

However, the incidence of work-related MSD remains high among construction workers. In particular, labour unions around the world have sought to reduce the physical and mental deterioration of construction workers (Choi et al., 2016). One of the main barriers to reducing MSDs in construction lies in the fact that much of the work done in construction is non-routinised and undertaken in a wide variety of different physical work and environmental conditions (Buchholz et al., 1996). Due to the dynamic nature of construction work, the content, frequency and impact of tasks varies across individuals, and the changing external environment contributes to thes

e complexities (Paquet et al., 2005). These issues have made it difficult to measure ergonomic exposures and interventions systematically (Tak et al., 2011). Nevertheless, the following presents a review of the findings in the field to date.

Incidence, prevalence and recurrence

Between 2009 and 2013, acute and chronic MSDs accounted for more than half (54 per cent) of all workers’ compensation claims in Australia (Safe Work Australia, 2015). In 2012, the incidence of workers’ compensation claims in the Australian construction industry stood at 17.5 claims per 1000 employees (Safe Work Australia, 2015). This was an improvement relative to previous performance – in 2002 the rate was 27.5 claims per 1000 employees. However, the rate was still higher than that of all Australian industries combined, which recorded 12.0 claims per 1000 employees in 2012 (Safe Work Australia, 2015). Thus, the prevalence of work-related injury in the construction industry is higher than in other industrial sectors.

Lee et al. (2005) found that, in Taiwan in 1998, the prevalence of upper extremity musculoskeletal pain was higher among workers in the construction and agricultural industries than all other industries. In the US, the Bureau of Labor Statistics reported a high incidence (43.7 cases per 10,000 full-time workers) of work-related MSDs in construction workers in 2012 (Wang et al., 2015). Meanwhile, in the Netherlands the prevalence of MSDs among bricklayers and construction supervisors was 67 per cent and 57 per cent respectively (Boschman et al., 2012). Further, 47 per cent of bricklayers and 31 per cent of construction supervisors who suffered from MSDs reported recurrence of their complaints (Boschman et al., 2012).

It should be noted that these figures only provide estimates, with the true number of affected construction workers unknown. There are two main reasons for this. First, work-related injury and illness are under-reported due to the nature of relationships between employers and workers, and the extent of contracting, subcontracting, labour hire, and casual or precarious employment in construction (Buchholz et al., 2003). Second, the burden of illness and disease is often borne by workers and their private insurers. Further, workers may experience disincentives to report, such as fear of losing the job, risking the status of ‘zero injury’ programs, and increasing the workers’ compensation costs borne by the company. Meanwhile, in most developing countries and some developed countries, current systems tend to focus more on acute injuries than chronic disorders. This is because it is easier to associate acute injuries with work tasks and many chronic MSDs progress gradually over years before becoming evident (Dale et al., 2015).

Site and type of injury

In 2015, Safe Work Australia reported that injuries to the back accounted for 20 per cent of all workers' compensation claims in Australia, and injuries to the hand, fingers and thumb accounted for 17 per cent (Safe Work Australia, 2015). Other commonly injury sites were the knee and upper leg (12 per cent), shoulder and upper arm (10 per cent), ankle and lower leg (9 per cent) and the wrist, elbow and forearm (8 per cent) (Safe Work Australia, 2015).

Research conducted in Taiwan in 2005 showed that construction workers cited the shoulder (22.1 per cent of construction workers), hand and wrist (18.6 per cent), neck (17.9 per cent), elbow (13.9 per cent) and upper back (10 per cent) as sites in the upper body where pain occurred and medical treatment was sought (Lee et al., 2005).

Meanwhile, in the US, the Center for Construction Research and Training (CPWR) noted that back injuries accounted for almost 50 per cent of all work-related MSDs in 2010 (Bratcher et al., 2010). That same year, the rate of back injuries resulting in days away from work stood at 24.5 back injuries per 10,000 full-time employees (Bratcher et al., 2010). Bricklayers most frequently reported MSDs of the back and elbow, while construction supervisors reported MSDs of the lower arm or wrist and upper leg (Boschman et al., 2012).

A detailed description of the specific disorders experienced by construction workers has been provided by Holmström et al. (1995). This research indicates that injuries to the musculotendinous unit are typically caused by strain, especially following repeated eccentric muscle contractions (Holmström et al., 1995). Examples of joint injuries are osteoarthritis of the knee, hip and acromioclavicular joints (Holmström et al., 1995; Reid et al., 2010). Spinal disorders include degeneration of intervertebral discs in the cervical and lumbar spine, and disc space narrowing (Holmström et al., 1995). Finally, a commonly observed peripheral nerve entrapment disorder is carpal tunnel syndrome, which can be caused by nerve compression at the wrist (Holmström et al., 1995).

Risk/contributing factors

According to Hoonakker and van Duivenbooden (2010), a number of factors interact to influence the musculoskeletal health system:

1. Physical factors
2. Psychosocial factors
3. Thermal (environmental) factors
4. Individual factors (age, gender, body mass index, and personal habits), and
5. Broader social, economic, and cultural factors.

The main focus of this report is on physical, psychosocial and individual factors, which are discussed in further detail below.

Physical risk factors

MSDs generally occur when physical workload exceeds the physical capacity of the human body. This can occur due to occurrence of a single event or as a result of repeated suffering (Weigall et al., 2005).

Safe Work Australia (2015) states that the most common causes for acute and chronic MSDs in the Australian construction industry between 2009 and 2013 were ‘body stressing’ mechanisms and falls, trips and slips. Muscular stress while lifting or handling objects was the most common sub-mechanism of ‘body stress’. Falls on the same level and from a height were the most common sub-mechanisms of falls, trips and slips (Safe Work Australia, 2015). Lee et al. (2005) state that for Taiwanese construction workers, job stress due to poor physical working conditions was a significant risk factor for upper extremity musculoskeletal pain.

According to a recent review by Wang et al. (2015), the following risk factors are commonly associated with work-related MSDs in construction workers: repetition, force, awkward posture, vibration, and contact stress. These may be specific to particular tasks. Repetitive movements can cause strain in tendons and muscles as a result of their direct involvement in these movements, and due to the need to stabilise limbs involved in these movements. The force required to perform a task or maintain control of tools and equipment can also lead to MSDs due to the stress placed upon muscles, tendons and joints (Holmström et al., 1995; Wang et al., 2015). Additionally, awkward postures, in which joints are bent or twisted excessively beyond neutral positions, can cause sprains and strains in the wrist, shoulder, neck, lower back and mid back (Holmström et al., 1995; Kittusamy & Buchholz, 2004; Wang et al., 2015).

Vibration is another factor frequently associated with MSDs in construction workers which can cause damage to body organs and tissues (Boschman et al., 2012; Holmström et al., 1995; Kittusamy & Buchholz, 2004; Wang et al., 2015).

Specific tasks in construction work seem to be associated with an elevated risk of causing, or aggravating, MSDs. For example, among bricklayers, the following tasks are reported to either cause or aggravate work-related MSDs: working with a bent back; carrying and lifting; working with arms above shoulder height; and kneeling and stooping (Boschman et al., 2012). Further, Reid et al. (2010) state that knee osteoarthritis is associated with knee bending postures and activities, such as kneeling, squatting, frequent stair or ladder climbing, lifting heavy items, and a combination of these activities.

One task that results in MSD is manual materials handling (MMH). MMH is a common activity in construction. Workers involved in MMH activities are frequently exposed to occupational risk factors including poor and awkward postures, repetitive movements, hand-arm vibration, heavy lifting and handling, high physical stress, and overexertion (Parida & Ray, 2012). Exposure to these risk factors may cause occupational injuries, such as back pain, strain and sprain injuries, MSDs, and severe fatigue and loss of energy (Parida & Ray, 2012). According to Schneider and Susi (1994), increased risk of occupational injuries can be attributed to two major causes: first, characteristics of work environment and practices, and second, characteristics of individual workers. It is important to consider these causes and to control the associated risk factors through the ergonomic-based design of construction work systems.

In a study of occupational risk factors for MMH activities, Parida and Ray (2012) collected data from six groups of workers: masons, mason helpers, carpenters, welders, gas cutters and ground level helpers. The aim of the study was to identify the different occupational risk factors associated with MMH activities and assess their impact on the risk of MSDs. Data were collected through observing workers, discussions with workers, a survey of workers via a questionnaire, and reviewing relevant records. A strong correlation was identified between the presence of occupational and work-related risk factors, and the presence of injuries and subsequent MSDs. The construction trades with the highest risk of developing MSDs were carpenters (due to repetitive stress), welders (due to awkward posture), masons (due to MMH associated with static body posture), and ground level helpers (due to extreme climate conditions) (Parida & Ray, 2012). Parida and Ray (2012) suggest evaluating the risk factors through biomechanical, physiological and physical analysis may help to identify effective preventative measures to address these risks and improve workers' health and performance.

Finally, the pressure of production can play a role in the presence of risk factors for MSDs. Research suggests workers sometimes feel pressured to 'cut corners' in order to keep pace with speed and productivity expectations. This can increase risk related to MMH in terms of the number of lifts, load, and time spent working in awkward positions – a phenomenon scholars refer to as 'brutal rhythms' of work (Ajslev et al., 2013). Currently, most knowledge on the dose-response relationship between occupational physical risk factors and MSDs is based on self-reported data, or data obtained from biomechanical laboratory tests in which static postures are evaluated. However, there is a need to assess the factors that drive actual working conditions in the context of active construction sites (Wang et al., 2015). These factors will potentially include issues relating to the organisation and design of work, as well as the physical site environment.

A summary of the key physical risk factors affecting workers in the construction industry is presented in Table 2.1.

Table 2.1: Key physical risk factors affecting construction workers.

Factor	Definition	Damage and symptoms	Examples of correlated tasks
Repetition	Using the same muscles repeatedly without rest.	Strain in tendons and muscle groups involved in direct repetition motions.	Masonry work, assembly, roofing, bricklaying.
Force	The physical effort required to perform a task or maintain control of tools.	Stress on the muscles, tendons and joints which is associated with risk of injury at the shoulder, neck, lower back, wrist, etc.	Lifting drywall sections, trusses and materials, manual materials handling (MMH).
Awkward posture	When any joint of the body bends or twists excessively, or any muscles stretch beyond a comfortable range of motion.	Sprain and strain in wrist, shoulder, neck and lower back.	Scaffolding, roofing, concrete works.
Vibration	Any movement that a body makes about a fixed point.	Damage caused to body organs buffered by relatively low frequency and breakdown of body tissues resulting from continued absorption of high energy vibration.	Sitting or standing on a vibrating surface such as hole drillers, pile drivers.
Contact stress	Injury by hard, sharp objects when grasping.	Nerves and tissues beneath the skin of the wrist, palm or fingers injured by pressure when a hard or sharp object comes into contact with the skin.	Carpentry, masonry work.

Source: Jaffar et al. (2011)

Example: Design of hand-held tools

Research has demonstrated a strong association between the excessive use of poorly designed hand-held tools and MSDs (Mital & Kilbom, 1992). Some employers have attempted to address this issue by providing construction workers with tools of high ergonomic quality and usability, thereby minimising workers' physical constraints and the physical effort needed. Duca and Attaianese (2012) observed that, although much research has assessed the ergonomic quality of hand-held tools, there has been limited research on the usability of hand-held tools. In their study, they sought to develop a range of usability criteria to help employers select ergonomically well designed hand-held tools. Duca and Attaianese (2012) conducted the research in the context of construction masonry activities. They evaluated usability using a definition that took into account health and safety issues, as well as the adequacy of hand-held tools in terms of effectiveness, efficiency and operators' satisfaction.

The first stage of the research involved a detailed task analysis of masonry activities on construction sites to understand the major constraints experienced by operators when using hand-held tools for bricklaying. The analysis revealed that various factors influenced the usability of hand-held tools. These factors informed the authors' development of five main categories of usability requirements, which included comfortable use, maintainability, comprehensibility, injury protection and health protection. Under each category, a set of specific requirements was developed. For example, under the injury protection category, the following six requirements were specified: 'mechanical resistance', 'thermal shock proof', 'electrocution proof', 'stable hold', 'accidental activation proof' and 'minimum wastage'.

The second stage of the research sought to elicit a set of detailed technical specifications for each usability requirement. The elicitation process resulted in 106 technical specifications in total.

In the third stage of the research, the technical specifications were used to evaluate the usability of five selected bricklayer tools across different brands. The features of each tool were identified from technical sheets, sales literature, and information that was visually observable or measurable with a simple instrument. The researchers then reviewed the extent to which each of the tools' features aligned with the respective technical specifications developed in the second stage of the research. They found the selected tools failed to demonstrate many of the characteristics in the technical specifications; for example, visibility, ease of recognising handle points, handling stability, and weight.

The results of this study suggest the technical specifications developed by Duca and Attaianese (2012) can be used as a guide for the design of ergonomic construction hand-held tools, as well as a guide for employers in selecting tools that are ergonomically suitable for construction activities.

Source: Duca and Attaianese (2012)

Psychosocial risk factors

Much research has focused on the physical and biomechanical aspects of MSDs. However, in recent years there has been increasing recognition that social theories should also be taken into account. Social theories they enable consideration of the broader context factors, as well as considering the interrelation between the human body, environment, and other factors.

Figure 2.1 represents one such model developed by (Bongers et al., 1993; Bongers et al., 2002). The model provides a useful framework for understanding the relationships between psychosocial, biomechanical and individual factors that can contribute to MSD through various mechanisms (Figure 2.1).

In this model, biomechanical loads and psychosocial factors are considered to be risk factors, reflecting the organisational dimensions underlying work. However, symptoms of MSD are both directly affected by biomechanical loads, and indirectly affected through workers' perceptions of stress, and their physiological responses. Importantly, individual factors are recognised as having an impact through moderating the relationships between psychosocial factors and perceived stress, and perceived stress and physiological responses.

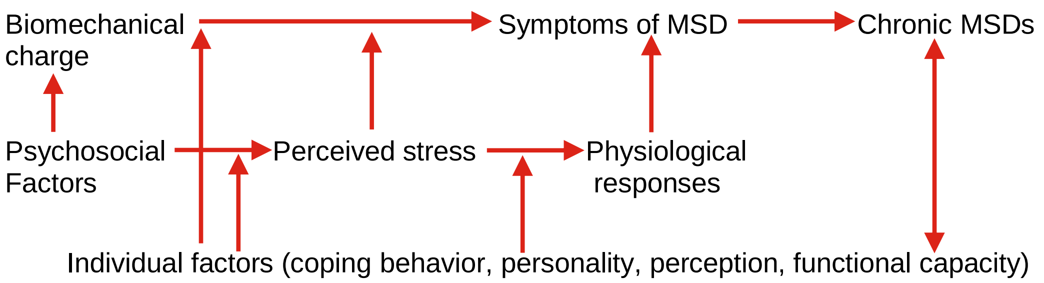


Figure 2.1: Bongers' model.

Source: Bongers et al. (1993), Bongers et al. (2002)

According to this model, perceived stress occurs in situations where the organisation's operational requirements place increased demands on workers, and members of the workforce assess these demands as surpassing their own resources (Lanfranchi & Duveau, 2008). Perceived stress is also related to psychosocial demands in the work or organisational environment.

Understanding psychosocial phenomena requires the consideration of a system of relations (Huang et al., 2002). In particular, a balance is needed between workplace demands and available resources. In environments where this balance does not exist, workers are more susceptible to developing psychological disorders (Dejours, 2000).

Indeed, workers are frequently left with no other option but to yield to arduous work demands in which fatigue and stress are the first symptoms of a vicious cycle that ultimately contributes to an increased risk of MSDs (Lanfranchi & Duveau, 2008). Psychosocial risk factors can be divided into two categories (Marras & Karwowski, 2006):

1. Those that are specific to the workplace (for example, job satisfaction, work pace, etc), and
2. Those that are related to individuals' experiences (for example, depression, perceived high-perceived stress).

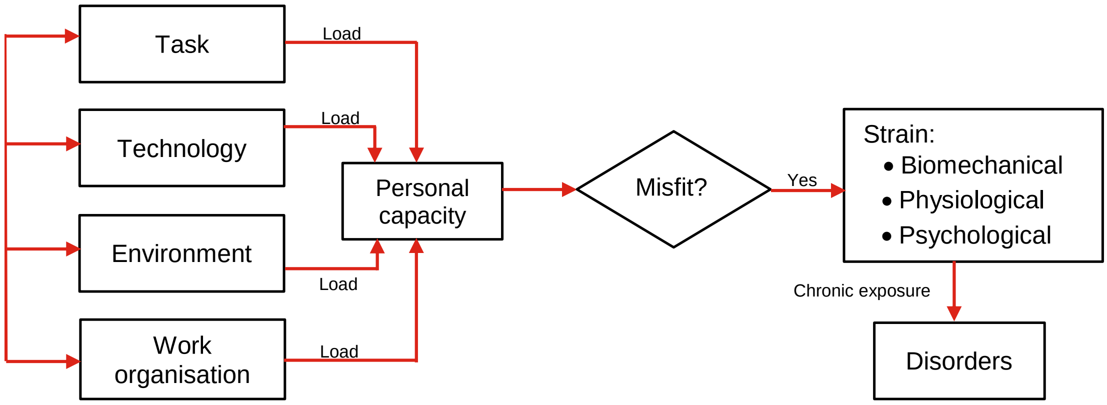


Figure 2.2: Conceptual model for the development of work-related musculoskeletal disorders.

Source: (Karsh et al., 2001)

Figure 2.2 presents an alternative multifactorial model showing the combined impact of loads arising from work tasks, technologies, environments and the organisation of work. Where these loads exceed workers' personal capacity, misfit occurs which produces biomechanical, physiological and/or psychological strain. Chronic exposure to this strain produces MSDs.

In the construction industry, workers often have tight work deadlines and may have poor job security, combined with low levels of autonomy, job control and social support. Sobeih et al. (2006) reviewed psychosocial risk factors and MSDs in construction and reported that the two most important factors associated with MSDs among construction appear to be high job stress, followed by low job satisfaction.

Other factors include low job control, high job demands, stress unrelated to work, low social support, and low stimulus from work (Sobeih et al., 2006). Construction workers experience a higher level of stress than workers in other industries (Petersen & Zwerling, 1998). Stress can modify human behaviour, and has been shown to influence work (Tucker et al., 2009), health (Glanz & Schwartz, 2008), eating (O'Connor & Conner, 2011), emotion (Liddell, 1956), and safety (Choudhry & Fang, 2008).

In addition, the use of piece rate (performance based) wage systems is common in the construction industry (Ajslev et al., 2015). Studies have linked performance-based wages with signs of deteriorating health, including risk of MSDs. For example, Vinet et al. (1989) found the use of stomach medication was higher among piece rate workers than workers receiving hourly wages. In a study by Ajslev et al. (2015), construction workers identified the piece rate wage as a contributing factor to the intensification of work, and risk of injury and ill-health.

Thermal risk factors

Thermal risk factors are predominantly caused by exposure to cold temperatures. It has been identified that pain in the lower back and knee are frequently experienced by workers in a cold working environment. Exposure to cold temperatures, in tandem with repetitive wrist movements, can also increase the risk of carpal tunnel syndrome (Tam & Fung, 2015).

A number of studies suggest an association between exposure to cold, and musculoskeletal complaints (Hildebrandt et al., 2002; Jin et al., 2000; McGorry et al., 1998; Niedhammer et al., 1998; Pope et al., 1997). One reason for this could be that working in cold conditions results in a higher muscular load, which can affect workers directly or indirectly. Direct effects may be felt on the body tissue, while indirect effects may be linked to factors such as the need to wear personal protective equipment and to walk on slippery floors (Piedrahita et al., 2004).

Individual risk factors

Holmström et al. (1995) identified certain behaviours and attributes of construction workers that may be linked to an elevated risk of MSDs, although as we shall indicate, the evidence in support of these relationships is not consistent or conclusive.

These individual risk factors include smoking, height and weight, leisure time activities, and muscle strength and endurance.

Increased height and weight have also been associated with back pain (Holmström et al., 1995) and knee osteoarthritis (Reid et al., 2010). Less leisure time, less physical activity and poor physical fitness have been associated with back pain (Holmström et al., 1995). However, Holmström et al. (1995) observed that lifting heavy loads at work, in combination with sports activities that require use of the arms, was associated with osteoarthritis of the acromioclavicular joint and shoulder tendonitis. Similarly, Reid et al. (2010) and Boschman et al. (2012) identified leisure time physical activities as a factor contributing to knee osteoarthritis and other MSDs. Back and abdominal muscle strength and endurance have also been shown to be significantly associated with sciatic pain and lower back disorders (Holmström et al., 1995). Another individual risk factor includes past knee injuries or surgeries, with Reid et al. (2010) stating that injury history is significantly associated with knee osteoarthritis.

A study by Leclerc et al. (2014) identified that French workers who had a MSD, which then led to job loss or reduction in work time, more often started their working lives in the construction industry, compared to those with no MSD experience. They also state that education level is associated with MSDs among construction workers.

Smoking has been shown to be associated with lower back pain, as well as neck and upper extremity disorders, in construction workers (Holmström et al., 1995). However, the links are unclear and inconsistent. Some research indicates smoking can be a risk factor for MSDs (Holmström et al., 1992), while other research indicates it is not (Riihimäki et al., 1989). Generally speaking, due to methodological limitations it has not been possible for researchers to establish a clear and direct link between smoking and MSDs. However, some researchers have argued the existence of an indirect association between the two, noting that nicotine reduces blood flow and nutrition supply which, in turn, negatively affects tissue metabolism, and this can increase susceptibility to injury. It must be noted that while smoking may be a cause of MSDs, it may also be an effect of MSDs (Borenstein, 1992).

Similarly, alcohol consumption has not been strongly or consistently linked to MDS. Some studies have shown that alcohol abuse is significantly more frequent among people who also experience lower back pain (Sandström et al., 1984). However, the nature and direction of this relationship remain unclear.

Age as a risk factor

Many countries are experiencing an ageing population and the construction industries in these countries increasingly rely on experienced, older workers. There is a recognised need to retain these workers in the active workforce. The need to work longer and later in life is also reflected in social and economic policy and is exacerbated in the construction industry by a shortage of younger, appropriately skilled construction workers (De Zwart et al., 1999).

Some researchers suggest the links between age and experience of MSD are not simple, but depend upon multiple factors, including the health status of workers, occupation, and specific forms of MSD or body parts affected. For example, Hoonakker and van Duivenbooden (2010) report that the impact of age on injury experience depends upon the body part in question.

Safe Work Australia (2015) reports that, in Australia, younger construction workers are more likely to injure extremities such as the hands, fingers, feet and toes, while older workers are more likely to injure the shoulder, knee, lower leg, abdomen and pelvic region (Safe Work Australia, 2015).

In Taiwan, age has been shown to be a significant risk factor for upper extremity musculoskeletal pain among construction workers, with those aged over 26 years at increased risk (Lee et al., 2005). Arndt et al. (2005), in their investigation of the German construction workforce, found older workers are a particularly vulnerable group with respect to the risk of occupational disability and MSDs. A study in Sweden by Holmström et al. (1995) has also revealed that a range of MSDs increase in prevalence with age. Specifically, disorders affecting the neck, shoulder, elbow, hand, upper back, lower back and foot were found to be significantly associated with age in construction workers. Finally, a study by Reid et al. (2010) conducted in the US identified that in those aged over 55 years, knee osteoarthritis is associated with kneeling, squatting or stair climbing.

Ueno et al. (1999) conducted a cross-sectional epidemiological study to determine the prevalence of self-reported MSDs in construction workers. They found that age is a risk factor for MSDs, noting that bone mineral density and muscle strength decrease as age increases, making workers more susceptible to musculoskeletal injuries in their senior years (Lindle et al., 1997). However, one study has suggested that the impact of age on MSD risk differs depending on the kind of pain or the duration of pain (Leboeuf-Yde et al., 1997). Another study has indicated age is not a significant risk factor for MSDs (Skov et al., 1996).

Further, in another study conducted in Sweden, lower back pain was found to be the most commonly reported complaint among older workers (Holmström & Engholm, 2003). Hoonakker and van Duivenbooden (2010) revealed that older construction workers have fewer complaints about physically demanding jobs and psychosocial workload, but have more complaints about working in awkward postures.

Considering all these findings, the weight of the evidence points to the existence of a relationship between age and risk of MSDs. However, the strength and nature of this relationship is difficult to determine. Similarly, the mechanisms linking age to MSD remain unclear.

It is noteworthy that a range of workplace modifications have been devised to assist construction workers to maintain their health as they age. In this regard, many scholars have cited the use of participatory ergonomics approaches for older construction workers. Eaves et al. (2015) found construction workers of all ages were able to offer useful ideas for workplace design which facilitated healthy ageing in the industry. Eaves et al. (2015) concluded that involving workers in the design of tasks can significantly increase productivity and reduce the risk of MSDs

Design-related factors

Experts in health, safety and ergonomics have done considerable work to identify potential risks to workers and develop practical solutions to identified problems. Despite the importance of this work, the solutions developed so far only cover a subset of the relevant components within the broader system. In 1990, the prevailing standard for the ergonomics process involved the following five steps identification, analysis, solution development, implementation, and evaluation (Rosecrance et al., 2000).

However, given subsequent advances in technology and a host of other factors, it is recognised that a more complex approach to understanding and addressing ergonomics in the workplace may be needed.

In particular, the need to adopt a participatory/consultative approach is recognised. Consultation should occur with workers as well as other stakeholders whose decisions could impact the risk of MSDs, including architects, engineers and construction/project managers.

As an example, design professionals responsible for specifying building materials have required greater use of rebar reinforcements for concrete block construction (Inyang et al., 2012). This allows them to comply with more stringent building codes. However, it also led to increased physical workload and affected workers' level of exposure to MSD risk (Inyang et al., 2012). Thus, it is important to understand how decisions taken to satisfy one project performance requirement can inadvertently introduce MSD risks.

Smallwood (2012) also highlighted the important role construction designers can play in addressing hazards associated with handling heavy materials during construction. MSDs, including back injuries, sprains and strains, and overexertion in lifting, have been identified as a common consequence of heavy material handling. Smallwood (2012) argues that designers regularly consider ergonomics in their designs. However, their main focus is on the exposures for end-users and building occupants, rather than on those experienced by construction workers. Smallwood argues that construction materials are specified by designers and the characteristics of these materials, including their mass and weight, directly impact workers who handle and position them onsite.

Smallwood (2012) sought to examine designers' level of knowledge about, and practices in relation to, the mass and density of the construction materials they choose. A survey of practising design professionals was undertaken. Respondents were asked to record the mass and density of several construction materials. The questionnaire also asked respondents to indicate how frequently they considered the mass and density of materials when making design decisions, their opinions about the extent to which the mass and density of materials impacted on construction ergonomics, and their knowledge on this matter. The study revealed that the designers' level of knowledge in relation to mass and density of material was limited and that they did not generally consider the mass and density of materials when making choices about materials. However, the designers did understand that mass and density could impact on risk experienced by construction workers (Smallwood, 2012). Smallwood (2012) recommended improving designers' knowledge through education to enable them to understand the impact of their decisions on MSD risk and make more informed selection decisions in relation to building materials.

In the construction industry, the notion of designing for construction workers' safety is now well established (Gambatese et al., 2006). However, the practice of actively reducing risks to health through design is less well established. Arguably, as a design is being developed from initial concept through to detailed specification, designers have the pre-emptive opportunity to eliminate hazards and/or reduce risks that can arise during the construction phase. Consideration should be given to designing the processes of construction, as well as the design of the finished product (that is, the building or facility). Project managers and site engineers can also play an important role as they coordinate the delivery, storage and handling of materials, as well as managing site layout, procuring plant and equipment, and establishing project schedules.

Protective equipment/clothing

Construction workers are required to wear personal protective clothing (PPC) so they are protected from external hazards. The garment is constructed in a particular style and made of specifically designed materials, which in combination give it this protective quality. However, PPC can resist heat loss and be impermeable to water vapour, thereby reducing heat transfer and increasing the risk of heat stress (Holmer, 2006; Kofler et al., 2013). This increases the likelihood of workplace injuries such as heat exhaustion and fatigue-induced musculoskeletal injuries. In addition, poorly designed PPC can limit workers' range of movement and dexterity, giving rise to greater metabolic production and heat generation by the body (Dorman & Havenith, 2005).

Strenuous work activities and long daily work hours increase the likelihood of fatigue, which is associated with a higher risk of acute workplace injury (Australian Safety and Compensation Council, 2006). In addition, frequently requiring workers to work under these conditions can lead to ongoing injuries, and this is linked to elevated stress levels (Australian Safety and Compensation Council, 2006).

The principal physiological objective of PPC is to support maintenance of body temperature within an acceptable thermal range. The clothing should either permit the necessary level of heat transfer to occur, or restrict heat gains and heat losses to the extent that internal temperature does not vary beyond satisfactory limits (Parsons, 2014). As PPC presents a barrier to heat transfer and dissipation, optimisation of heat loss through PPC is vital to thermal homeostasis and efficient cognitive function, particularly in high temperature workplace conditions.

Hot and humid conditions create high potential for heat stress, dehydration, heat exhaustion and heat stroke, all of which can develop or be exacerbated through strenuous work activities (Brake & Bates, 2003). Heat stroke can be fatal (Donoghue, 2004), while dehydration can slow working speed and reduce productivity (Wong et al., 2014). There is extensive research demonstrating that PPC has an influence on heat loss impairment (Holmer, 2006; Parsons, 2014; Yoo & Barker, 2004; Yoo & Barker, 2005), and significantly contributes to physiological stresses on workers that can lead to cognitive impairment or discomfort, fatigue, reduced manual performance, and injury (Holmer, 2006; Mannion & Nichevich, 2013).

As physical exhaustion is approached, wearing PPC (which is commonly associated with increased bulk and mass) can also reduce mechanical efficiency when walking or performing high intensity activities (Dorman & Havenith, 2005; Duggan, 1988; Teitlebaum & Goldman, 1972). The considerable bulk and weight of PPC also increases the energy cost of work, raising the potential of harm from physical work (Holmer, 2006). The onset of physical fatigue associated with PPC reduces body movement efficiency, resulting in excessive limb movements and body sway. This further increases metabolic energy expenditure (Aoyagi et al., 1997) which is exacerbated by exposure to hot environments.

A study of work-related musculoskeletal disease (Australian Safety and Compensation Council, 2006) identified that possessing an understanding of the optimisation of ergonomics when considering workplace risk factors can be effective in reducing injury hazards. This principle can be directly applied to PPC design. The key elements to focus on when optimising PPC are sizing, fit, design and materials. For example, to minimise restriction of movement, a PPC garment must allow a relatively uninhibited range of movement (Huck et al., 1997). An incorrectly fitting garment will contribute to an increase in metabolic heat production during physical activities due to the restriction of range of movement and dexterity of the wearer (Dorman & Havenith, 2005), and may also compromise the level of protection provided by the PPC (Huck et al., 1997). For instance, strains placed on garments due to tight fit may result in tears and breakage that expose the wearer’s skin to hazards and potential injury (Huck et al., 1997).

Finally, a worker provided with ill fitting, uncomfortable PPC may wear the garment incorrectly, or be tempted not to wear the protective clothing at all (Huck et al., 1997; Wagner et al., 2013), thus creating potential for mishap or injury when performing physical tasks.

To provide the most effective PPC for protection and injury prevention, it is not enough to consider only body shape and size. It is also important to understand the physical tasks undertaken by workers and the dynamic movement required for their efficient completion. For example, PPC design optimisation should consider key areas of the body that place strain on garment mobility in the performance of tasks, such as the elbow, knee, buttocks and back (Kirk & Ibrahim, 1966).

Outcomes

Financial and labour costs

In 2012, the median compensation payment per serious workers' compensation claim in the Australian construction industry was AU$11,000 (Safe Work Australia, 2015). Meanwhile, relative to other industries in the US, construction contractors typically experience higher workers' compensation insurance costs for employees and employers (Wang et al., 2015). One insurance company in the US reported that almost one-third (29 per cent) of claims in the construction industry were the result of work-related MSDs (Wang et al., 2015). Other indirect costs include those relating to time lost due to stoppage of work, and the cost of training and replacing employees (Inyang et al., 2012; Wang et al., 2015). Inyang et al. (2012) have reported that in the US, repetitive strain injuries lead to an annual workers' compensation cost of more than US$20 billion. In British Columbia, Canada, the cost of insurance claims due to MSDs in the construction industry in 2008-2009 was US$144 million (Inyang et al., 2012).

Reduced work capacity

Reduced work capacity of injured workers leads to the need for work modifications and the training of replacement staff, both of which incur a financial cost (Inyang et al., 2012). Work-related MSDs incur both explicit and implicit costs. Inyang et al. (2012) suggest there are four associated cost factors. First, there is the cost of work absences due to MSDs. Second, there is the cost of training new hires to replace injured workers. Third, there are the costs of reduced morale and quality of life for injured workers, increased insurance premiums, and company reputation. Finally, there are productivity losses due to workers working longer hours to cover the workload of injured workers.

Disability, premature retirement and overall wellbeing

Severe work-related MSDs can lead to permanent disability, resulting in early retirement (Inyang et al., 2012). This can lead to poor worker morale and reduced quality of life (Inyang et al., 2012). Stattin and Järvholm (2005) examined the rate of musculoskeletal injuries leading to disability using health examination data from 389,000 construction workers. They demonstrated that rock workers, roofers, insulators and concrete workers are among the types of construction workers most likely to qualify for a disability pension. Workers in these four construction trades are also the most likely to incur musculoskeletal injuries during their work life.

Occupational health services and MSDs

Construction workers are highly exposed to ergonomic problems because they are engaged in physically demanding jobs. These jobs sometimes require them to work in awkward positions involving twisted postures, and to deal with repetitive movements and vibration. Construction workers need to be provided with support to reduce the impact of those ergonomic risks on their health and wellbeing. According to Minna and Mika (2012), in some European countries, such as Finland, employers are obligated by law to organise and pay for occupational health services for their employees. It has been reported that in Finland's construction industry, 77 per cent of employers have organised occupational health services for workers (Kauppinen et al., 2009). However, the impact of occupational health services on construction workers' ergonomic problems is uncertain. As a result, Minna and Mika (2012) conducted a study to investigate whether there is any relationship between construction workers' MSDs and the presence of occupational health services.

Minna and Mika (2012) conducted telephone interviews with 261 construction workers and asked them about their experiences with MSDs, as well as occupational health service activities. Workers' responses were categorised and subjected to statistical analysis. The results indicated that workers were more likely to experience fewer body disorders if they considered they had received sufficient information, advice or guidance from occupational health services regarding work posture, work performance, and work tools. This was also the case for workers who indicated they had received adequate support from occupational health services concerning maintenance of their work ability. The study results suggested it may be useful to provide workers with appropriate educational or intervention programs to help them address ergonomic challenges.

However, other research suggests that educational or intervention programs may not be effective if they are not well tailored. For example, Viester et al. (2015) examined the effectiveness of a worksite health promotion intervention on musculoskeletal symptoms, limitations in physical functioning and work-related outcomes (such as work performance and work ability). The intervention program focused on improving physical activity levels and dietary behaviours of construction workers. The researchers assessed the intervention effects at two points: six months after the intervention program, and 12 months after the intervention program. However, no significant intervention effects were observed on musculoskeletal symptoms, physical functioning or work-related outcomes. Vester et al. (2015) recommended that organisations ascertain the factors that can contribute to reduced musculoskeletal symptoms and improve work-related outcomes, and tailor their intervention programs to more effectively target those factors.

2.3 Methods used to assess the risk of work activities

Data on the way construction workers perform their work tasks can be used to determine their likelihood of developing MSDs. The data can also be used to redesign work tasks to minimise the likelihood that musculoskeletal injuries will occur. Work tasks can be redesigned by requiring workers to perform them in a different manner, or through the aid of equipment intervention, or work environment or work process redesign.

Construction workers often perform very physically demanding duties. Their work involves high forces, awkward postures, repetitive motions and prolonged durations, all of which are known injury mechanisms for developing MSDs. The literature identifies three methods which can be used to assess the risk of developing MSDs: self-report, expert observation and direct measurement. For each method, models of varying complexity have been used to quantify the level of risk.

Self-report

The self-report method relies upon musculoskeletal injury data provided by construction workers. Self-report is relatively low cost and frequently used for collecting data and objective measurements from a large sample of workers (for example, on pain and workload). Several self-report measurement tools have often been used to collect critical information relating to MSDs and occupational requirements in the construction industry. These tools include the Nordic Musculoskeletal Questionnaire (Crawford, 2007; Dickinson et al., 1992), Borg Scale (Kilbom, 1994; Takala et al., 2010), Job Requirement and Physical Demands Survey (Marcotte et al., 1997), National Institute for Occupational Safety and Health (NIOSH) symptom survey (Feuerstein et al., 2001; Huang & Feuerstein, 2004; Shaw et al., 2001), and Task Analysis (Luttmann et al., 1991; Van der Molen et al., 2004). Data recorded through these tools are typically used to examine individual risk factors (for example, awkward posture), conduct detailed ergonomic analysis, and yield a score for each risk factor. These tools, which take the form of survey questionnaires, can be administered in various ways, such as a paper-based survey (Fredricks et al., 2004), a face to face interview (Fung et al., 2008), telephony communication (Minna & Mika, 2012) or webpage form (Engelen et al., 2017).

In their survey of 450 workers, Johansson and Rubenowitz (1994) administered the Nordic Musculoskeletal Questionnaire to investigate the relationship between work type and musculoskeletal symptoms. The survey results suggested construction workers are more likely than office workers to suffer from work-related MSDs. Meerding et al. (2005) used the Borg Scale to examine the relationship between working with high physical load and health-related productivity loss among 570 construction and industrial workers. Rosecrance et al. (2002) recruited 1142 construction apprentices to participate in a NIOSH symptom survey to investigate the extent to which construction workers suffered from carpal tunnel syndrome during their apprenticeship. Based on the survey results, the authors concluded that the majority of workers suffering from the syndrome did not seek medical advice for their health condition. The NIOSH symptom survey uses a body map to help workers identify parts of the body where musculoskeletal symptoms occur (Rosecrance et al., 2002).

While it is relatively easy to administer, self-report methods for assessing MSD risk are limited. Thus, self-report methods may not provide reliable data on musculoskeletal injuries as it is difficult to validate the data collected (David, 2005). More importantly, self-report is not a reliable measure as it suffers from intra-subject variability, data bias and poor reliability (David, 2005).

Lenderink et al. (2012) conducted a review on the self-report method’s ability to provide a valid measure of work-related disease. The authors found low to moderate evidence of agreement between self-report and expert opinion. Michener and Leggin (2001), in their review of the self-report method, highlighted the importance of adopting a self-report method that is appropriate for the intended purpose.

Expert observation

Expert observation involves the expert assessment of postures adopted by workers. Under this method, an expert observer collects data in relation to body segment, repetition, exertion and duration, and then examines this data to identify the risk of musculoskeletal injuries associated with a work task. Expert observers use observational tools which require them to quantify and record risk factors via a checklist. Data collected through this process is used to assess the physical and psychosocial demands placed on the worker. Observational tools do not influence or disrupt workers performing their work tasks. They can provide a low cost solution to risk assessment in the workplace. Some expert observation has been performed using videotaping observation methods (Juul-Kristensen et al., 2001; Spielholz & Davis, 2001). Videotaping allows more information to be captured and enables careful evaluation post data collection. However, expert observation ultimately relies upon the availability of expert assessors and suffers from intra- and inter-assessor variability (David, 2005; Takala et al., 2010).

Expert observation methods provide information on posture, load, motion rate and duration of tasks. These observation methods measure external loads and do not determine the internal loads imposed on a worker. Four expert observation tools are commonly used:

1. OVAKO working posture-analysing system (OWAS): This system was developed by a steel manufacturing company seeking to redesign their production line. It uses visual observation to identify and assess poor working postures. Postures may be classified into more than 250 different poses through assessing the position of the trunk, arms and legs, as well as the weight of the load. For ease of analysis, each posture is allocated a code (Valero et al., 2016). Kivi and Mattila (1991) were pioneers in applying the OWAS method in the field of construction, initially developing a basic portable computer system to manually score the observed tasks, and later using the same system to evaluate the use of tools, such as hammers.

2. Posture, Activity, Tools and Handling (PATH): This model, proposed by Buchholz et al. (1996), uses the same codes for postures as the OWAS method. However, this model also introduces a set of new codes to reflect different activities, loads and equipment. It allows assessors to evaluate images recorded during work activities, and to identify the proportion of time workers spend in postures classified as neutral or non-neutral (Valero et al., 2016).

3. Rapid Upper Limb Assessment (RULA): McAtamney and Corlett (1993) developed the RULA survey to evaluate specific postures of the neck, trunk and upper limbs. Ergonomists code each posture by visually evaluating the angles between the studied body parts to obtain a grand score that is used to decide whether a movement is considered acceptable (Valero et al., 2016).

4. Rapid Entire Body Assessment (REBA): This method emerged as a result of improvements made to RULA. Similar to RULA, it evaluates and scores the postures of workers, but expands upon these capabilities by visually evaluating the positions of the legs, considering postural loading factors, and evaluating awkward positions in upper limbs. Kim et al. (2011) were among the first researchers to adopt the REBA method, which they used to study the movements of workers during installation of prefabricated walls in an effort to improve panel design and construction processes.

Most of these methods analyse work posture, and to a lesser extent, work rate (repetition) and force (static loading). These methods often provide the data and framework that underpin the design of computer-based ergonomic analysis and decision support models (Inyang et al., 2012). However, the methods suffer from major shortcomings due to their limited or partial risk analyses. For example, recovery and vibration are typically neglected by observation methods, despite being important factors for the risk analysis of work-related MSDs (Punnett & Wegman, 2004). In particular, analysis of recovery data is needed to properly model the behaviour of human tissue and joint dynamic properties. The NIOSH lifting observation method considers recovery time during work tasks (Dempsey, 2002), and is generally used to determine the recommended weight limit during manual handling tasks. Waters et al. (1999) suggest that the NIOSH lifting equation is appropriate for minimising the risk of back injury induced by unsafe manual lifting practices.

On the matter of vibration, segmental or whole-body vibration is common in construction activity and is a significant risk factor for work-related MSDs (Punnett & Wegman, 2004). However, while whole body vibration in the context of work tasks affects the musculoskeletal system of workers (Boshuizen et al., 1992; Dupuis & Zerlett, 1987; Zimmermann et al., 1997), its causal relationship is not well understood (Kittusamy & Buchholz, 2004). Additional research is needed to understand the impact of whole body vibration on exposures and the broader health of construction workers.

Example: Analysis of manual handling risk in shovelling and grinding tasks

Parida and Ray (2012) proposed a framework for the biomechanical evaluation of two manual materials handling activities: shovelling and grinding. As stated by the authors, manual materials handling activities normally involve adoption of awkward body postures, repetitive work, use of heavy tools and equipment, and extreme environmental conditions, all of which may lead to injuries and MSDs. The authors conducted a biomechanical evaluation of work postures to identify and measure forces at different body joints and regions. Over a number of work cycles, they collected data through observation and videography of the workers. The analysis was undertaken in three parts: static modelling of the human body, dynamic modelling of the human body, and addressing improvement potentials. The analysis involved several steps including representing work pressures in free body diagrams, formulating and measuring forces and moments on joints, evaluating forces and comparison with threshold values for each joint, analysing risk factors, and identifying preventative measures.

The study suggested that forces and movements in the lower back body region were significant for shovellers, and movements at the elbow and wrist were significant for grinders, making them susceptible to MSDs in these body regions. Parida and Ray (2012) recommended that conducting this type of analysis can be helpful when designing jobs to minimise the risks of MSDs, and can reduce fatigue and physical disorders for workers performing manual materials handling activities.

Source: Parida and Ray (2012)

Direct measurement

As mentioned earlier, existing knowledge on the dose-response relationship between physical risk factors in the workplace and MSDs is mostly based on self-reported data, or data obtained from biomechanical laboratory studies in which an experiment involving static postures is conducted in a controlled environment. However, there is a significant advantage to conducting experiments in real working conditions – that is, on construction sites when dynamic lifting is being performed. Undertaking technical measurements of physical work exposures during the working day may provide more realistic information than that obtained thus far. The development of small wearable sensors has enabled measurement of physical load during an entire working day (Brandt et al., 2015). Further, measurement through wearable sensors allows quantitative risk assessment to be undertaken while minimising the level of subjectivity that acts upon that assessment – a previously noted flaw of expert observation.

Sensors placed on construction workers can record a variety of relevant measurements. A non-exhaustive list of these measurements includes: external force (Uğurlu & Özdoğan, 2011), joint angle (Ray & Teizer, 2012), muscle activity (Jia et al., 2011), heart rate (Sillanpää et al., 1999), and body temperature (Weerasinghe & Ruwanpura, 2009). In general, sensors such as goniometers, force sensors and accelerometers, can quantify and record joint angle, the angle between body segments, and physical load. Sensor data can be used to compute three-dimensional biomechanical models representing human movement.

In recent years, some studies have undertaken technical measurements using electromyography (EMG) accelerometers and video recordings to quantify the physical load imposed on workers engaged in strenuous work. Accelerometers are sensors that measure the acceleration of objects in motion along reference axes. Since acceleration is relative to external force, these sensors can also record the intensity and frequency of human movement (Yang & Hsu, 2010). In addition, some accelerometers respond to gravity and thus provide tilt sensing abilities with respect to reference planes. The resulting inclination data can be used to classify body postures. All these qualities make the accelerometer a highly useful device, as it offers a great deal of information on physical movement and a range of human activities.

EMG is often used to investigate body loads by adhering pairs of electrodes to the skin over the muscle-belly of interest. The level of muscle activity identified through EMG can be used to determine the level of muscle tension and fatigue. In the early 1990s, Granata and Marras (1993) used an electro-goniometer to evaluate MSD risks with a focus on lower back pain. More recently, Nimbarte et al. (2010) used EMG to study the major neck muscles in handling and lifting tasks. These devices delivered improved levels of wearability and reduced intrusiveness compared to previous technologies.

In laboratory settings, an optical marker-based and force measurement system is used to measure the kinematics and kinetics of the human body (Baker, 2006). The marker kinematics are used to create a subject-specific computer model and compute joint angle data during an activity. When data is available on the external force generated by either the upper- or lower-limbs, joint moments can be computed to discern the muscle forces generated by joint-spanning muscles (Baker, 2006; Schache & Baker, 2007). EMG can be used to extract both intensity data and temporal data relating to muscle contraction (Lim et al., 2014). However, this tool is mainly restricted to laboratory use as it has limited measurement volume, is sensitive to environmental influences, and requires controlled lighting conditions and specialised training to operate.

Biomechanical computer models are used to calculate joint kinematics and kinetics from marker and external force data (Baker, 2006; Schache & Baker, 2007). Clinical gait models are mainly derived from the conventional gait models (see, for example, Davis et al., 1991; Kadaba et al., 1990; Kadaba et al., 1989). Systems, such Vicon Clinical Manager, can develop these models. However, subject-specific models and soft tissue artefacts are the two known sources of error in such modelling processes (Baker, 2006). Functional calibration is often used to overcome errors in marker placement and joint-centre estimation. Musculoskeletal modelling overcomes three limitations of traditional rigid-body motion analysis (Lim et al., 2014). The first limitation is that the human musculoskeletal system is mechanically redundant. Secondly, it is debatable whether the amplitude of EMG correlates to muscle intensity. Thirdly, a non-spanning muscle can accelerate a body segment/joint. Understanding the contribution of individual muscles to the acceleration of joints and the body's centre of mass during motion is necessary for the investigation of muscle and joint functions (John et al., 2013; Neptune et al., 2008; Pandy & Andriacchi, 2010).

Small, wearable sensors are now available as a result of the reduction in size of electronic devices (for example, microelectromechanical systems or MEMs). These sensors can record the movement of different body parts. These devices, when integrating sensors such as accelerometers, magnetometers and gyroscopes, are called Inertial Measurement Units (IMUs). IMUs can provide real-time measurement of acceleration, velocity, orientation, and the earth's gravitational forces and magnetic fields (Valero et al., 2016).

An inertial sensor is a type of force sensor that can sense linear acceleration along one or several directions, or angular motion on one or several axes (Yang & Hsu, 2010). Researchers aiming to measure postures and body motions have deployed these devices in various contexts. Gait analysis was an initial area of investigation for the application of IMUs. For example, Simcox et al. (2005) studied the movement of lower limbs and trunk during walking experiments by comparing the angle measurements calculated by a camera motion analysis system and those obtained from IMUs. Simcox et al. (2005) conclude that these sensors are accurate to measure trunk and lower limbs in real-time, and have relative advantages compared to other previously used methods. However, one potential problem in their system was that the sensors were wired to a hand-held computer, which was invasive and impractical in non-laboratory conditions. This problem was analysed by Novak et al. (2014) and an algorithm was proposed to detect turns during walking activities by using wireless wearable sensors.

However, some inertial based measurement systems can undertake measurements in work environments because the reference frame is within the subject (participant) and there is no specific requirement for spatial reference points. Thus, such systems are suitable for undertaking field-based data collection. Using such systems requires placing multiple IMUs onto different body segments of participants (Valero et al., 2016). Each IMU is equipped with an accelerometer, gyroscope and magnetic sensor. Accelerometers are used to determine the orientation of the gravity vector and magnet sensors are used to identify the earth's magnetic field. This information is used to correct the error accumulated from integrating the gyroscopes' output, which is used to calculate the angular displacement. A data fusion algorithm is often used to overcome the inherent limitations of each sensor within the IMU (Sabatini, 2006; Won et al., 2010).

Using an inertial based measurement system to measure work tasks outside a laboratory setting can lead to three key issues. First, the number of reliable external force transducers that can be operated may be limited. This means external forces and joint kinetics cannot be measured accurately. Second, inertial based measurement data is noisy compared to data obtained from an optical based system. Third, an inertial based measurement system does not provide accurate joint estimation due to a lack of information on where sensors are located in relation to each other.

Movement classification is necessary to autonomously determine the activity under consideration. Inertial sensors can be used to classify movement either through threshold-based methods or statistical methods. The threshold-based method is based on prior knowledge of movement and uses a hierarchical data structure to discriminate between different types of movement (Mathie et al., 2004). Under this approach, activity classification is best conducted using statistical methods (Mannini & Sabatini, 2010). Proper feature extraction and machine training are necessary to ensure sensitivity and specificity of movement classification.

In recent years, various studies (Wang et al., 2015) have promoted the increasing use of accelerometers and IMUs. For example, Jebelli et al. (2014) proposed using an IMU sensor attached to the ankle to prevent accidents through characterising the fall risk of workers on the jobsite. Kim et al. (2011) presented a load-measuring tool for construction workers based on four accelerometers located on the arms. However, as with the previous studies, the size of this wired solution was a problem because it was intrusive and difficult to wear.

Valero et al. (2016) proposed a novel system that could accurately measure body motion without being limited by any of the issues affecting previously developed systems. The new system, called Activity Tracking with Body Area Network (AT-BAN), was based on a concept proposed by Sivanathan et al. (2014). It operates around a cyber-physical body area network that possesses real-time activity tracking capabilities. It has the advantage of being unobtrusive, wireless and wearable. It contains sensors (an accelerometer, gyroscope, and magnetometer), a microprocessor, wireless transmission and a power supply. It can measure acceleration, angular velocity and dimensions on three axes in real-time situations. Compared to the traditional vision-based motion analysis system, AT-BAN has clear advantages. Most importantly, it can operate in any workspace (even in harsh conditions and with limited visibility) as it is unaffected by light levels and other environmental factors. In addition, it provides more accurate measurements.

The mechanism upon which this system is based uses calculations of angles rotated by the back and legs. This is achieved by using a combination of acceleration and velocity data provided by the accelerometers and gyroscopes of the IMUs located on the lower back and legs.

However, the system is not entirely problem-free. For example, in the study conducted by Valero et al. (2016), it was observed that, on occasion, the system incorrectly detected a bending motion when, in fact, the trainee was standing up with their knee flexed on a bench. This indicates that using one sensor is not at all sufficient and that stooping motions should be detected by considering the motions of both legs. There is a need for more research in this area.

More recent systems (such as those selected for use in the present study) are flexible. They are relatively lightweight, wireless EMG systems that capture the rotary motion of up to 23 body joints (for example, ankle, knee, hip, lower and upper back, shoulder, elbow, wrist, neck), and movement of up to 15 body segments (for example, foot, lower leg, thigh, pelvis, upper and lower back, upper arm, forearm, hand, neck, head). Such systems can capture the muscular activity (tension) of 16 muscles. This capability allows the investigation of full body motion which is important in determining potential mechanisms behind work-related MSDs. For example, leg muscle activity and joint motion can affect back motion, as can arm, neck and head motion.

Such systems are increasingly used for measuring human movement in non-laboratory settings (Brandt et al., 2015; Ha et al., 2013; Pellegrini et al., 2013).

2.4 A review of the efficacy of workplace interventions

Workplace ergonomics is the study of characteristics and limitations of a human's physical, cognitive and psychological abilities in a workplace (Wang et al., 2015). A workplace ergonomics intervention is defined by Denis et al. (2008) as a targeted set of actions, conducted in a workplace, intended to implement changes directly related to a work task, so as to prevent or address work-related musculoskeletal disorders (WMSDs). While assessing exposure to risk factors for MSDs has been shown to be an effective way of reducing the incidence of this injury, the field remains underdeveloped due to a lack of comprehensive knowledge on optimally effective techniques (Wang et al., 2015).

Workplace ergonomics interventions are generally undertaken using methods of self-report, expert observation, direct measurement through motion analysis (in which sensors are placed on the body and movement is captured on video), or a combination of these methods (Wang et al., 2015). Information collected through these methods is then analysed and used to design safe, comfortable and effective tools, machinery, work tasks, jobs or work environments.

Using self-report as a method of assessing workplace ergonomics has several advantages (Wang et al., 2015). For instance, it enables large numbers of workers to report problems that may be difficult for others to observe (for example, pain). It is also cost effective and can be employed across a wide range of occupations (Wang et al., 2015). The technique, however, has some major limitations (Wang et al., 2015). Self-reporting takes time for workers to complete, interrupts work practice, and is often inaccurate due to workers having difficulty naming their body parts. Overall, WMSDs are hard to detect through self-report surveys (Wang et al., 2015). Perhaps the best self-report survey was developed by the University of Western Ontario (University of Western Ontario, 2011). The method uses a body map with a set of questions regarding work-related MSD risk factors (for example, symptoms) for each body part.

Expert observation is a systematic method used to assess postures in a workplace (Wang et al., 2015). Buchholz et al. (1996) incorporated this method into their development of an enhanced tool named PATH (Posture, Activity, Tools and Handling) which was designed to assess work risks for highway construction workers. The tool evaluates working posture and describes work activity, tool use, load handling, and types of grasp. The tool can be used with minimal disturbance to workers and through the use of very few instruments. However, PATH relies upon expert observation and subjective evaluations. This means the assessment can only be conducted in discrete bouts, with a limited number of observations made during an expert visit. In addition, inter-rater differences can lead to disagreement over the results generated by different experts.

The direct measurement of body posture through using motion analysis sensors has been adopted to increase the accuracy of risk assessment. It is often used to assist or replace expert observation (Wang et al., 2015). This technique is highly accurate, provides detailed information, and can be used for continuous assessing and monitoring onsite WMSD risks. However, when used in an onsite setting it has disadvantages in terms of cost, set-up time and functionality.

2.5 Workplace ergonomics intervention approaches

Workers in the construction industry experience a high level of exposure to heavy manual materials handling (MMH), repetitive movements, awkward postures, contact stresses, vibrations and forceful exertions. They also experience a number of psychosocial stressors. Given the difficult nature of this work, including the fast-paced and evolving nature of construction projects, direct risks to workers in this industry are much higher than in other industries. These risks include various health and safety risks, including MSDs. Van der Molen et al. (2005) have described construction as ‘a sector known for its peripatetic workforce, complex projects and organisational arrangements, and traditional customs and practices on site’. Thus, the construction industry is ripe for ergonomic intervention.

With this mind, various approaches to ergonomics intervention have been established. These approaches include ‘classical’ models as well as those with a greater level of complexity. A good ergonomics intervention simultaneously addresses a combination of technical, organisational and environmental challenges (Borstad et al., 2009). Currently, two key and yet opposing positions exist on the most appropriate approach (Coutarel et al., 2005). The first position takes the view that the goal of ergonomics intervention is to promote the physical, mental and social wellbeing of workers, and MSDs are seen as the result of biomechanical and psychosocial pathogenic risk factors. From this perspective, an ergonomics intervention must adapt working conditions to the individual’s needs. The second position on this subject, however, defines health as a dynamic inter-subjective matter in which individual workers should be given the opportunity to have a say in what happens to them (Lanfranchi & Duveau, 2008).

According to Denis et al. (2008), a classical workplace ergonomics intervention is implemented in three phases. The process begins with the ‘Preliminary Analyses’ phase, followed by the ‘Diagnosis’ phase, and concludes with the ‘Solution-Development’ phase. Variables or measures frequently used in the ‘Preliminary Analyses’ phase are health indicators, workload-related difficulties and, to a lesser extent, pain symptoms. These interventions typically employ data collection methods where a high number of measures or variables are used to document problems in a workplace. The data is then collated during the ‘Diagnosis’ phase to find the causes for (or determinants of) identified workplace problems, to which changes in work practices are directly related. In the ‘Solution-Development’ phase, recommended changes to the work situation are developed and implemented.

It should be noted, however, that classical interventions do not sufficiently address the complicated nature of the problems faced by construction workers today. Further innovation is needed in workplace ergonomics if the prevalence of MSDs is to be reduced. As stated by Kramer et al. (2009), ‘innovation in the construction sector is defined as a set of processes, tools or materials that have the potential for preventing MSDs, but that do not necessarily need to be new (inventions)’. Kramer et al. (2009) argue that one of the major barriers preventing the adoption of ergonomics innovations is that the construction sector is entrenched in tradition. They argue the key barrier is cultural rather financial: it is the culture, that opposes innovation.

Another difficulty is that proposed workplace interventions are often not implemented to the degree recommended (Denis et al., 2008). A possible reason for this could be that during the development of interventions, holistic analysis (a key aspect of an intervention in which organisational resources as well as inter/intra politics are considered) is not properly undertaken. Many complexities exist, and over-reliance on only one or two aspects of an intervention, such as training, does not solve the problem. This means that in addition to design-related factors, the nature of the intervention must be taken into account.

Studies have revealed many reasons for the lack of proper implementation. Cost, effectiveness of the program, conflicting priorities within an organisation, and culture of an organisation, are all factors that can prevent an appropriately executed implementation from occurring (Trevelyan & Haslam, 2001). Lee et al. (2010) have pointed to the important role organisational culture can play during an intervention, arguing that it provides the overarching framework in which required changes are supported or rejected. This specifically applies to MSD prevention programs, where workers who have a shared understanding of the causal and preventive factors have been shown to influence the organisational response to MSDs. This suggests there is a need for consultants to frame their advice in a manner that will maximise its potential adoption (Rothmore et al., 2015). As a result of these findings, many scholars recommend participatory ergonomics interventions.

Methods of participatory workplace ergonomics have been used to prevent and reduce the prevalence of MSDs. These methods use participative techniques and various forms of participation in the workplace (Hignett et al., 2005). In particular, staff are engaged in planning and controlling a significant amount of their own work tasks. Staff are also equipped with the knowledge and power to effect changes in procedures and outcomes so as to achieve designated goals. Haines et al. (2000) posited five categories of participatory ergonomics, comprising ‘Problem Analysis’, ‘Creativity Simulation and Idea Generation’, ‘Idea Generation and Problem Analysis’, ‘Concept Evaluation’, and ‘Preparation and Support’. Therefore, any ergonomics intervention requires work at both the macro and micro level (Oakman et al., 2016). Figure 2.3 illustrates the steps involved in this participatory approach.

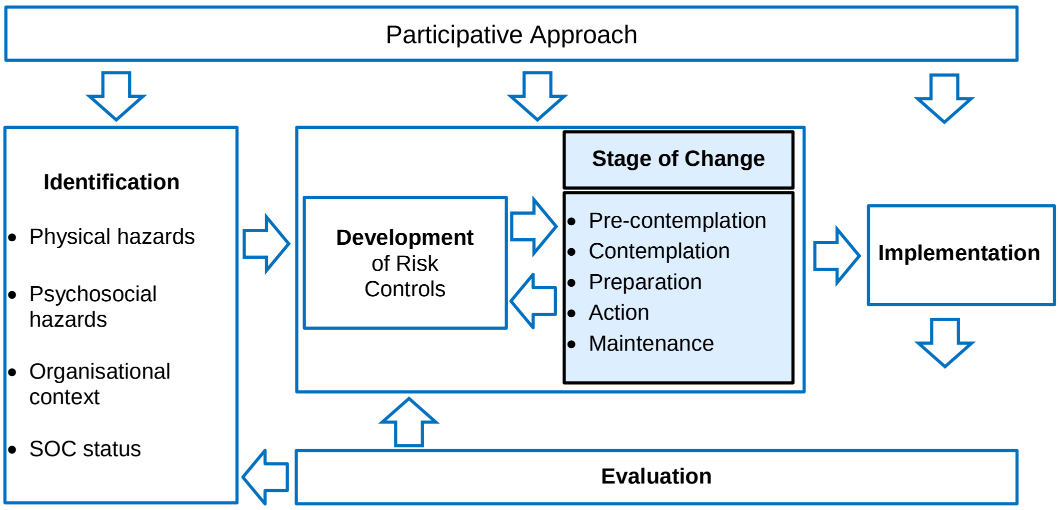


Figure 2.3: Participatory approach.

Source: Oakman et al. (2016)

As shown in Figure 2.3, the State of Change (SOC) is an important factor in any ergonomics intervention. In this behavioural change model, which was introduced by Prochaska et al. (2001), an organisation's readiness for change can be categorised into to one of five stages:

1. Pre-contemplation (unaware or unconcerned about workplace hazards)
2. Contemplation (considering change but not yet ready to act)
3. Preparation (intending to change in the near future)
4. Action (made changes in the previous six months)
5. Maintenance (made changes and is working to consolidate gains and avoid relapse).

To improve receptiveness, then, recommendations must be tailored to the organisation's level (or stage) of readiness to change. However, some scholars have doubts as to whether the participatory approach to ergonomics is always applicable and useful, and whether it always represents an appropriate means of preventing MSDs (Denis et al., 2008). Having said this, studies to date have shown that participatory ergonomics programs are the most practical to implement.

Construction specific tasks with high risk of MSDs and possible ergonomics solutions

Each construction trade is responsible for different tasks and draws upon a different set of skills. Some tasks require workers to work close to the ground, while others require them to work overhead. Given these differences, it is not surprising that the nature of the work performed in each construction trade is linked to the nature and site of workers' injuries. As an example, a Swedish study (Engholm & Englund, 1993) identified that the prevalence of neck symptoms was highest among crane operators, shoulder symptoms were most prevalent among scaffolding erectors, and knee symptoms were most prevalent among floor layers. The trades in which construction workers are at the greatest risk of developing MSDs are discussed in detail below.

Drilling (concrete)

Drilling into concrete is a physically demanding task. Workers are exposed to hand vibration, noise, and strong forces (particularly in the upper body). For this reason, upper body MSDs are very common. As an example of the work activities involved in this trade, drilling holes into concrete is a common method of putting into place anchor bolts or setting rebars for retrofitting. This work is highly fatiguing and a great deal of force must be applied to support the drill and push the drill into the concrete (Hagberg, 1981). These forces and handle vibrations are transmitted through the hands, arms, shoulders and back (Hagberg, 1981).

As a result of ergonomics prevention strategies, the weight of hammer drills has been reduced, and devices to support smaller hammer drills for overhead drilling have been developed. (Rempel et al., 2010). However, no practical smaller devices exist for scaffolding or use from the ground. In their study, Rempel and Barr (2015) analysed a universal drill rig and found that drilling using this device led to improved accuracy, increased stability and reduced vibration compared to traditional methods. In addition, levels of perceived fatigue were lower among workers and they were able to perform their drilling tasks much faster, thus increasing productivity.

General construction labour (manual handling)

The building materials and equipment used on construction sites must be unloaded at the job site, transported to a storage location, stored until needed, and transported to the location where they will be used. Continuous changes on the building site often lead to task repetition. Most of the time, workers lift and transport materials by hand.

Construction labourers generally report musculoskeletal pain in the back, shoulders and upper extremities (Punnett & Wegman, 2004). To date, pragmatic solutions to contain the risk of developing MSDs have included raising awareness through training and improving the design of the work system relating to the location, transport and storage of materials and equipment. Improving communication and coordination between the different contractors and trades is also regarded as a practical approach.

Some systems have incorporated consideration of packaging, transport, delivery sequencing, stacking and erection sequencing in the design of prefabricated housing components. These systems minimise the need to move materials during delivery and onsite construction, and represent an effective method for incorporating MSD risk reduction at the design stage of a construction project (Kim et al., 2011).

Concrete reinforcement tasks

Implementing ergonomics interventions for this trade can be difficult as content and duration of the work changes frequently. To address this barrier, a task-based exposure assessment method has been recommended. Buchholz et al. (2003), in their investigation of construction workers at a highway construction site in Boston, used PATH (Posture, Activity, Tools, and Handling) analysis to review the work of 17 ironworkers (steel fixers) performing five job tasks. The authors observed that reinforcing work is very physically demanding, involving awkward postures and heavy manual materials handling (MMH). The most critical ergonomic hazard was the large percentage of time workers spent in non-neutral trunk postures (particularly flexed and twisted, and severely flexed).

The study further revealed that, depending on the location of the task being performed (on ground, elevated surface, etc.), the risk of MSDs differed. For instance, ground level rebar construction was performed at ground level and a flexed trunk posture was adopted most of the time. On the other hand, ventilation rebar construction required awkward trunk postures to be adopted a greater proportion of the time, due to the higher frequency of side bending and twisting. The fact that exposure levels varied between ground level, wall, and ventilation rebar construction tasks could be attributed to differences in work area layout and job requirements (Buchholz et al., 2003). Other possible reasons for these differences in exposure include: rods for each task often having different diameters; rebar mats for each task having a different number of intersections per unit area; and tie type differing between tasks (Buchholz et al., 2003).

Among recommendations put forward to address this trade's ergonomic hazards, one proposes using cranes to position rebars so as to reduce the amount of MMH required of ironworkers who perform concrete reinforcing tasks. However, some stakeholders have viewed this as too costly. Moreover, administrative control can require the use of two-person lifts on heavier pieces of rebar. Finally, interventions recommended by Riihimäki et al. (1989) include using ready cut and pre-bent reinforcement bars to reduce manual work, and using prefabricated elements to reduce the amount of tying and manual handling onsite.

Roofers

Roofers undertake strenuous physical tasks which can involve heavy lifting, climbing, bending and kneeling. Both residential and commercial roofers are typically required to go outdoors in all types of weather. As a result, environmental factors such as cold weather must be taken into account. Musculoskeletal symptoms among roofers are strongly associated with work limitation, missed work and reduced physical function (Welch et al., 2009). MSDs that affect roofers frequently involve the back, shoulders, hands and knees (Choi et al., 2005). In addition, roof work entails MMH activity at different roof inclinations. For instance, residential roofers often complain about ankle discomfort and pain with an increase in slope/pitch (Choi & Fredericks, 2008). In general, administrative controls are used to limit exposure to MSD risks.

Formwork (carpenters)

In many countries, carpenters constitute the majority of workers in the construction trades. In concrete formwork specifically, carpenters construct the forms that will ultimately contain the reinforcing rods and hold poured concrete into place until it cures. The height at which this work is performed cannot be changed, although the forms may be constructed at any level relative to the worker. In addition, removing the forms often involves pulling shoring and wood slabs off forms located in different positions. For example, if a form is used to make a slab floor, the worker must position their hands above their head. This requires forceful movements in awkward positions. In their study of carpenters, LeMasters et al. (1998) found that carpenters performing concrete formwork had the highest prevalence of shoulder and elbow disorders. The effects of many of these tasks can be prevented through changes in materials, work equipment or work practices. Administrative controls are typically used to reduce the impact of these physical tasks.

Bricklayers and masonry workers

MSDs are highly prevalent among bricklayers and masonry workers. Bricklayers are frequently required to perform repetitive motions (that is, perform a task repeatedly), often resulting in cumulative trauma disorders or MSDs. Entzel et al. (2007) cite the Construction Safety Association of Ontario (2003) as indicating that approximately 60 per cent of injuries caused by over-exertion among bricklayers are back injuries. Entzel et al. (2007) state that major risk factors for back injury among masons involve the weight of bricks, the frequency of tasks, the height at which blocks are picked up and positioned, the height of stands, the distance of blocks from a worker's body, the degree and frequency of twisting involved, and expected production rates. Stakeholders have also claimed that design issues negatively impact their health. For example, architects' and engineers' reliance on rebar and grout as a barrier to widespread diffusion of pre-stressed masonry has been mentioned. Removing this practice would eliminate the physical stress that is required for lifting block over rebar and performing grouting tasks (Entzel et al., 2007).

Hess et al. (2010) have specified nine ergonomic best practices within the masonry trade:

- Mortar silos: Traditionally, mason tenders are required to manually handle 43 kg bags of mix. Silos are now designed to deliver mixed or pre-blended mortar to the work site.
- Grout delivery systems: These gravity feed systems deliver grout to walls. Having these systems in place means workers no longer need to lift and empty heavy bags of grout into mixers using buckets or pumps.
- Mechanical scaffolding: Van der Molen et al. (2007) have identified that adjusting working height and mechanisation (in lifting) can reduce the workload of bricklayers. These systems include adjustable tower scaffolding that allows ready modification of work height using either a hand crank or hydraulics. Studies show that working with a scaffolding console to adjust the working height at which stored materials are accessed results in a significant reduction in frequency and duration of trunk flexion.
- Half-weight cement bags: 21 kg bags of cement reduce the load lifted and handled by mason tenders.
- H-blocks and A-blocks: H-blocks are moulded without two ends and thus are open-ended. In contrast, A-blocks are moulded without one end. Having the freedom to choose between these two block types allows bricklayers to place blocks around rebar, pipes etc., without needing to lift any blocks.
- Lightweight block (LWB): LWBs are constructed of aggregates that make them more porous, and therefore more lightweight, while still being able to achieve the same structural standards as medium weight blocks.
- Half-size pallets: Half size pallets are lighter and easier to handle. They are set on scaffolding using lifts.
- Two-person lift teams: The general method used when working with a 30cm concrete masonry unit (CMU).

Floor layers

According to Dale et al. (2015), construction workers' risk of developing MSDs is much higher (nearly double) when they are involved in constructing floor layers than when they are involved in other industry tasks. While kneeling on the floor, workers must use a great deal of force and adopt repetitive postures to spread adhesive, lay ceramic tiles and nail boards. The National Institute for Occupational Safety and Health (NIOSH) has published a set of recommendations to reduce the prevalence of knee disorders among carpet layers. These recommendations include using kneepads and power kickers.

Another ergonomic solution suggested for floor layers is to use mechanised equipment. Burdorf et al. (2007) conducted research on the effects on floor layers of using mechanised equipment. They found that using a hydraulic clamp or vacuum lift to assist road makers (floor layers) substantially reduced the amount of time spent in a kneeling/squatting position, and also reduced the frequency of lifting loads. In this study, floor layers who used the mechanical equipment reported a lower prevalence of lower back pain and less associated sick leave.

Finally, training and experience could play a major role in this trade. A study by Dale et al. (2015) revealed that the youngest floor layers were most likely to make claims involving the knee and neck. This could be the result of younger workers more frequently adopting incorrect postures.

Sheet metal workers

The prevalence of shoulder pain among sheet metal workers has increased dramatically in recent years (Borstad et al., 2009). In this trade, workers spend most of their time performing tasks with their arms elevated at or above shoulder level (Ludewig & Borstad, 2003). The repetitive nature of their work, and the force required to perform their tasks, increases their risk of developing MSDs. Prevention strategies can include: tool and/or task modification, using platforms for workers, education and training, and exercise programs that enable workers to better meet the job's physical requirements (Albers et al., 2005).

Holmström and Ahlborg (2005) have evaluated the effectiveness of a 10 week general exercise program. The morning program included body activities to warm up tissue, increase heart rate and stretch muscles. Compared to a peer control group, the exercise group demonstrated greater mobility, range of motion, strength and endurance. However, the effectiveness of these exercises as a method of combatting MSDs is still under contention.

Ironwork

Construction ironwork (CI) comprises four main specialisations:

1. Structural ironwork (SIW)
2. Reinforcing ironwork (RIW)
3. Ornamental ironwork (OIW)
4. Machinery moving/rigging ironwork (MMRIW).

As each CI specialty has a unique physical ergonomic exposure profile, no general recommendations and conclusions can be made for this trade. For example, it has been demonstrated that, compared to other workers, those mostly involved in RIW are more likely to exhibit upper extremity symptoms, affecting the wrists and hands in particular. This has been attributed to the highly repetitive nature of their work which involves the tying of rebar rods. Meanwhile, workers engaging primarily in either RIW or SIW show a higher prevalence of lower back symptoms. This has been attributed to the high frequency of severe non-neutral trunk postures required of these groups (Cuzick, 1985). Moreover, in research conducted by Forde et al. (2005), ironworkers who exhibited MSD symptoms were most likely to have them in the lower back, followed by the wrist and knees, and finally, the shoulders.

Scaffolding

Scaffolding work is a mandatory aspect of most construction jobs and is one of the highest risk jobs in the field. The task components involved in the erection and dismantling of frame scaffolds include:

- preparing the foundation
- carrying scaffold parts
- erecting/removing end frames
- erecting/removing cross braces
- installing/removing access ladders
- installing/removing planks
- installing/removing guardrails, and
- securing/removing scaffold tiebacks.

An investigation carried out by Hsiao and Stanevich (1996) identified that lifting scaffold end frames, carrying end frames, handling scaffold planks, removing cross braces, and removing guardrails are all activities that place biomechanical stresses onto the worker, and thus increase the risk of overexertion injuries. These activities involve handling bulky materials, adopting awkward working postures, or working in restricted workspaces or on elevated work surfaces. In addition, van der Beek et al. (2005) report that scaffolders are at a particularly high risk of developing lower back disorders.

An open-type end frame weighs 22.7kg (50 pounds). In the workplace, however, due to dirt and other environmental factors, workers must exert greater force to lift an end frame. They may also need to adopt awkward postures to generate the power required to lift an end frame. To reduce the risk of overexertion injuries during erection/dismantling of frame scaffolds, Hsiao and Stanevich (1996) recommended the following:

- design assisting devices to allow scaffold erectors to adopt a better upper extremity posture and enable them to reduce the exertion (force) required during the scaffold dismantling phase
- redesign end frames using lightweight materials, and
- modify end frames by providing handgrips, and changing the shape and centre of mass of the frames.

Pile driving

To prepare and set the base of structures, pile drivers must install piling. This work involves using pile-driving rigs to drive metal, concrete or woodpiles into the earth. Different methods, such as vibration and impact force, can achieve this. One of the main challenges of pile-driving is that the job must be performed outdoors. Pile drivers face various workplace and environmental challenges, such as dust, mud, extreme humidity and wind (Dasgupta et al., 2012).

Dasgupta et al. (2012) state that for this trade, the development of MSDs is associated with adopting non-neutral trunk, leg and arm postures, as well as working on unstable ground. As an example, during a retaining wall operation, workers need to install steel or wood sheets into the ground. To install these materials, workers often lift one or both arms to an angle greater than 60 degrees, or adopt an awkward trunk posture. Unstable ground conditions are an unavoidable work condition for pile-drivers, which only adds to the number of risk factors. Administrative controls are generally used to reduce the risk of MSDs.

Screeding

Removing extra concrete, and leveling concrete to grade, is referred to as concrete screeding. The task can be performed using different techniques. It has been reported that the most serious risks of developing MSDs of the upper extremity and back are associated with manual and roller screeding (Albers et al., 2004). While the powered screeding technique is less risky than manual screeding, power screeding can include periods of medium/high exertion for lifting tasks. In addition, vibratory screeding operators are exposed to hand-arm vibration.

Generally speaking, manual screeding, which is the simplest and most widely used method of screeding, has been found to expose workers to the greatest number of back and upper-extremity MSD risk factors. It must be noted that workers gripping the vibratory, roller, and walk-behind laser screeds are exposed to segmental vibration. While workers operating the vibratory and walk-behind laser screeds must work in a neutral trunk posture, they are also required to pull heavy equipment while walking backwards.

Drywall workers

Drywall hanging is a carpentry sub-trade. In this trade, drywall workers lay out the interior wall system with studs and hang large drywall panels on the ceiling and sidewalls. Normally, drywall panels consist of a layer of gypsum between two layers of heavy paper. The task of a typical drywall worker can include measuring, fitting, carrying and lifting. These workers are at a high risk of developing MSDs, given the standard size of drywall panels is usually 4x8ft and 4x12ft, with a 5/8-inch thickness, with the panels weighing 70lbs (31.7kg) and 105lbs (47.7kg) respectively (Yuan et al., 2007). Adopting an elevated arm posture is necessary when installing drywall panel. Muscle overexertion in the context of drywall panel installation has been associated with injury risks (Pan et al., 2000). Dasgupta et al. (2013) concluded that using panels with smaller dimensions could reduce the risk of MSDs. In addition, due to the nature of this job, regular breaks are highly recommended.

Plant operators

Plant operators are perhaps the only tradespeople affected by MSDs through more subtle stressors. The sustained and awkward postures they are required to maintain, the controls they are required to operate, and the vibrating environments in which they work, are major risk factors for MSDs (Zimmermann et al., 1997). It must be noted that there are different types of operating engineer and thus appropriate ergonomics interventions will vary. Some of these include bulldozer operators, crane operators, forklift operators and power shovel operators. Zimmermann et al. (1997) recommended the following general solutions to manage the risk of MSDs for this trade:

- equipment should be designed to minimise the magnitude and frequency of vibration reaching the operator
- equipment controls should be located within the cab such that reach distance, trunk flexion and rotation are minimised
- cabs should be designed in a way to provide maximum operator visibility from an upright supported seated posture to reduce the sub-optimum postural load, and

- equipment operators need to have regular breaks to minimise the effects of sustained postures.

Example: Ergonomic design of crane cabins

Ray and Tewari (2012) conducted an ergonomics evaluation and redesign of a manually-operated Overhead Travelling crane cabin located in a steel plant in India. In addition to conducting this crane cabin evaluation and redesign, the researchers sought to fabricate a physical model of their new cabin design, and assess the physical model's performance.

A number of issues were identified by Ray and Tewari (2012) in relation to the existing cabin design. These included poor visibility, agronomical issues relating to the positions of controls and components which led to the adoption of extremely awkward postures, chairs being unsuited for task requirements, and congested cabin space. These issues resulted in health problems and injuries to operators, including: early fatigue; severe pain in the neck, shoulder and lower back; and reduced worker efficiency.

Ray and Tewari (2012) analysis of the existing work system involved:

1) Critical analysis of the existing components, and interviews with operators to identify issues. A questionnaire was used to obtain operators' feedback in relation to workspace, visibility, chair design, use of controls, and ingress and egress to the cabin.

2) An anthropometric study of crane operators that involved measuring 23 body dimensions.

3) Comparison of the results of the anthropometric study with the data obtained in Step 1 to identify incompatibilities between the existing crane design and the needs of crane operators. The incompatibilities were believed to lead to the adoption of awkward postures and body stress.

4) Real-time observations of crane operators while working. This facilitated identification of seven main postures adopted by the operators, as well as the duration and cycle of postures.

5) Obtaining data on the occurrence of pain in operators' bodies, which revealed that all operators suffered from pain in the lower back, upper back, neck, shoulders, arms, forearms, knees and legs.

This analysis of the existing design was followed by cabin redesign to improve visibility, chair redesign to improve for utility and comfort, redesign of controls, and ergonomic placement of components. In this phase of the study, computer models of the cabin were developed to evaluate the different features. A physical model of the new design was then manufactured and tested by end-users, resulting in design amendments. The new design was assessed as ergonomically improved and reducing the risk of MSDs. The new design also led to improved operator performance and increased overall system productivity.

Source: Ray and Tewari (2012)

Electrical and mechanical jobs

For electricians working in the construction industry, risk factors for MSDs are varied. Working with the arms elevated, especially with the hands or elbows above shoulder level, is the main factor associated with developing neck and shoulder disorders (Engholm & Holmström, 2005). This has been attributed to the fact that much of an electrician's job is to perform overhead work. Administrative controls, such as shift rotation or regular breaks, could reduce the risk of MSDs in this trade.

2.6 Outcomes of workplace interventions

In a critical review of workplace ergonomics interventions, Karsh et al. (2001) identified 101 relevant studies. The studies concerned interventions involving nurses, construction workers, baggage handlers, warehouse workers, manufacturing and assembly workers, postal workers, maintenance workers and fire fighters. Karsh et al. (2001) grouped these studies into six categories of primary workplace intervention:

1. Back belt use – 8 papers
2. Ergonomic and/or lift training – 21 papers
3. Tools/technologies – 10 papers
4. Exercise – 14 papers
5. Job design – 1 paper
6. Multiple components – 47 papers.

Studies in the final category focused on training, new tools, new workstations, exercise and/or changes in the organisation of work. These studies investigated the redesign of work methods and tools, factors such as work breaks and job rotation, and personal protective equipment.

Having looked at the weight of the evidence from rigorously controlled workplace ergonomics interventions, Karsh et al. (2001) concluded there was not a substantial amount of evidence supporting the use of workplace ergonomics interventions. However, they argued that the available evidence was still able to show that ergonomics interventions have benefits, primarily in effectively reducing musculoskeletal pain, discomfort and injury. It is notable that Karsh et al. (2001) were critical of the fact that most reviews in this field primarily focused on studies with experimental designs. They explained that while it is clear that randomised experimental designs are the gold standard in this domain, most ergonomics field intervention studies are unable to use such rigorous designs in a 'real world' workplace setting. To address this gap, the authors developed eight criteria to guide the conduct of future research on workplace ergonomics intervention:

1. Use randomised experimental designs whenever possible.
2. If unable to satisfy the first criterion, use other rigorous designs paying special attention to internal and external validity.

3. Ground the intervention in evidence from controlled laboratory studies or field observations and experience.

4. Use sample size calculations or power analyses.

5. Try to statistically or methodologically control for major potential confounds.

6. Measure and report on the effects of the interventions on intermediate outcomes.

7. Report effect sizes.

8. Use accepted or known methods for implementing the interventions.

In a review focused specifically on how workplace interventions are executed, Denis et al. (2008) identified 47 relevant papers. They concluded that most workplace ergonomics intervention processes are undertaken as a result of health problems being identified in the workplace and, to a lesser extent, reported work-related difficulties (for example, presence of risk factors or the deterioration of working conditions). Overall, it appeared to them that productivity-related problems are not the main precipitant of workplace ergonomics interventions. Denis et al. (2008) concluded that WMSD problems are only comprehensively dealt with when the problem is very specific; for example, when a back or upper body injury is involved.

In a review of interventions for preventing and managing neck and upper extremity work-related MSDs, Boocock et al. (2007) identified 31 relevant studies. The studies involved office workers, construction and industrial workers, and manufacturing and assembly workers. The studies were classified into three intervention categories that were developed by Westgaard and Winkel (1997). Ten papers were classified as mechanical exposure interventions, two as production systems/organisational culture exposure interventions, and 19 as multiple modifier interventions. The first category of papers involved adjustments to the work environment and workstation for office workers (for example, lighting, office layout), introduction of new tools, or redesign of tools for manufacturing workers. The second category of papers involved organisational alterations, assigning different work tasks, ergonomic education, and exercise/stretching for office workers and construction and industrial workers. The third category of papers predominantly combined exercise program interventions with approaches employed in the previous categories for groups of office and assembly workers.

Boocock et al. (2007) drew three conclusions from their review. First, they concluded there was some evidence to support using mechanical and modifier interventions for managing upper extremity MSDs and fibromyalgia. Second, they felt that evidence in support of the benefits of production systems/organisational culture interventions was lacking and required further investigation. Finally, they concluded there did not appear to be a clearly defined research strategy to identify effective interventions for high risk industrial workers.

2.7 Workplace ergonomics interventions in the construction industry

Given the aforementioned complexities of the construction industry, any successful ergonomics intervention must address a number of barriers. One of these barriers is the widespread belief among construction workers that MSDs are an unavoidable part of their job and that task modifications cannot change the nature of their work (Boatman et al., 2015). This attitudinal barrier, combined with the paucity of available research on the effectiveness of workplace ergonomics interventions in the construction industry, makes any intervention difficult. For example, a systematic review by Rinder et al. (2008) identified only eight relevant intervention studies in the construction industry. Another notable barrier is frequent confusion about the characteristics required to ensure an intervention program is effective. Importantly, the design and evaluation of an intervention program (if intending to reduce physical work demands) must distinguish between knowledge about the effectiveness of ergonomics measures and knowledge about the efficiency of strategies used to implement those measures (Van der Molen et al., 2007). In this regard, Rogers et al. (1995) offer five criteria for evaluating any new intervention program:

1. Relative advantage (perception of how the new system of work is better than the old system of work)
2. Compatibility (how innovation is perceived as being consistent with existing values, structures, etc.)
3. Complexity (the easier the innovation is to understand and implement, the better)
4. Trialability (the degree to which an innovation may be tested on a smaller scale)
5. Observability (the degree to which the outcomes of the innovation are visible).

Of the eight studies reviewed by Rinder et al. (2008), one was undertaken by Ludewig and Borstad (2003) which reported reduced levels of pain and disability following the administration of a therapeutic exercise program involving stretching and strengthening movements. A study by Luijsterburg et al. (2005) recorded a 20 per cent decline in absences due to sickness after a 10 month period, during which time a device for raised bricklaying was used. Of the remaining six studies, three studies introduced devices to adjust work height and/or mechanise transport (Hess et al., 2004; Van der Molen et al., 2004; Vink et al., 2002), one study used different belt types (Holmström & Moritz, 1992), one study used modified equipment (Mirka et al., 2003), and one study implemented a before-work exercise program (Holmström & Ahlborg, 2005).

However, Rinder et al. (2008) rated the methodological quality of these studies as between marginal and average. Rinder et al. (2008) concluded there is an urgent need for more construction intervention studies to fill the gaps in this research area.

Ergonomics interventions are typically based on a hierarchy of controls. Oxenburgh's Productivity Model (Oxenburgh et al., 1991) can be used as a guide for those wanting to assess the effectiveness of these controls. Training solutions are assessed as being up to 20% effective, while changing work methods through job design is estimated as being between 20 and 40% effective. The most effective form of controls are engineering solutions which make physical changes to the work environment (estimated to be greater than 70% effective).

A range of engineering controls have been recommended for the construction industry. These controls include redesigning tools and materials, and using mechanised equipment. In addition, as noted by Choi and Fredericks (2008), modifications to the work process can play an important role. Changing the way work is performed can reduce both labour intensity and the amount of time it takes to complete a job. Administrative controls have also been widely adopted. Job rotation, for instance, is used to reduce the level of accumulated exposure on different body regions. Leider et al. (2015), however, have argued that main defensive strategy, job rotation should be used less often than it is currently used. They state that for job rotation to achieve long-term sustainable outcomes, various factors must be considered. Specifically, the authors argue that an individual's characteristics and the organisational context are two key components which can play either positive or negative roles (as a barrier or facilitator), and that both must be studied carefully before job rotation is implemented. Generally speaking, control over when and how to do their job enables workers to rotate between activities, or with their coworkers, either pre-emptively or so as to reduce musculoskeletal complaints. With regard to job characteristics, workflows can help to facilitate job rotation so long as certain task sequences are followed so that the required work is completed.

To enable a number of stakeholders (with differing levels of knowledge) to understand and contribute to implementing an ergonomics intervention, a construction ergonomics intervention matrix has been developed by the Environmental, Safety and Health Department of the Intel Corporation. As can be seen in Figure 2.4, there are four categories of construction ergonomics intervention that can be adopted under this model (Rinder et al., 2008):

1. Short-term and simple intervention
2. Long-term and simple intervention
3. Long-term and complex intervention
4. Short-term and complex intervention.

In this model, an intervention can either be simple or complex. According to this matrix, an appropriate intervention program can be developed for any given trade in the construction industry if the trade's physical, psychosocial, organisational and individual factors are considered. However, it is still unclear whether it is better to implement a simple intervention (for example, change a material's weight) or a complex intervention (for example, modify the worksite logistics and schedule). What does remain clear is that no single solution is applicable to all situations. The appropriate solution is dependent on the specific project, the construction trade and stakeholder opinion.

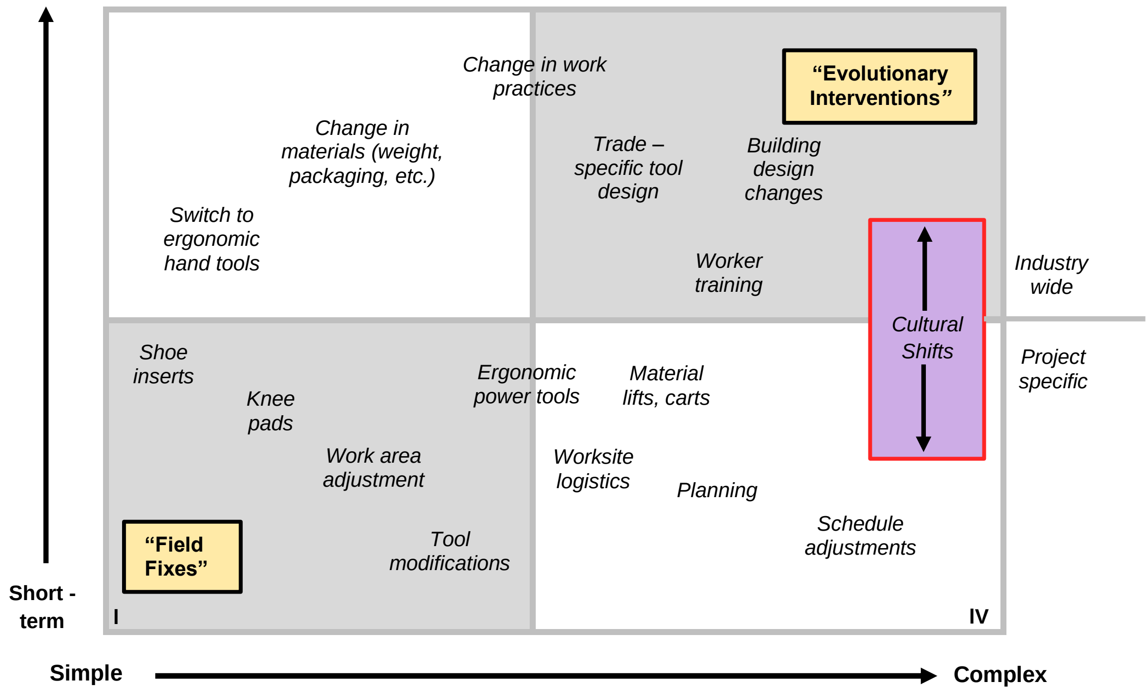


Figure 2.4: Construction ergonomics intervention matrix.

Source: Rinder et al. (2008)

To facilitate both developing and implementing ergonomics intervention programs, Abaeian et al. (2016) recommend using system dynamics theory. According to this model, all components within the system are interconnected, and there is continuous interaction between the components (

Figure 2.5: Example of system dynamics.

). This means system dynamics (SD) modelling is suited to any dynamic system characterised by mutual interactions, information feedback, and interdependencies between variables. Abaeian et al. (2016) have demonstrated that SD modelling is beneficial both because it graphically depicts the logical link between cause and effect, and because it improves knowledge on how ergonomic risks can emerge while 'task cycles' are performed. Using this approach can assist ergonomic job designers to gain a better understanding of potential barriers.

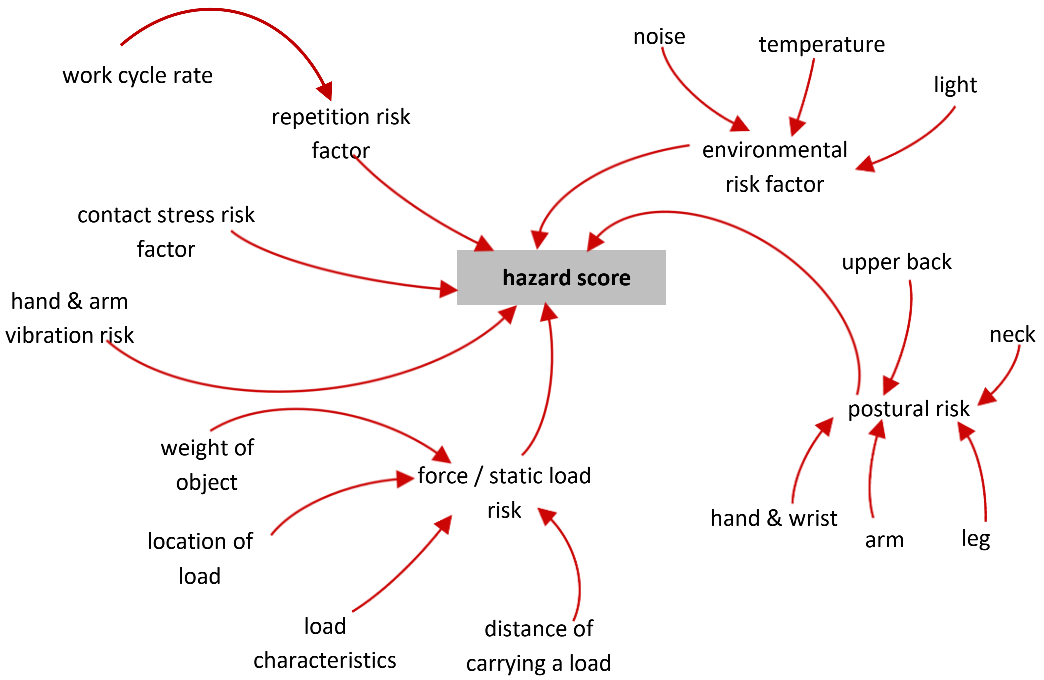


Figure 2.5: Example of system dynamics.

Source: Abaeian et al. (2016)

Despite limited knowledge on how to implement a successful ergonomics intervention, it would still appear that at present participatory ergonomics interventions are being implemented more effectively than other approaches. A study by Dale et al. (2012) has revealed that participatory ergonomics training interventions were inconsistent in their ability to precipitate a reduction in physical exposure and workers' symptoms when used as the primary method to address MSDs across several work populations. However, there were few details available about workers' response to training, ability to properly implement the interventions, and sustainability of new work methods over time. This lack of data makes it difficult to assess these interventions' impact on physical exposure or broader health outcomes. It must be concluded that process measurement is a critical aspect of any intervention evaluation. An example of ergonomics process evaluation is presented below.

Example: Process evaluation of a participatory ergonomics training program

Dale et al. (2012) conducted preliminary research to evaluate the effectiveness of a participatory ergonomics training program. The study's objective was to determine whether participatory ergonomics interventions reduce workers' physical exposure and improve health outcomes. In the study, workers' self-reports on their own status were compared to the researchers' assessment of physical exposures in work tasks, both before and after the delivery of a six month training program. The training program included general training and problem-solving group facilitation. Preliminary results based on a group of 16 floor layers suggested that workers found the training program provided useful information, with 82 per cent of workers preferring one-on-one interactions and problem-solving sessions. After three months of the program, 92 solutions were identified for problematic tasks.

Overall, the authors considered process measures to be a critical but often ignored aspect of intervention evaluation. They argued that process evaluation of ongoing interventions can help researchers and ergonomists to understand the extent to which intervention programs reduce physical exposure.

Source: Dale et al. (2012)

2.8 Conclusions

The literature review has revealed that the construction workforce is at high risk for work-related MSDs. These risks are linked to the physical nature of work in which there is a significant amount of manual materials handling, and workers are required to work for extended periods in awkward postures, or are subjected to repetition, force, awkward posture, vibration, and contact stress. However, psychosocial stressors and thermal risk factors (sometimes exacerbated by personal protective clothing) also contribute to MSDs in construction. Thus, there is a growing understanding that holistic approaches to understanding and addressing work-related MSDs are needed. Consequently, solutions need to address multiple factors in the work environment, individual work practices, design and provision of tools and equipment, and design of work.

MSDs can be chronic or acute, and sometimes it is difficult to distinguish between these. MSDs are also associated with diminished mental health and long term work disability.

Different construction trades are susceptible to different types of MSD. Most affected body parts also vary by trade and have been linked to specific work exposures.

Various methods have been used to measure the risks of work-related MSDs, including self-report methods, expert observation and direct measurement. Self-report measures have been criticised as being low in reliability. Expert observation methods are susceptible to bias. Direct measurement is increasingly recommended as the most reliable way to measure MSD risk inherent in various tasks.

The development of lightweight, wireless and reliable inertial sensing systems to measure human movement, now offers the possibility of undertaking effective direct measurement in field-based work settings.

Such a system was selected and tested for use in the remainder of this research project.

Ergonomic interventions have been implemented targeting various trades. In some cases, these have been relatively simple adaptations or modifications of tools or equipment. In other cases, they have represented more complex approaches to addressing ergonomic issues in computer-based design systems that seek to minimise manual materials handling.

Whatever form of ergonomics initiatives is implemented, a participatory and consultative approach is recommended.

It is as important to evaluate the benefits of modified work processes, tools or equipment, as it is to evaluate the intervention process itself.

2.9 Gaps to be addressed in the research

In the remainder of this report we:

- describe the methods used to deploy an objective system of sensors to measure whole body movement, and
- present the results of using the system to objectively evaluate the work-related MSD risks associated with the performance of five selected manual rail construction tasks.

The research addresses the following knowledge gaps or opportunities identified in the literature review:

- Limited analysis of the risks of work-related MSD in manual rail construction work tasks.
- Reliance on self-report data or expert observation, and consequent lack of objectively collected evidence of the movement-based risk factors for work-related MSD in manual rail construction tasks.
- The opportunity to implement an evidence-informed approach to redesign of work tasks and/or equipment to reduce the risk of work-related MSD in manual rail construction work tasks.
- Collection of objective evidence quantifying the impact of task or equipment redesign
- in particular rail construction scenarios.

Part 3: Methods

To address the aims of this project, an applied experimental design was combined with using wearable sensors to capture objective measurement of body movement patterns (that is, joint motion and posture) and muscle activity. The sensors enable a series of measures to be undertaken; this ‘repeated measures’ approach yields a robust and extensive data set

Forces exerted by workers in occupational settings have two components. The first is the magnitude of force exerted and the second is the line of application. For MSD risk exposure, these components must be considered in light of the postures and movements adopted by a worker. Moreover, the duration and frequency of these movements must be considered. In general, MSD risk increases with high or sustained levels of force, in combination with awkward postures and movements performed frequently or for sustained periods of time, separately or cumulatively.

It is important to note that force exertion by a worker may not move an object. To statically hold a weight or tool (no net movement), due to gravity a person must apply an equal and opposite force to counter the object’s weight or downward force. This type of holding force may also occur in other directions, such as horizontal, when a person is holding an object that exerts force in this direction, such as the reaction force that results in the flow of material being pumped through a hose.

The best way of understanding force is to measure it directly. This is possible but can be complex in workplace settings where it may be difficult or dangerous to use force measurement systems. Currently, the nature of these systems limits, and in most scenarios precludes, their use in settings such as construction sites. In these situations, it may be more suitable to measure these forces in mocked up or laboratory situations.

For this project, the forces exerted by participants were not measured. This was stipulated in the original method. However, as the project assessments proceeded it became relevant to consider the nature and level of forces exerted. The Xsens technology measures and describes whole of body actions and movements in real-time by capturing the space and time measures of the movement (for example, joint angle, movement speed). It does not measure the forces exerted in any way. This requires a different type of measurement system that can be difficult to use in field settings. To further consider force exertion within tasks, RMIT researchers initially used observational methods and sought feedback from participants to understand the likely levels of force exerted, on an anecdotal rating basis only. To extend this level of consideration, muscle activity or EMG data was recorded and analysed. EMG data is a measure of the electrical activity in a muscle which correlates with the level of force generated in a muscle. That is, the higher the electrical signal, the greater the muscular force exerted. However, this information can only be regarded as an indicator of likely levels of force exerted as it does not provide any true measurements of the forces exerted.

3.1 Research design

The research design had three stages that used a repeated measures and a case study approach.

Stage 1: Selection of work tasks

This stage involved selecting work tasks to investigate. Representatives of the Major Transport Infrastructure Program (MTIP), WorkSafe Victoria, and construction contractors engaged in delivering MTIP projects, initially identified seven manual rail construction work tasks associated with work-related MSDs. Based on the literature review and following further consultations with representatives from MTIP and WorkSafe Victoria, the research team collectively agreed that investigation focus on five work tasks commonly performed by the rail construction workers. These tasks were identified as being associated with high frequency of work-related MSDs, and having the potential for risk reduction through task redesign. The selected tasks were steel fixing, shotcreting, cable pulling, shovelling and jackhammering.

Stage 2: Baseline assessment of work tasks

This stage involved the baseline assessment of work tasks. Technical data on participant movements and muscle activity were collected while participants performed the work tasks identified in stage 1. Field-based task assessments, including pilot work, were carried out at a number of different active construction sites. During the assessments, the participants (construction workers) wore an array of wearable sensors described in detail in section 3.4. The assessments also involved simultaneous video capture of the work tasks, and discussions with site participants, managers and other stakeholders. Collected data were analysed and used to identify movement patterns (body joint motion and posture) and muscle activity during the participants' performance of the tasks. Where possible, physical loads were estimated from these data. These data were used to critique MSD risks for each task.

Stage 3: Potential risk reduction solutions

This stage identified potential risk reduction solutions for work-related MSDs. For three of the five tasks assessed, prototypes of these solutions were developed, implemented and assessed. For two of the five tasks assessed, more complex conceptual designs were proposed but could not be tested within the scope of this project.

These prospective solutions were based on conclusions drawn from stage 2 task assessments and changes that could be made to reduce the risk of work-related MSDs. This approach focused on exploring the potential to redesign work tasks, the work environment and other relevant elements.

The following sections describe the overarching methodological approach, which was consistent across all tasks, as well as specific methodological considerations for each task.

3.2 Participants and research team

Study participants were 12 healthy male adult volunteers (age: 32.1 ± 11 yrs.; mass: 92 ± 21.2 kg; height: 177.8 ± 9.2 cm) (Table 3.1). The construction site participants were recruited from worksites forming part of the Major Transport Infrastructure Program (Victoria). However, in one case (shotcreting), a non-MTIP worksite was visited due to lack of availability and access to shotcreting activities at MTIP sites. Shotcreting at this construction site was performed by a contracting agency also engaged in construction at MTIP sites. The work performed was reported to use the same approach as that used in transport infrastructure construction work.

The tasks assessments took place at one construction trial site, seven active construction sites, and one non-construction site (based at RMIT University) where a modified shovel was tested. Participants at all sites, except the non-construction site, met requirements under the Rail Industry Worker program for working at rail worksites. This program, overseen by the Australasian Railway Association, requires specific training and competency requirements as well as a medical health assessment. Prior to testing, potential participants were screened for the following: (1) competency to perform the work tasks; (2) to be of an age appropriate for the normal working population of the industry; (3) musculoskeletal injuries; and, (4) the ability to communicate in English via self-reporting. Participants at the non-construction site were members of the RMIT research team and were selected as a sample of convenience.

Approval to conduct this project was obtained from the RMIT Human Research Ethics Committee (HREC20500). Each participant received a written informed consent form prior to participating in the project. Before consent was obtained, all procedures and potential risks were explained to prospective participants using a plain language statement (see Appendix A: Participant information sheet and consent form) and through face to face discussions with an RMIT research team member. Participants were given the opportunity to ask questions before giving their consent to participate in the project. Once consent was granted, the participant was asked to provide consent (or not) to use photographical images of themselves in publications. One participant chose not to participate in the study. Another consented for his image to be published provided he could not be identified.

Table 3.1: Data collection dates, sites, participants and work tasks assessed.

Assessment Date	Site	Participant ID	Task	Age (yrs)	Height (cm)	Mass (kgs)
8 June 17	1	1	Testing	55	170	80
29 June 17	2	2	Shovelling	55	165	82
29 June 17	2	3	Steel Fixing	29	178	85
25 July 17	3	4	Jackhammering	30	180	89
3 Aug 17	4	5	Steel Fixing	18	182	68
10 Aug 17	5	7	Shotcreting	24	190	125
18 Aug 17	4	6*	Steel Fixing	28	173	73
25 Aug 17	6	8**	Cable pulling	34	162	74
22 Sept 17	7	9	Shotcreting	55	170	110
23 Sept 17	3	10	Jackhammering	39	187	112
6 Oct 17	8	8**	Cable pulling – trestle test	34	162	74
6 Oct 17	4	6*	Steel fixing – tool tests	28	173	73
21 Oct 17	9	11	Shovelling – supplementary handle test	25	82	180
21 Oct 17	9	12	Shovelling – supplementary handle test	60	72	173

* Indicates repetition of the task with tool modification (same participant).

** Indicates repetition of the task with tool modification (same participant).

RMIT University's onsite assessment team (Chris Fitzgerald, Dong Na, and Alf Camilleri) travelled to the construction sites to collect data. Before entering construction sites, the team completed a series of training and induction sessions before the visit. These were: (1) Workplace Health and Safety Construction Induction (commonly known as the White Card in the Victorian construction industry); (2) a Railway Industry Worker Identification and Medical Examination; (3) Level 1 Train Track Safety Awareness course; (4) various project-specific induction training requirements; and (5) relevant site-specific pre-start sessions.

In order to fully understand the research context, other research team members (Distinguished Professor Helen Lingard, Dr Isaac Selva-Ra, Associate Professor Noel Lythgo and Associate Professor Olga Troynikov) also completed various training courses including White Card induction training, the Level 1 Train Track Safety Awareness course, and relevant project-specific health and safety induction courses.

3.3 Tasks

General descriptions of tasks assessed are outlined below. Detailed descriptions of these tasks, conditions and environments encountered during assessments, and the results, discussions and conclusions, are given in Part 4 to Part 8 (pages 86 to 191) of this report.

3.3.1 Steel fixing

Steel fixing is the task of positioning and joining reinforcing steel bars and mesh in accordance with previously prepared engineering plans. This process is ongoing until the required shape is established. The constructed steel framework is then either surrounded by formwork sheets to form the overall shape of the structure, and concrete poured into it until the shape is complete, or the steel frame is lifted into position for the formwork and concreting pouring to be completed around the frame in that location.

The reinforcing steel bars and mesh are tied together with wire. ‘Spacers’ and ‘chairs’ are also positioned within the frame to ensure the correct amount of concrete cover. The steel fixer uses a pinching/snipping tool to twist the ends of a length of wire around the two parts of the frame to be fixed together. Once the required tension is achieved, the steel fixer squeezes this hand tool to cut both wires and finish that fixing task before quickly moving on to the next section.

Steel fixing is a common ‘everyday’ task undertaken on rail construction projects in the building of various concrete structures and foundations. The task is often completed in situ due to the size and individual nature of the concrete structure or foundation being built, although it was reported and observed that, increasingly, steel fixing is first conducted on the ground adjacent to the structure being built, and then lifted into place for completion.

This work is manually intensive. It can require the steel fixer to remain in a stooped, bent over position for significant periods of time, or to adopt awkward reaching postures to access the bars to fix. Steel fixers also handle the steel bars and position them for fixing as a usual part of the work. Steel bars can be very long (approximately 10 metres) and require several operators to handle them. Smaller and lighter bars can be handled individually. Steel fixing is regarded as highly skilled work.

3.3.2 Shotcreting

Shotcreting involves spraying liquid concrete onto a wall to form a vertical or oblique structural wall. This is typically done around the perimeter of an excavated area. The concrete is pumped to the area via a long hose coupled with a high pressure air hose. The outflows of both hoses overlap at their nozzle ends so the concrete can be sprayed.

Shocreting is a common ‘everyday’ task undertaken on rail construction projects which stabilises excavated rail cuttings and other soil surfaces. The task involves the operator moving the hoses into place and holding them in a position to apply the sprayed concrete. Adoption of sustained postures while holding shotcreting hoses was reported and seen to be common practice. To limit the level of manual force exerted to hold shotcreting hoses in place, operators counter the backward force of the hose by leaning forward.

Shotcreting is regarded as highly skilled work. The operator needs to both minimise waste and ensure required levels of concrete compaction are achieved as the wall is built up.

3.3.3 Cable pulling

Cable pulling involves laying electrical and/or communication cables within a previously prepared trench, cable tray or conduit (tubing). Within the MTIP rail construction environment, this work was reported to mostly involve pulling cables through underground conduits, between a series of pits, to supply communication lines for a new signalling network.

The continuous length and integrity of the cable is important to ensure it is operational once installation is complete. Cable lengths can be very long. Cables are delivered to installation locations on storage drums mounted on the rear of a truck.

Commonly, cables are manually pulled through conduits by small teams of up to four operators. Mechanical (powered) cable pullers are available and used, but many sites preclude their use due to access problems. Manual cable pulling was reported to be the most common method.

Cable pulling is a common ‘everyday’ task undertaken on rail construction projects to provide electrical and communications systems for newly commissioned facilities and infrastructure.

3.3.4 Shovelling

Shovelling is the task of using a hand-held shovel to dig, lift and move loose granular materials (such as soil, concrete, sand, ballast) from one position to another. Large scale excavation or movement of these materials is conducted using mechanical or digging excavators, or suction devices. While shovelling is a common ‘everyday’ task undertaken on rail construction projects, it was reported and seen to be undertaken for small volumes of material.

3.3.5 Jackhammering

Jackhammering is the breaking up of hard surfaces such as concrete and rock into pieces that can be removed. The jackhammer is a portable chisel normally operated by compressed air (pneumatic). The jackhammer action combines a hammer and chisel process. It operates by driving an internal hammer up and down while the operator holds the upper end of the device to stabilise it.

It is a common ‘everyday’ task undertaken on rail construction projects to remove existing footpaths and footings in preparation for new works. Within this project, unconventional jackhammering was assessed where it was routinely applied to large concrete columns (end caps) above ground level, for the purpose of exposing structural steel bars within a column.

3.4 Measurement instrumentation

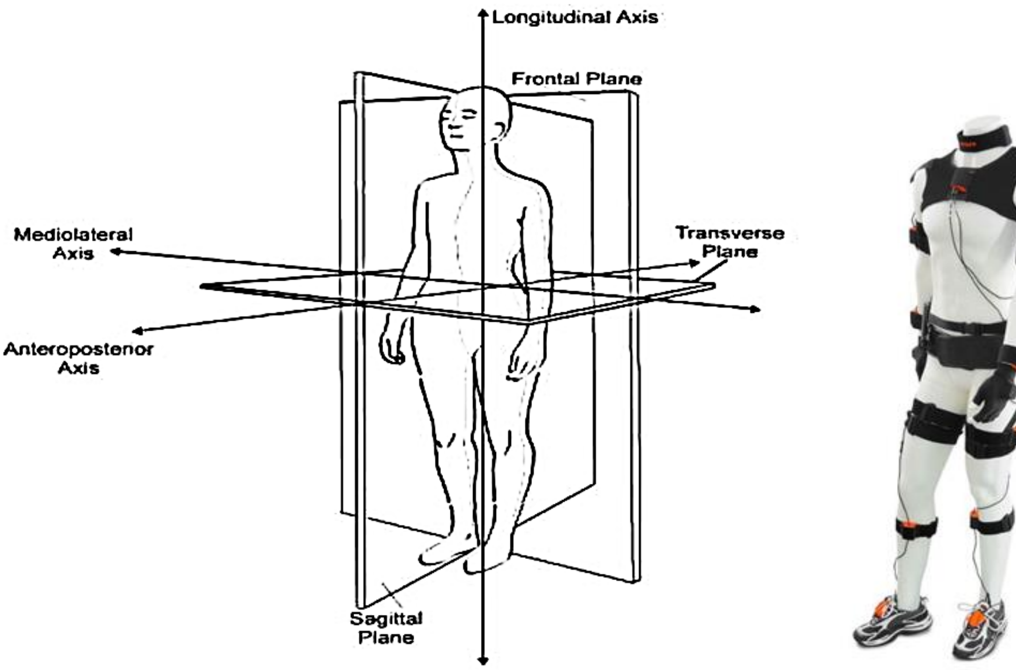
Body movement patterns (that is, joint motion and posture) were collected with a three-dimensional (3D) portable motion analysis system (Xsens Pty Ltd, MVN BIOMECH Enschede, Netherlands). Electromyography (EMG) data were recorded using a portable wireless EMG system (Zero Wire, Milan, Italy).

3.4.1 Movement pattern

An Xsens three-dimensional motion capture system was used to record participants' movement patterns (that is, joint motion and posture), with a sampling frequency of 240 Hz. Seventeen light-weight inertial sensors (36mm length; 24.5mm width, 10mm height; 10g mass) were attached to different body sites of the participant (described in Section 3.5).

Using the 3D Xsens system significantly enhanced this investigation's ecological validity since it allowed capture of participants' movement patterns while they performed work tasks on a construction site. The system uses small inertial sensors attached to the body to capture movement patterns.

Each sensor has a built-in gyroscope, magnetometer and tri-axial accelerometer. The gyroscope measures changes in the orientation and rotational velocity of each body segment about the longitudinal, anteroposterior and mediolateral axes (Figure 3.1). The magnetometers measure the ambient magnetic field of the surrounding environment. The accelerometer measures the acceleration (both angular and linear) or the rate of change of velocity of a particular body segment. Linear and angular displacements are derived from these data through the process of integration (Munem & Foulis, 1978). For example, forward trunk flexion is one form of trunk inclination and is determined by the change in position and orientation of sensors located on the trunk. Similarly, shoulder movement is determined by the change in position of a sensor located on the upper arm relative to the sensors located on the trunk.



Left panel **Right panel**

Figure 3.1: Left panel: planes of movement and axes of rotation. Right panel: an example of the placement of Xsens sensors.

Source: Xsens website – www.xsens.com

3.4.2 Muscle activity instrumentation

A portable and wireless electromyography system (Wave Plus Wireless EMG, Cometa Pty Ltd, Italy), sampling at 1000 Hz, was used to record muscle activity. This involved attaching 14 light-weight sensors (30mm length, 25mm width, 15mm height, 7g mass), consisting of a pair of electrodes and a transmitter, to the participant’s body.

Electromyography data was obtained for each assessment to provide information on muscle activity within an assessed task that could be used for further analysis of that task if required.

3.4.3 Pilot study of Xsens system

RMIT University’s assessment team tested the Xsens system and onsite protocols at site 1 (participant 1). Site 1 was not an active construction site, but an equipment depot where construction tasks could be demonstrated and tested. The tasks assessed were jackhammering, shovelling and drilling.

The participant was fitted with the Xsens and EMG sensors in a nearby office.

Each task was assessed as a ‘mock up’. Jackhammering involved breaking up three blocks of bluestone rock that were approximately 25cm high. The blade did not go lower than ground level at any time, and did not move to an oblique angle (relative to the ground) as is typically done.

Shovelling involved moving sand in a pit. The task involved digging (vertical shovel head), scraping (horizontal shovel head), scraping to deliver the load to one side, and scraping to load sand into a (mocked up) wheelbarrow.

The drilling task involved drilling three rows of seven holes into a timber sleeper at ground level. Each row involved the participant adopting a different self-selected posture.

After assessment of each task, the participant and project stakeholders who were observing, were asked for their views about how the well the tasks represented typical onsite work tasks. They confirmed the tasks were representative. This was to become an essential feature of the site assessments as the RMIT research team would rely on the participant and observing stakeholders to confirm the range of different methods, postures and movements used to perform each task.

Fitting the sensors took approximately 35 minutes and the three assessments took approximately 1 hour. After assessing the third task, drilling, the sensors were removed from the participant. This took approximately 5 minutes. An additional 10 minutes was required to pack up the computer and measurement equipment and load it into the vehicle.

The data were reviewed after this site visit and found to be ‘clean’ and usable.

The success of this pilot work confirmed that the equipment and RMIT assessment team were ready to commence the construction site assessments.

3.5 Experimental protocol and data acquisition

The following protocol (Figure 3.2) was used to record participants' anthropometric data, apply and calibrate sensors, record data during work tasks, and remove sensors after assessment.

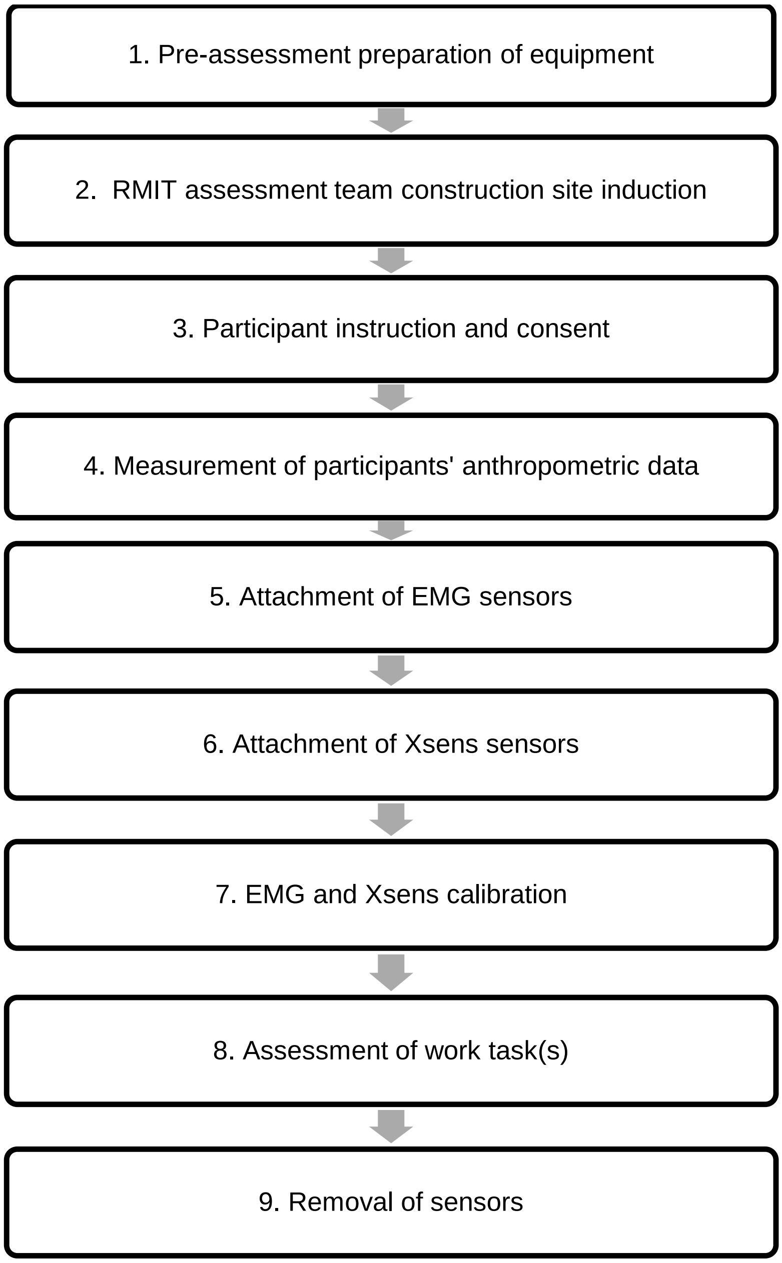


Figure 3.2: Consort diagram showing an overview of the research protocol.

More detailed information is provided below about each step in the protocol. Task assessment sessions lasted approximately 2-3 hours (from preparation to removal of sensors).

Step 1 – Pre-assessment preparation of equipment

Prior to each site and participant assessment, the Xsens and EMG equipment were prepared. This involved: charging the battery for the Xsens body pack; charging the batteries or the wireless connection modem; ensuring all sensors, the Xsens sensor body straps and shaver had been cleaned and were ready for fitment. In addition, to attach sensors to a participant's skin required applying double-sided tape to the sensor surface of all EMG sensors and 8 of 17 Xsens sensors.

Step 1 ensured the equipment was ready for the assessment(s) and reduced onsite preparation time for sensor fitment. This procedure was adopted after a reviewing the pilot study, and resulted in reducing sensor fitment time from approximately 60 minutes to 35-40 minutes.

The computer, and back up computer, were fully charged. Two, high speed cameras were charged and memory cards emptied to ensure they were fully prepared for maximum data capture.

Where alternative tools were being tested as part of a second phase of assessment of a specific work task, as occurred for steel fixing, cable pulling and shovelling, preparation for each tool was also conducted to ensure they could be operated competently and safely during the assessment. This involved a risk assessment for each tool and pre-assessment practice.

Step 2 – RMIT assessment team construction site induction

If RMIT assessment team members arrived before commencement of work for the day, they participated in the 'pre-start' meeting of all workers and managers for that site. This meeting is conducted every day. It outlines the requirements of that day's work. A focus of these meetings was communicating safety issues to attendees to help maintain a focus on safe work practices and behaviours at each site. At each of these meetings, the assessment activity of the team was described to attendees to make them aware of the project.

On occasions, RMIT's assessment team did not attend the meeting, but instead participated in a pre-assessment safety induction session with the work crew before commencing assessment.

Step 3 – Participant instruction and consent

At the outset of each assessment, the plain English statement (Appendix A: Participant information sheet and consent form) was read to each participant by a member of the RMIT assessment team. All except one participant agreed to be involved and signed the consent form.

Step 4 – Measurement of participants' anthropometric data

Each participant's age, height, mass and body dimensions were recorded (Table 3.2). These body dimension data were required for system calibration to create a full body 'avatar' of each participant.

Table 3.2: Participants' anthropometric data.

Body dimension (cm)	Participants											
	1	2	3	4	5	6	7	8	9	10	11	12
Body height	178	182	173	180	187	190	170	162	165	187	180	173
Shoulder width: left AC to right AC	43	37	39	43	45	49	43	37	41	45	44	40
Arm span: finger-tip to finger-tip	176	181	179	180	193	196	175	162	171	193	173	174
Hip height: trochanter height	91	88	92	88	96	102	88	84	83	96	96	90
Hip/pelvic width: left to right ASIS	27	23	28	29	36	30	32	29	29	36	27	30
Knee height: lateral femoral condyle	48	54	43	53	54	55	50	45	47	54	45	46
Ankle height: mid-lateral malleolus	8	9	7	8	8.5	7	8	7	7	8.5	8	8
Foot size/length	27	28	26	29	30	31	29	26	24	30	27	27
Shoe/boot heel height	3.5	5	5	5	5	5	5	5	5	5	4	2

Step 5 – Attachment of EMG Sensors (including skin preparation)

Attachment of sensors and associated transmitters (later referred to as 'attachment of sensors') onto participants occurred in two stages to minimise the need for participants to completely undress down to their underwear. First, Xsens and EMG sensors were fitted to participants' head, trunk and upper limbs body. To facilitate this, the participants removed their upper body clothes and boots only. Once upper body fitment was completed, and prior to the fitment of the lower body sensors, the participants put on their upper body clothes. They then removed their trousers and the sensors were fitted to their lower limbs. When this was completed, the participants put their trousers back on, then their boots, which usually required the laces to be loosened to comfortably accommodate the foot mounted sensors.

Prior to attaching EMG sensors, the participant's skin was prepared by shaving body hair with an electric shaver (cleaned with alcohol), gently abrading the skin surface with fine abrasive material, and cleaning it with alcohol wipes.

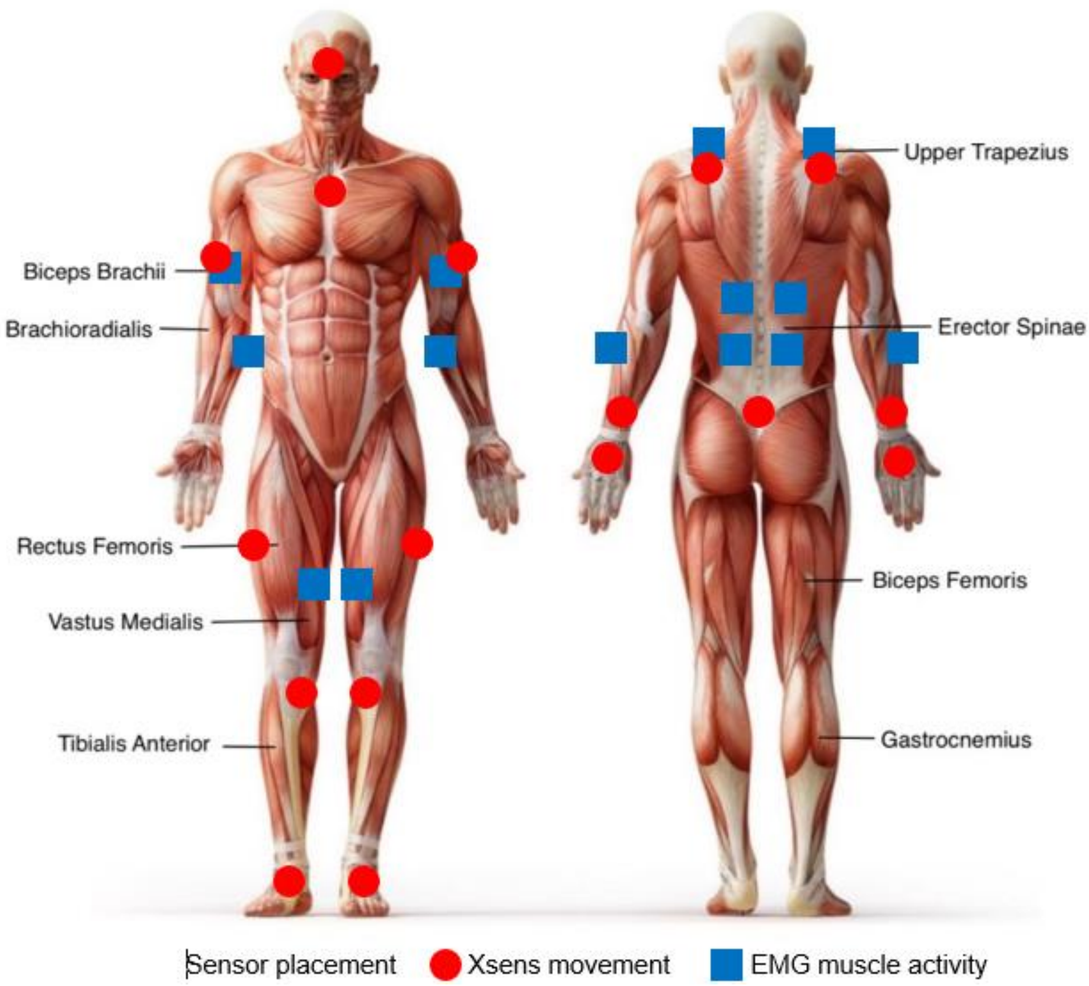


Figure 3.3: Xsens and EMG sensor placement sites.

EMG sensors have two components: a pair of silver chloride electrodes connected to a transmitter. The transmitters were attached to the skin using double-sided non-allergenic tape (Figure 3.3, Figure 3.4 and Table 3.3). The electrodes (inter-electrode distance 20mm) were placed on the skin directly over the bellies of three muscles on the upper limbs (biceps brachii, brachioradialis and flexor carpi ulnaris), two major trunk muscles on each side of the back (erector spinae at T8 and L3 levels, and upper trapezius), and two lower limb medial muscles on the thighs (vastus medialis). Locations for EMG sensor placement are described in Table 3.3.

Table 3.3: Site of EMG electrode placement.

Segment	Muscle	EMG electrode location	Muscle Action
Trunk	Trapezius (upper)	50% on the line from the acromion to the spine on vertebra C7	Elevation, adduction (retraction) and upward rotation of the scapula
	Erector Spinae (longissimus)	2 fingers width lateral from spinus process at T8 and L2/3 levels	Extension of the back
Upper Limb	Biceps Brachii	On the line between the medial acromion and the fossa cubit at 1/3 from the fossa cubit	Flexion of the forearm at the elbow
	Brachioradialis	On the most prominent bulge of the muscle after forearm pronation	Extension of the hand at the wrist
	Flexor carpi Ulnaris	On the most prominent bulge of the muscle on the medial or ulnar side of the forearm when in supination	Flexion of the hand at the wrist
Lower Limb	Vastus Medialis	80% on the line between the anterior spina iliaca superior and the joint space in front of the anterior boarder of the medial ligament	Extension of the knee joint

Step 6 – Attachment of Xsens Sensors

Seventeen Xsens sensors were attached to each participant's body (Figure 3.4 and Table 3.4). Nine sensors were attached to known body landmarks (described in Table 3.4) by using non-allergenic, double-sided tape. Eight of the remaining sensors were attached to limb segments by using velcro straps that went around a limb. Sensors were then connected by cables to the Xsens, MVN Bodypack, a lightweight transmitter and data logger, and the battery pack. Both items were fixed to the velcro waist strap over the rear of the participants' pelvis. Please refer to Figure 3.3, Figure 3.4 and Table 3.3 that show and describe site of placement of Xsens sensors.

Figure 3.4: Sensor placement shown on one participant's front, side and back. Xsens sensors are orange. EMG sensors are blue.

Table 3.4: Description of Xsens sensor placement.

Segment	Location	Placement	Method of attachment
Trunk/ head	Head	1-2cm above eyebrows, on the midline	Double-sided tape on skin
	Shoulders	On the upper border of the scapula , midway between the spine and shoulder joint	Double-sided tape on skin
	Sternum	On the level of Manubrium (T3-4)	Double-sided tape on skin
	Pelvis	On top of the sacrum in the midline	Velcro on lower side of sensor, adhering to the pelvic band
Upper limb	Upper arms	On the middle of the upper arm, on the lateral side of each arm	Velcro on lower side of sensor, adhering to upper arm band
	Forearms	Just above each wrist	Velcro on lower side of sensor, adhering to forearm band
	Hands	Centre of the dorsum of each hand	Double-sided tape on skin
Lower limb	Upper legs	Midline of the upper leg on the lateral side of each leg	Velcro on lower side of sensor, adhering to upper leg band
	Lower legs	On the head of tibia on the medial side of each lower leg	Velcro on lower side of sensor, adhering to lower leg band
	Feet	Where the metatarsal bones meet phalangeal bones of each foot	Double-sided tape on skin or sock

Step 7 – EMG and Xsens calibration

Each participant then performed maximal voluntary contractions (MVCs) of the muscles over which the 14 EMG sensors were placed (Table 3.5). The participants performed these MVCs by having an RMIT assessment team member provide active resistance against their attempt to maximally activate the muscle. The team member placed their hands, arm or foot against the relevant part of the participants' body to provide a stabilising 'anchor' for the participant to endeavour to move that part of their body in the prescribed direction of movement for the targeted muscle. Once a perceived MVC was obtained, after approximately 2-3 seconds, the participant and team member would relax and release their resistance and move on to the next muscle(s).

Table 3.5 describes the actions used to collect MVC data. The MVC sequence was conducted in the same order for each participant.

Table 3.5: Description of method used to capture initial data on maximal voluntary contractions (MVC).

Segment	Muscle	MVC Method
Trunk	Trapezius (upper)	Participant seated. Assessor placed both hands on top of the participant’s shoulders. Participant shrugged both shoulders towards his ears and held until asked to relax.
	Erector Spinae (longissimus) at T8	Participant standing with their trunk leaning slightly forward. Assessor placed both hands on top of the participant’s shoulders. Participant asked to extend trunk rearwards, towards an upright standing posture, until asked to relax.
	Erector Spinae (longissimus) at L2/3	Participant standing. Assessor placed one foot behind the foot of one of the participant’s legs. Participant grasped the top of a chair, or placed his hand against a wall for stability, while endeavouring to extend the hip of that lower limb while keeping the knee and whole leg straight. Participant asked to relax once MVC obtained. This was then repeated with the other leg.
Upper Limb	Biceps Brachii	Participant standing. Assessor placed hands on the fists of each of the participant’s supinated hands (arms extended). Participant flexed the elbows until asked to relax.
	Brachioradialis	Participant standing with both hands open and in a pronated position, and elbows at 90 degrees. Assessor placed both hands on the knuckles of the participant to resist their wrist extension movement, until asked to relax.
	Flexor carpi ulnaris	Participant standing with both hands open and in a supinated position, and elbows at 90 degrees. Assessor placed both hands over the participant’s fingers to resist their wrist flexion movement, until asked to relax.
Lower Limb	Vastus Medialis	Participant squatting slightly. Assessor placed both hands on top of the participant’s shoulders. Participant attempted to extend hips and knees to stand up against the assessor’s resistance. Participant maintains this effort until asked to relax. Note, the strength of some participants exceeded the assessor’s resistance capacity. Additional MVC measures were not employed as they may have been hazardous for the participant and assessor.

The method used is shown in Figure 3.5 below.

Erector spinae T8 sensors using back extension

Erector spinae L3/4 sensors using hip extension

Biceps brachii sensors using forearm flexion

Flexor carpi ulnaris sensors using wrist flexion

Figure 3.5: Selected images of an RMIT assessment team member obtaining a participant's MVC values adjacent to a work area.

EMG systems record electrical signals that cause a muscle to contract. These electrical signals are recorded in volts and increase as the contraction (force output) of a muscle increases, and vice versa. These electrical signals can be used to calculate the percentage (relative to a maximal voluntary contraction) of muscle activation during a work task (%MVC). The equations below show how to calculate %MVC:

$$\%\mathrm{MVC} = \frac{\mathrm{V_{work\ task}}}{\mathrm{V_{MVC}}} \times 100\% \qquad (1)$$

Where, $\mathrm{V_{work\ task}}$ is the peak EMG voltage of a muscle recorded during a work task.

$\mathrm{V_{MVC}}$ is the peak EMG voltage of a muscle recorded during a maximal voluntary contraction.

For example, if the recorded $\mathrm{V}_{\mathrm{work\ task}}$ of a muscle was 3 volts during a work task, and the recorded $\mathrm{V}_{\mathrm{MVC}}$ of a muscle during a MVC was 6 volts, the %MVC is given by:

$$\%\mathrm{MVC} = \frac{3}{6} \times 100\% = 50\% \qquad (2)$$

The participant's body dimensions were then entered into the Xsens software program. The participant then adopted one or two of three calibration poses. The first pose was the T-pose where the participant stands upright, feet slightly apart and toes facing forward, both arms raised at the shoulders so they reach out to each side and are observed to be level with their palms of the hands facing downwards to the ground. The second pose was an N-pose. This required the participant to stand upright, looking forward with their feet slightly apart and with their arms and hands beside their body in a relaxed posture. RMIT's assessment team was informed by the Xsens support group that they recommended using the N-pose as the preferred calibration pose.

Once RMIT's research team was provided with the new 4.98 Beta version of the Xsens MVN Studio software program, a third calibration protocol was employed. This involved the participant adopting the N-pose for approximately 4 seconds, walking forward for 7 steps, turning and walking back to the original standing spot, turning and standing on the original standing position, and adopting the N-pose again for a further 4 seconds. The Xsens technical support group advised that the new calibration method was needed to use the new Xsens software platform (Version 4.98).

Once Xsens calibrations were completed, the participant, assessment group and any other project stakeholders moved to the assessment site.

Step 8 – Assessment of work tasks

Two methods of Xsens data capture, using the same technology, were used for assessments of work tasks.

The first involved using the system's wireless capability where a signal was transmitted from the Xsens bodypack to a wireless modem, and then to a notebook computer connected to the modem. This method enabled the participant's avatar, a real-time representation of their image, to be viewed on the computer during an assessment. This method is recommended by Xsens and enables real-time monitoring of data capture, postures and movements used to perform the task. However, approximately midway through the assessments, the connectivity of this setup became unstable and this problem could not be fully resolved via active support from Xsens in the Netherlands.

An alternative data capture method was then used to ensure predictability and surety of data capture. In this method, called 'on body recording' or OBR, the Xsens bodypack was used as a data logging device, rather than a data transmission device. This method was found to provide consistent and stable data capture and was used exclusively for the remainder of the project's assessment schedule.

To assist in developing a solution to this connectivity issue, Xsens provided a new bodypack device. However, as the current device could be used effectively in OBR mode, it was used to complete the assessment phase of the project.

Several site visits did not proceed to participant fitment and task assessment because of a change in the work schedule for that day which was only determined once the RMIT assessment team was onsite and induction had been completed.

Data capture commenced once all equipment was set up at the worksite and the participant and assessment team had confirmed what was to be done. This involved setting up a table for the computer and other equipment, as well as setting up two high speed CASIO cameras (EXLIM, CASIO). The cameras were usually set up on a tripod at oblique or side-on positions to the participant. For some assessments, only a single camera was used.

For most assessments, RMIT's assessment team was able to set up and position themselves very close to the participant while they worked. In other locations, the assessment team had to set up approximately 10-40 metres away as it was considered hazardous for the team to be any closer. In these circumstances, any resulting assessment complexities were overcome by enlisting the assistance of local stakeholders who could be closer to the participant during their work. Hence, they were able to operate a camera or activate the OBR recording mode on the Xsens bodypack.

Once the participant was ready to commence the task, recording on the Xsens, EMG and video systems commenced so these data were collected simultaneously. To provide a synchronisation signal to all three forms of data recording (Xsens, EMG and video), the participant performed three slow shoulder abduction movements. These movements provided a unifying marker on each of the data recording media to enable post assessment data alignment.

During each assessment RMIT's research team monitored the data capture process and observed the participant to check integrity of the sensors and data capture. They also interacted with the participant as required, but not to distract him. The assessment process usually attracted the attention of those working nearby, so while retaining a focus on the assessment and data integrity, a member of RMIT's assessment team would engage with those interested to inform them of the project and the process being undertaken.

Upon completing the work task, a discussion occurred with the participant and any stakeholders involved in the session to confirm that the task performance and data capture period was representative of the work as it would usually be undertaken. This was confirmed for each assessment and participant which then enabled the assessment recording to be stopped, or for the group to proceed to the next part of the task for assessment.

Step 9 – Removal of sensors

After completing a task assessment, the participant, other assessment stakeholders, RMIT's research team and all equipment returned to the set up area, or a suitable alternative if that area was no longer available or occupied by other people.

The Xsens and EMG sensors were then removed, and data capture confirmed, for the assessments conducted via the wireless connection, or the data were downloaded and checked for assessments that used the Xsens body pack as a data logger.

During this period, discussion continued with the participant to obtain their feedback on the assessment, nature of work performed, and their views about whether they regarded the task to be physically demanding or hazardous, and if so, what they considered could be done to eliminate or reduce these demands and hazards.

At the conclusion of most task assessments, the participant was provided with a data stick with a 2-3 minute video displaying the movement of their 'avatar' image recorded during the work task. This was provided for them as a memento of their participation in the project and for them to be able to show others if they wished. For some assessments it was not possible to provide these to a participant because of a combination of factors, such as the participant not having sufficient time to wait to receive it, slow download of data onto the computer, and the priority for RMIT's research team to check and preserve data files that appeared to have been corrupted.

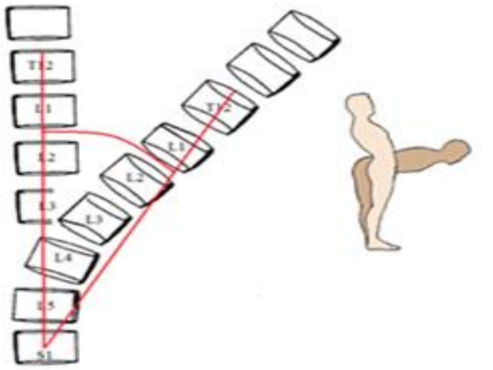
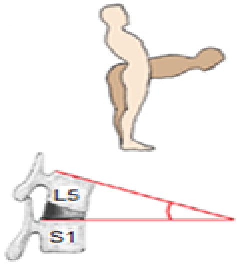
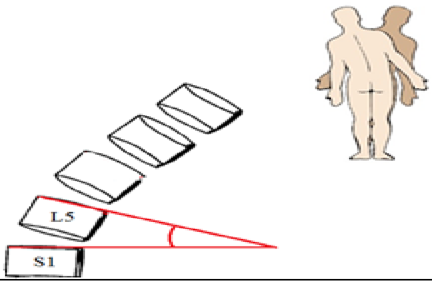
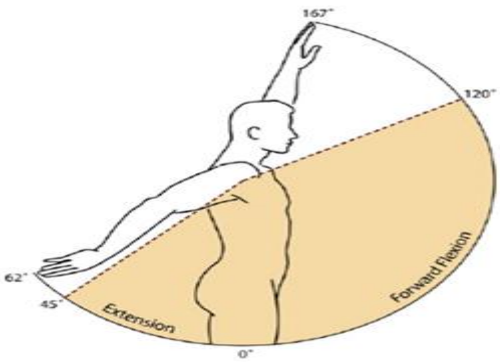
Some participants also requested a member of RMIT's research team take images of the set up of the sensors on their body, using the participants' mobile phones, for them to show others after the assessment.

Data analysis

Some data analyses methods were the same for all tasks (general), and some were task-specific.

3.6.1 Outcome measures

The data extracted focussed on the inherent postures and movements performed by the workers. The data extracted were trunk inclination in the sagittal and frontal planes (that is, trunk forward and lateral flexion relative to the vertical), lumbar flexion (that is, lower back curvature), shoulder motion the sagittal and frontal planes (that is, vertical flexion/extension and abduction/ adduction), and wrist radial/ulnar abduction and flexion/extension (Figure 3.6) is a schematic representation of the measures).

	Illustration
<u>Trunk inclination (T12/S1)</u> Forward flexion (+ve) Backward extension (-ve) <u>Lumbar Flexion (L5/S1)</u> Forward flexion (+ve) Backward extension (-ve) <u>Trunk Lateral Flexion (L5/S1)</u> <u>Right lateral flexion (+ve)</u> <u>Left lateral flexion (-ve)</u>	  
Shoulder joint motion Vertical flexion (+ve) Vertical extension (-ve)	

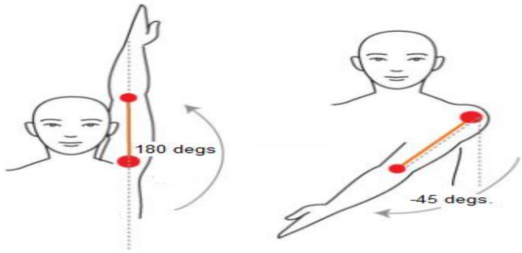
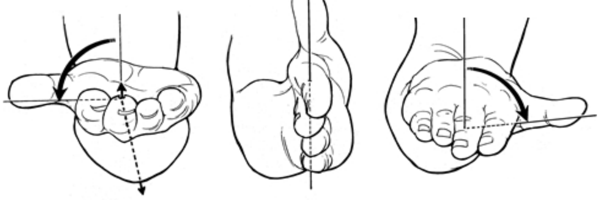
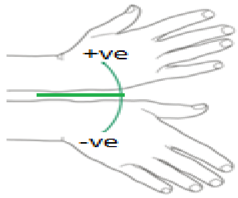
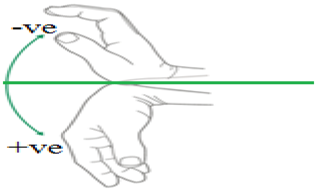
<u>Shoulder joint motion</u> Left panel: Abduction (+ve) Right panel: Adduction (-ve)	
<u>Wrist joint motion</u> Wrist supination (-ve) Wrist pronation (+ve)	
<u>Wrist Joint motion</u> Radial deviation (+ve) Ulnar deviation (-ve)	
<u>Wrist Joint motion</u> Wrist flexion (+ve) Wrist extension (-ve)	

Figure 3.6: Schematic representation of trunk inclination in sagittal and frontal planes (i.e. trunk forward and lateral flexion relative to vertical), lumbar flexion (i.e. lower back curvature), shoulder motion in sagittal (flexion/extension) and frontal planes (abduction/ adduction), and wrist motion in sagittal,frontal and transverse planes (i.e. flexion/extension, radial and ulnar devaition, pronation/supination).

Using the Xsens software, windows of work-related joint angular and task duration data were identified by marking or tagging key events (for example, beginning and end of a work task). Synchronised video recordings were also used to confirm these data were only work-related.

Joint angle and tagged data were exported as Excel files. These files were imported into dedicated software programs developed in Matlab, a high-performance language for technical computing and mathematical analysis (The Maths Works Inc, 2007). These programs were used to extract outcome measures. These measures were: range of movement; peak, mean (during task) and minimum postural joint angles; and task duration. Please refer to Table 3.6 for a detailed list of the outcome measures extracted for each work task.

A novel approach in this project was to categorise work heights for each task. Work height categorisations were based on the height of application of the tool or product (for example, steel fixing tool or shotcreting cement): (1) ground level; (2) ankle-to-ground; (3) ankle-to-knee; (4) knee-to-hip; (5) hip-to-shoulder; and, (6) above-shoulder. Where appropriate to a work task, the outcome measures (Figure 3.6) listed in (Table 3.6) were extracted for each work height.

Table 3.6: Outcome measures extracted for each work task.

Xsens Data	**Work task**				
Measure	**Steel fixing**	**Shotcreting**	**Cable pulling**	**Shovelling**	**Jackhammering**
	Trunk inclination (T12)				
Mean (°)	Yes	Yes	Yes	Yes	Yes
Peak (°)	Yes	Yes	Yes	Yes	Yes
Minimum	Yes	Yes	Yes	Yes	Yes
% task above 40°	Yes	Yes	Yes	Yes	Yes
	L5/S1 flexion				
Peak (°)	Yes	No	Yes	Yes	No
Minimum (°)	Yes	No	Yes	Yes	No
Range (°)	Yes	No	Yes	Yes	No
	L5/S1 lateral flexion				
Peak (°)	Yes	No	Yes	Yes	No
Minimum (°)	Yes	No	Yes	Yes	No
Range (°)	Yes	No	Yes	Yes	No
	Shoulder (abduction/adduction)				
Peak (°)	Yes	No	No	Yes	No
Minimum (°)	Yes	No	No	Yes	No
	Wrist				
	Dominant - R			Non dominant - L	
Flexion/extension					
Peak (°)	Yes	No	No	Yes	No
Minimum (°)	Yes	No	No	Yes	No
Ulnar/rad deviation					
Peak (°)	Yes	No	No	Yes	No
Minimum (°)	Yes	No	No	Yes	No
Rotation					
Peak (°)	Yes	No	No	Yes	No
Minimum (°)	Yes	No	No	Yes	No

3.6.2 Statistical analysis

Statistical analyses of the data were performed using the IBM SPSS statistical software package (Version 23, SPSS Inc., Chicago, Illinois). For steel fixing, repeated measures one-way ANOVAs were used to analyse the effect of the tool and working height. For shovelling, repeated measures one-way ANOVAs were used to analyse the effect of the handle type and type of shovelling task. Interaction effects between the tool and working height factors for steel fixing and between the handle type and type of shovelling task for shovelling were not investigated. An alpha level of 0.05 was employed. Significant differences ($p < 0.05$) were further assessed by post-hoc testing using Bonferroni corrections to reduce the risk of a type I error (i.e. a false positive finding). Descriptive statistics were generated for all outcome measures (mean $\pm$ SD).

Part 4: Steel fixing

4.1 Description of work tasks

4.1.1 Overview of steel fixing work

The current method of steel fixing involves the operator pulling out the end of a reel of wire from a belt located on their left hip so it can reach the sections to be bound together. The right hand bends the end of the wire over to form a hook shape. The wire is then fed around the sections and pulled towards the operator (with their left hand) so the rear part of the hook is attached firmly against the rear of the sections to be joined. The end of the wire is pushed over the top of the length that leads from the reel to commence the process of them being twisted together. A small hand tool (pincer/cutter) is then used to grasp these wires within the cutting head, slightly in front of this twist. The operator then holds the wires and quickly twists the tool one-and-a-half rotations in a clockwise direction with their dominant hand. This creates the required tension to bring and hold the steel sections together. Once this is complete, the operator presses the handles of the tool together to cut both sections of wire to finish the fixing cycle. The cut end of the wire falls to the ground and the operator then grasps the other end to create the hook end and place it around the next sections to be fixed together.

This cycle takes approximately two seconds, provided the operator has sufficient access to reach the sections being connected.

4.1.2 Steel fixing equipment

See Section 4.2.1 below.

4.1.3 Locations and environmental conditions

Data collection was undertaken at two construction worksites. Site 2 involved working in an outdoor environment at a level crossing removal site. Site 4 involved offsite construction within a dedicated facility, under a large roof with open walls at each end.

4.2 General assessment of steel fixing

Initial data gathering for steel fixing was determined by opportunity and access to sites. Site 2 involved field work where the participant (#3) was fixing steel rods onto a frame structure resting on the ground (Figure 4.1). Once the steel framework for that structure, a large structural beam for an adjacent bridge, was complete, a crane would lift it up onto the bridge pylons. In this position, the framework would be surrounded by timber sheets to define its shape. Concrete is then poured into it to complete the onsite fabrication of the bridge section.

Figure 4.1: Site 1 showing steel fixing a bridge beam frame.

At Site 2, the participant carried long steel rods with a coworker and fixed them in horizontal positions, between ground and shoulder levels, against the vertical rods of the frame. We were informed this method of building the steel frame on the ground, and then lifting it into place, was increasingly being used as it limits the need for steel fixers to work at heights on scaffolding and platforms which create falling from height hazards. We were also informed that larger frames may require steel fixers to work inside the frame, or reach forward with awkward postures to reach the less accessible positions to fix sections.

At Site 4, the nature of steel fixing work performed was very different (Figure 4.2). This site used a factory approach. The process of constructing concrete sections for the overhead rail system is undertaken under a large, roof-covered, open air building with open ends for the inflow of raw materials at one end and the outflow of finished sections at the other.

Steel frames are constructed near the start of the process. Vertical sections are initially welded together and then placed in a jig to form the vertical members of the frame. Steel fixers then separately work inside and on top of the frame to insert long bars and fix them at right angles to the frame.

Figure 4.2: Site 2 showing upper section frame steel fixing.

Initial data collection at site 4 found:

1. The need to operate at all reaching heights, from ground to overhead levels.
2. Good horizontal access for the operator to all sections to be fixed.
3. Flat ‘ground’, and regular shaped ground surfaces, for operators to stand on and work.
4. Highly predictable and repeatable work conditions because of the very high number of sections to be constructed, and their similar shape and size.

These four factors combined to allow an opportunity to conduct a comparative assessment of different steel fixing methods.

A review of available steel fixing tools was conducted and two tools not used at either site were identified. Each manufacturer/distributor provided one tool and a sufficient supply of wire or staples for testing at no cost. Each manufacturer/distributor was offered a discrete report that provided a comparison between current manual methods and the method used with their tool.

4.2.1 Assessment of three steel fixing tools

Three tools were assessed. These tools and their characteristics are set out below.

Pincer/cutter

This is a small hand tool with a pincer/cutter head controlled by two handles (Figure 4.3). The handles are ‘gently’ bought together to ‘hold’ the items being manipulated. To cut these items, typically wire, the operator squeezes against the handles more firmly to bring together the two sections of the cutting head. During steel fixing, the operator continuously holds the tool in their dominant hand to manipulate and cut the wires.

Figure 4.3: Pincer/cutter tool.

Power drill style steel fixing tool

This tool looks and operates like a hand-held power drill (see Figure 4.4). The handle and power button are like those on a drill, while the tool's upper body houses a small reel of tying wire. The wire is fed through feeding gears that pull the wire through as required. The end of the tool uses a structure similar to the 'beak of a bird of prey' where the upper, head section has a curled and downward facing end, and the smaller lower section sits directly below. To use this power steel fixing tool, these head sections are placed around two intersecting sections of steel rod (rebar). When the button is activated, the wire is fed through the upper curled head. Its shape causes the wire to follow this curved trajectory until it interacts with the lower part of the head. While holding the button down, this wire performs two of these loops, and at the end the head creates a twisting action to generate the fixing tension required to hold the sections together. To remove the tool, it is rotated slightly upwards so the large upper head end does not catch onto the bar it has just fixed.

Figure 4.4: Power drill style steel fixing tool.

Long-handled fixing tool

This manually operated tool (Figure 4.5) operates like a long-handled stapler tool that has a single curved handle at the upper end, like that of an umbrella. A string of V-shaped staples is loaded into the cartridge and the tool has a V-shaped head end that is placed over the two sections to be fixed. When the head is in place, the operator quickly and assertively pushes down on the tool. When the tool cartridge stops (abruptly) the staple's two ends should have crossed over and joined together. The operator then quickly pulls the tool away to activate the feature that rotates the tool head, and consequently the fixing staple, during this action. Once the tool is pulled away, if the staple has connected properly it simply releases the staple so it is free to be applied to the next component. If the staple does not connect properly, or is not pulled away confidently, the tie may not be completed and the operator must manually free it from the head of the tool.

Figure 4.5: Long-handled stapler tool.

4.3 Risk assessments of the new tools

The two new tools were tested to confirm their suitability for the project, and to conduct a risk assessment. Risk control measures were only required for the power tying tool to ensure both switches were turned to the ‘off’ setting at all times, except when it is actively used. This is necessary to prevent unintentional activation that could wrap and tension wire around an operator’s fingers.

4.4 Research methods

4.4.1 Participant

Pilot testing found one participant was highly skilled and able to quickly adapt to the two new tools. This was validated by his low error rate in that he had a much lower number of missed fixes than the other participant. With this participant’s demonstrable competence, and the time constraints of the project, the assessment was conducted with only this operator (age – 28 years; height – 173 cm; mass – 73 kg).

4.4.2 Description of work task

The assessment required the participant to perform at least 12 consecutive repetitions of the task using the three tools at six predetermined height levels. The heights were: (1) floor or ground level; (2) ankle-to-knee; (3) knee-to-hip; (4) hip-to-shoulder; (5) above-shoulder; and, (6) directly overhead. Hence, in total there were 18 conditions (3 tools x 6 heights).

These six height categories represent the height at which the tool operates, relative to the participant. They do not represent the participant’s hand height. They categories were chosen because they better represent the impact on body posture and movement of each tool and method, independent of the position of the participant’s hands. The most accurate representation of change should be relative to the level at which the work is being performed. This is because the inherent features of these tools affect hand heights and, in turn, back, shoulder and wrist postures.

Operating at each height level was conducted in sequence, starting at ground level and moving up to the next level, finishing with the participant working directly overhead. The assessment sequence was the pincher/cutter tool first, followed by the power tying tool, then the long-handled stapler tool. Note that, on this occasion, the staples of the long-handled stapler tool were not joining adequately, resulting in a high error rate. This had not previously been an issue once the operator had become familiar with this tool. As the number of remaining staples was very limited, and given the participant's previous demonstration of a high level of competent use of this tool, it was decided to remove the staples and conduct all task tests without the staples for the long-handled stapler tool because it is possible to perform the same fixing action without the staples in the cartridge. The participant was observed to use the same method of performing the task during this testing as he had previously demonstrated.

The order of each height level tested was not randomised in the interest of keeping track of each method and level used, and to reduce the risk of an assessment error occurring. When the participant finished the task cycle at one level, he repositioned himself to commence work at the next height level. He identified the bars he would be fixing for that height level before commencing work to minimise the risk of working outside the nominated height zone. This was done to simplify the post assessment marking of each task cycle at the six different levels within the work performed at each height level. The participant reported this was consistent with usual operational practice. These periods between each session of task performance were excluded from the data that was assessed as they did not represent a usual part of tool use for steel fixing activity. Their inclusion would have created a bias in the data.

It should be highlighted that the assessment was conducted within a single steel frame section within the usual production area adjacent to vehicular and foot traffic. Curious observers were welcomed and the process was explained to them to encourage general participation in, and support for, the project. In addition, through previous assessments it had been identified that steel fixers would commonly work at the same level to fix the bar most recently inserted into the frame. Consequently, the method used for the assessment was consistent with the usual method of work and regarded to be representative of the participant's normal work task.

The data were collected in a single assessment session. The assessment of each tool was recorded and saved as a separate file on the data collection computer.

4.5 Data analysis

Two types of back posture and movement data were available for analysis from the Xsens system. These were trunk inclination and lumbar joint motion. Of these data, trunk inclination was found to be most descriptive of the back postures adopted when using each tool within the six height categories used to classify the height range at which each tool was applied to bring the fixed steel bars together.

Joint movement data on the participant's dominant, right upper limb, in particular the shoulder and wrist joints, were reviewed and found to be pertinent. These were also included in this analysis of results.

4.5.1 Trunk inclination

Trunk inclination data (trunk forward flexion and extension in the sagittal plane) were extracted by using the positions of the T12 and S1 vertebrae (Figure 4.6). This level was chosen as the data best matched a visual representation of the participant's trunk movements in this plane. A higher level such as T8 within the back was not used as angles from this level were greater than the apparent angle of the trunk, most likely reflecting greater mobility of the mid thoracic spine.

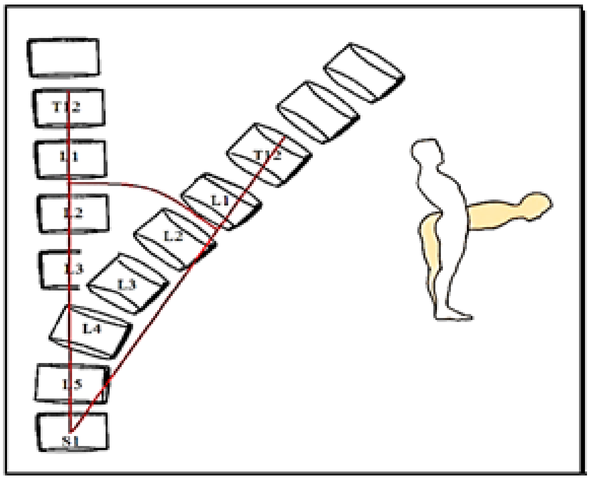
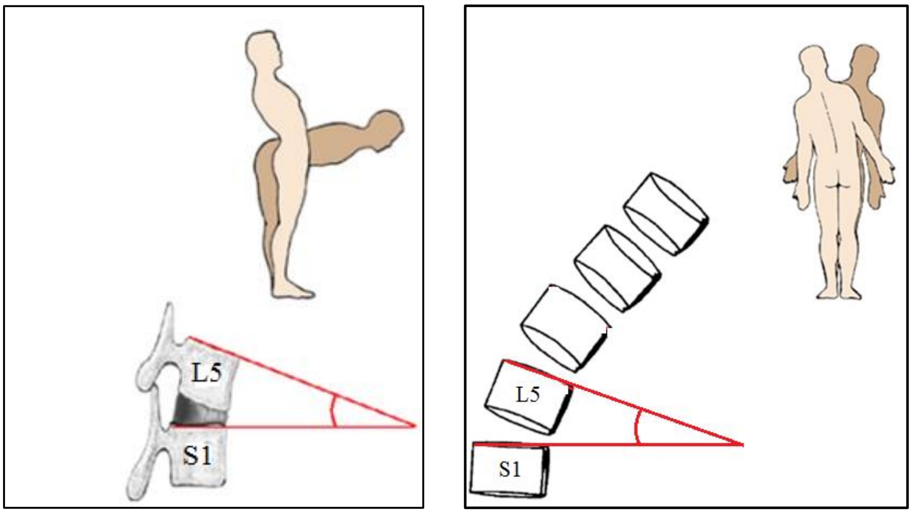


Figure 4.6: Position of T12 and S1 vertebrae during backward extension and forward flexion.

4.5.2 Lumbar flexion

Lumbar flexion data was calculated within the Xsens system at three levels of the lumbar spine (low back), T12/L1, L3/L4 and L5/S1. The range of overall lumber flexion is determined by the relative position of the Xsens shoulder and pelvic sensors. This value is divided by the number of spine represented within these movements and then allocated to the different levels of the lumbar spine according to previously established proportions.



Left panel Right panel

Figure 4.7: Left panel L5/S1 forward and right panel lateral flexion.

These data at all three lumbar levels were reviewed and data at the L5/S1 level only was selected for reporting. This was because the range of movement at this level, relative to the two levels above, was much greater and more likely to represent any changes between different tools and work methods. Also, this level is the base of the spine where high levels of leverage and disc compression can occur and is a commonly referred to location within workplaces.

Lumbar flexion data at the L5/S1 (Figure 4.7) level was analysed and reported for forward and lateral (side to side) flexion. Lumbar forward flexion has positive values while extension uses negative values. For lateral flexion, movements to the person's right side are positive while movements to their left side are shown with negative values.

4.5.3 Shoulder and wrist (right - dominant side)

The participant was right hand dominant. He controlled the movement and action of each tool with this hand, so the right upper limb was chosen to provide information on any shoulder posture or movement changes that occurred across the work tasks.

Analysis of shoulder data is complex and involves intrinsic rotations of the shoulder relative to the trunk in the three planes of motion (sagittal, frontal and transverse) about three axes of rotation (X – anteroposterior, Y – mediolateral, and Z – longitudinal). Respectively, these rotations represent shoulder abduction/adduction, flexion/extension, and internal/external rotation. These rotations are known as Euler angle rotations and determine the sequence or pattern of movement used by the shoulder to move into certain positions. There are six possible sequences of Euler angle rotations and the most appropriate sequences were used to extract the shoulder joint motion in this project. This was required to avoid the problem of gimbal lock.[1]

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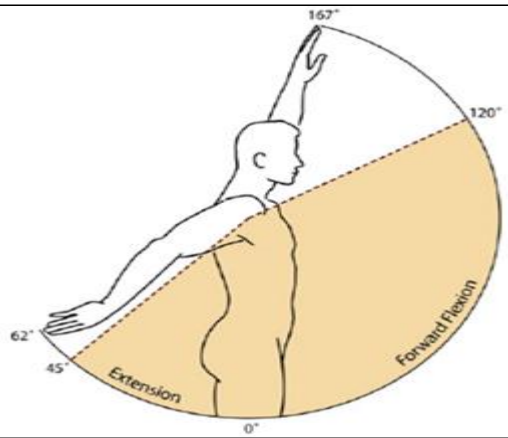
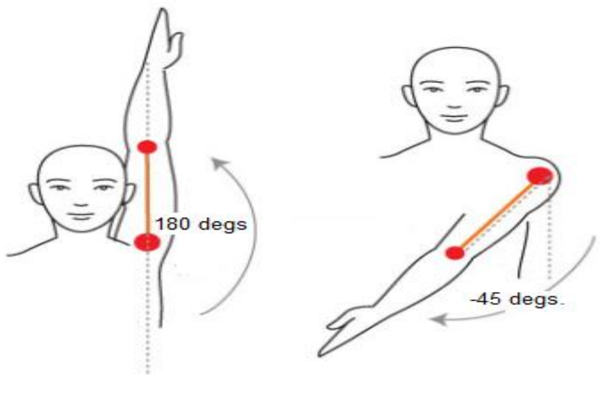
1 Gimbal lock is a problem that occurs in the three-dimensional analysis of a body or segment's motion in space. It refers to the loss of one degree of freedom in a three-dimensional, three-gimbal mechanism that occurs when the axes of two of the three gimbals are driven into a parallel configuration thereby "locking" the system into rotation in a degenerate two-dimensional space. This causes anomalous

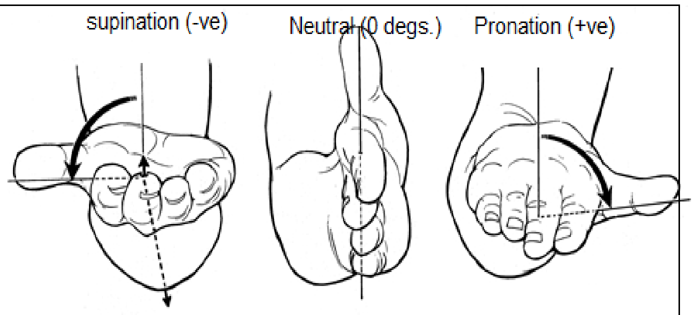
Upon initial analysis of the right shoulder joint motion, ‘avatar’ and video footage, RMIT’s research team decided to use two sequences of rotation (Euler angles) for extracting shoulder abduction/adduction joint motion (rotation in a frontal plane about the X-axis) when the participant’s hand was below and above shoulder height. When reviewing these data, it was determined that the shoulder joint motion of abduction/adduction was the most relevant for this project as it demonstrated the impact of the inherent design of each tool on the participant’s shoulder position. It also avoided gimbal lock problems.

Right wrist data was also reviewed. Data for the three planes of motion – flexion/extension, ulnar/radial deviation and pronation/supination (rotation) – have been described to demonstrate the differences in right wrist/hand postures and movements that resulted when using each tool (Figure 4.8 and Table 4.1).

Data (degrees)	**Illustration**
Shoulder joint motion Vertical flexion (+ve) Vertical extension (-ve)	
<u>Shoulder joint motion</u> Left panel: Abduction (+ve) Right panel: Adduction (-ve)	

measures of joint angular motion that do not reflect true motion. This phenomenon can be avoided by selecting appropriate Euler angle sequences for particular joints of the body.

<table>
<tr>
<td><u>Wrist joint motion</u>

Wrist supination (-ve)
Wrist pronation (+ve)</td>
<td>
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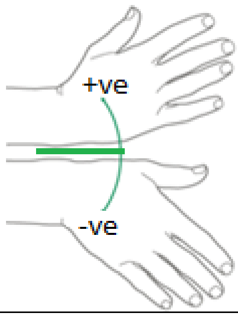
<tr>
<td><u>Wrist Joint motion</u>

Radial deviation (+ve)
Ulnar deviation (-ve)</td>
<td>
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<tr>
<td><u>Wrist Joint motion</u>

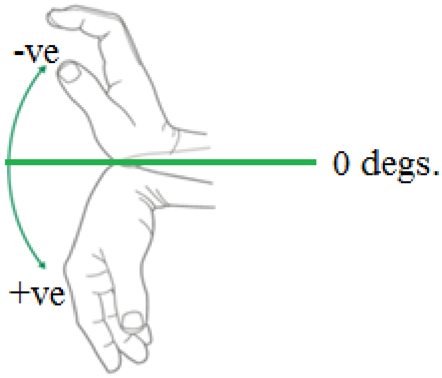
Wrist flexion (+ve)
Wrist extension (-ve)</td>
<td>
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Figure 4.8: Schematic representation of shoulder joint motion in frontal plane (i.e. abduction/ adduction) and wrist motion in sagittal, frontal and transverse planes (i.e. flexion/ extension, radial/ulnar deviation, internal/external rotation). Joint angular convention listed in left panels.

4.5.4 EMG – muscle activity

EMG data for steel fixing was reviewed. The focus was to understand any differences or similarities in hand/wrist movements when using the different tools.

Given the Xsens data for postures and movements demonstrated a high level of difference for trunk inclination and right shoulder posture when using the different tools at ground level, particularly for the long-handled stapler tool, this operating height was selected to investigate the impact of tool design on muscle activation. Working at ground level was also reported and observed to be very common within the construction industry, so this height was regarded to be broadly representative.

The EMG data for both upper limbs were also examined to investigate muscle activation when the participant worked at ground level with the three tools. Unfortunately, when reviewing the EMG data for steel fixing, it was discovered that the sensor for the right brachioradialis, that controls wrist and finger extension, had failed and did not transmit any data.

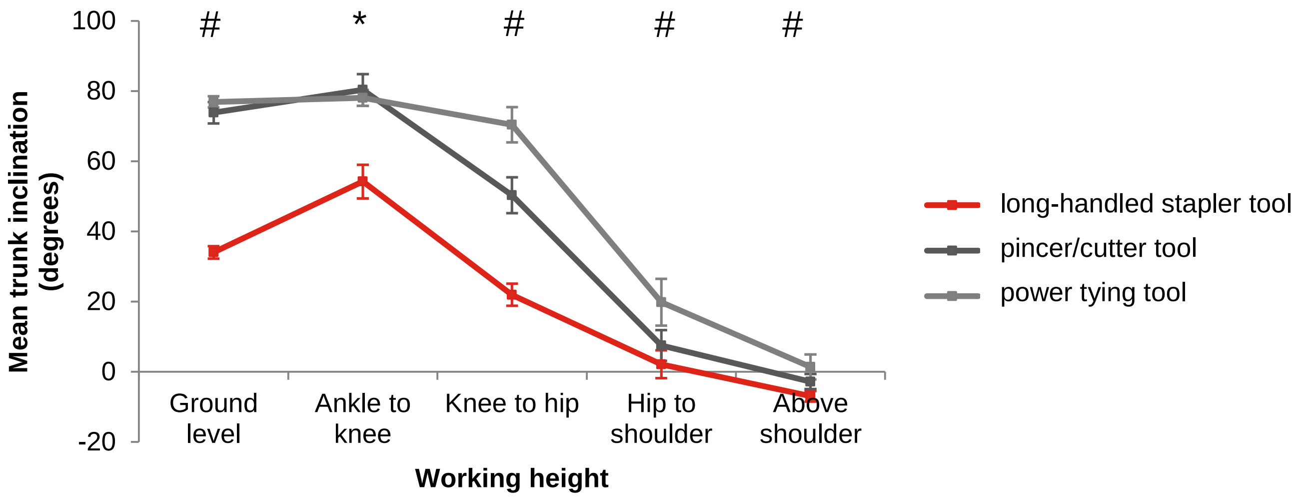
4.6 Steelfixing results

4.6.1 Trunk inclination

4.6.1.1 Mean forward trunk inclination

This measure is for the trunk inclination was sustained during the work task.

At all working heights, the long-handled stapler tool had significantly lower mean (average) trunk forward flexion than the manual pincer/cutter tool and the power tying tool (Figure 4.9). At all working heights, except ankle-to-knee, the power tying tool produced significantly higher mean trunk forward flexion than the manual tool.

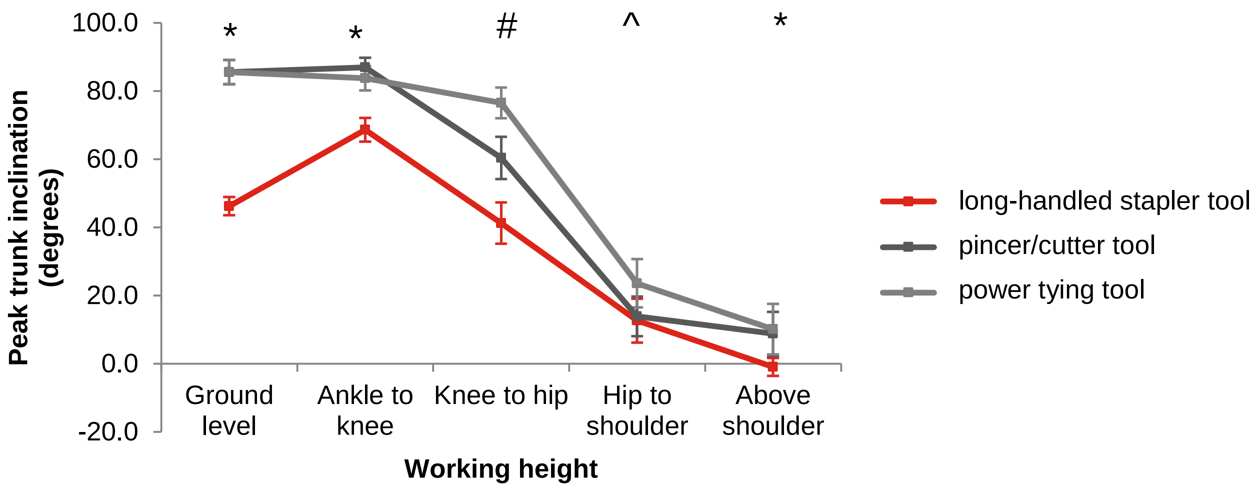


*Long-handled stapler tool significantly different to manual and power tying tool ($p < 0.05$).
All three tools significantly different to each other ($p < 0.05$).

Figure 4.9: Mean trunk inclination (Mean ± SD) at different working heights for each tool.

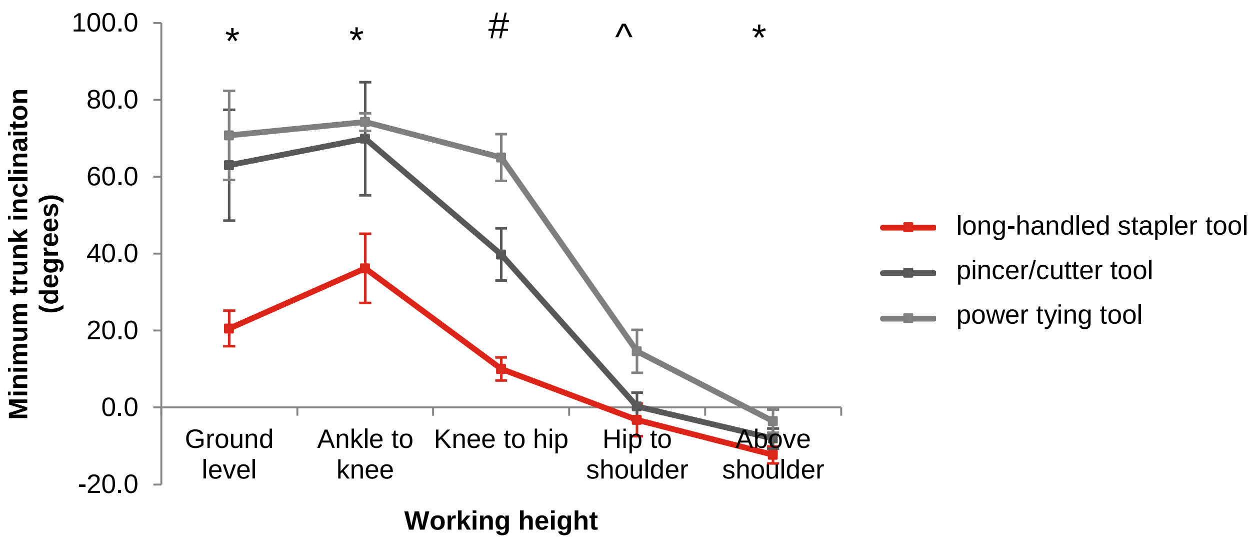
4.6.1.2 Peak and minimum trunk inclination

The long-handled stapler tool generally led to lower peak trunk inclination compared to the other tools (Figure 4.10 and Figure 4.11). This difference was greatest at ground level. At hip-to-shoulder height, the long-handled stapler tool was significantly lower than the power tying tool. A similar pattern was observed for minimum trunk inclination.



*Long-handled stapler tool significantly different to pincer/cutter and power tying tool ($p < 0.05$).
All three tools significantly different to each other ($p < 0.05$).
^ Power tying tool significantly different to pincer/cutter and long-handled stapler tool ($p < 0.05$).

Figure 4.10: Peak trunk inclination (Mean ± SD) at different working heights for each tool.



*Long-handled stapler tool significantly different to pincer/cutter and power tying tool ($p < 0.05$).
All three tools significantly different to each other ($p < 0.05$).
^Power tying tool significantly different to pincer/cutter and long-handled stapler tool ($p < 0.05$).

Figure 4.11: Minimum trunk inclination (Mean ± SD) at different working heights for each tool.

4.6.1.3 Per cent time duration above 40° trunk inclination

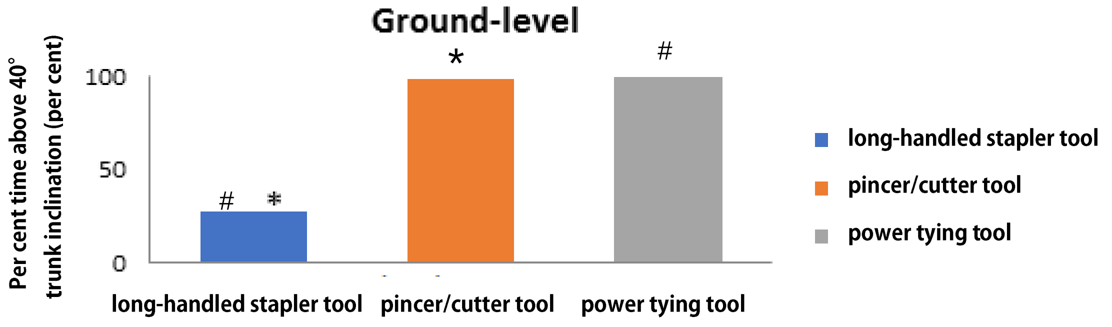
Another way of considering the impact of each tool on the participant's back posture and movements is what proportion of work cycle time was spent within postural categories.

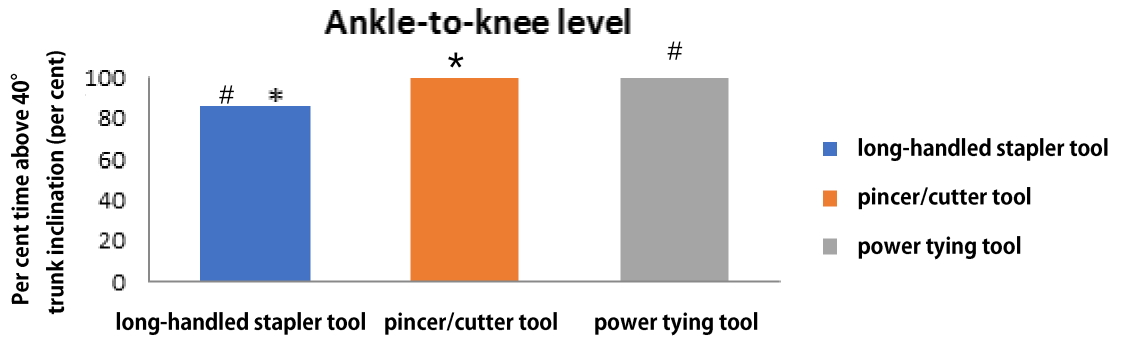
WorkSafe Victoria's *Manual Handling Code of Practice* (WorkSafe Victoria, 2000, p. 17) indicates trunk postures and movements greater than 20 degrees present a higher risk to workers than lower postures and movements. However, considering trunk inclination data above or below this value as being hazardous or safe is simplistic and provides little sensitivity regarding postures and movements greater than 20 degrees.

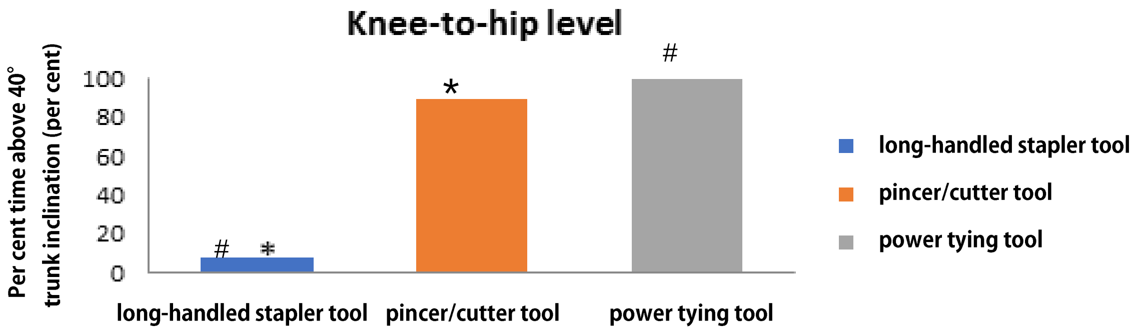
Considering trunk inclination in categories greater than 20 degrees can provide a more descriptive understanding of the nature of the task. This type of analysis is now possible with movement sensing technologies (for example, Xsens system). It provides a new way of investigating work exposures to awkward or hazardous postures and movements, typically observed in below-hip level steel fixing tasks.

A threshold value of 40 degrees was selected due to reports and observations that below-hip level steel fixing tasks typically exceed this value. An investigation of the proportion of work cycle time spent in the higher range of trunk movement (that is, above 40 degrees) provides critical insight into the inherent requirement of the task. The figures below show the percent of time spent in a trunk inclination posture of more than 40 degrees.

At ground, ankle-to-knee and knee-to-hip levels, use of the long-handled stapler tool resulted in a significantly lower proportion of time ($p < 0.05$) spent in trunk inclination above 40 degrees compared to the other tools (see Figure 4.12). No time was spent in trunk inclination above 40 degrees for the other operational heights for any of the tools.







*#Long-handled stapler tool significantly different to manual and power tying tool (p < 0.05).

Figure 4.12: Mean per cent of task time spent above 40° trunk inclination at ground, ankle-to-knee and knee-to-hip level heights.

These results show significantly less percentage of the work cycle spent above 40 degrees of trunk inclination when using the long-handled stapler tool. However, the difference between the tools was less at ankle-to-knee height, although still statistically significant. This was due to the need for the participant to place and hold the long-handled stapler tool at a right angle to the bars being fixed together, and the design of all tools tested had the least impact on reducing trunk inclination at this level.

Results for the manual tool and the power tying tool for ground and ankle-to-knee levels show the participant spent 100% of their work cycle time in a forward inclined trunk posture above 40 degrees. This level of movement was repeated for the power tying tool at knee-to-hip level but reduced to approximately 90% of work cycle time for the manual pincer/cutter tool. These very high proportions of the work cycle spent with the trunk above 40 degrees provide an unambiguous contrast to the much lower levels of trunk inclination found with the long-handled stapler tool.

4.6.1.4 Summary of trunk inclination findings

The long-handled stapler tool involved less trunk inclination or forward flexion at all work heights compared to the other tools (Figure 4.13 to Figure 4.15).

When operating at ground (Figure 4.14), and knee to hip levels (Figure 4.14), using the pincer/cutter tool and power tying tool required the participant to adopt an awkward and sustained forward flexion of the trunk that was more than 40 degrees for all or most of the work cycle time. This duration was considerably less when using the long-handled stapler tool at this level. This result was anticipated and is consistent with the likely design intention of a tool that uses a long and adjustable handle).

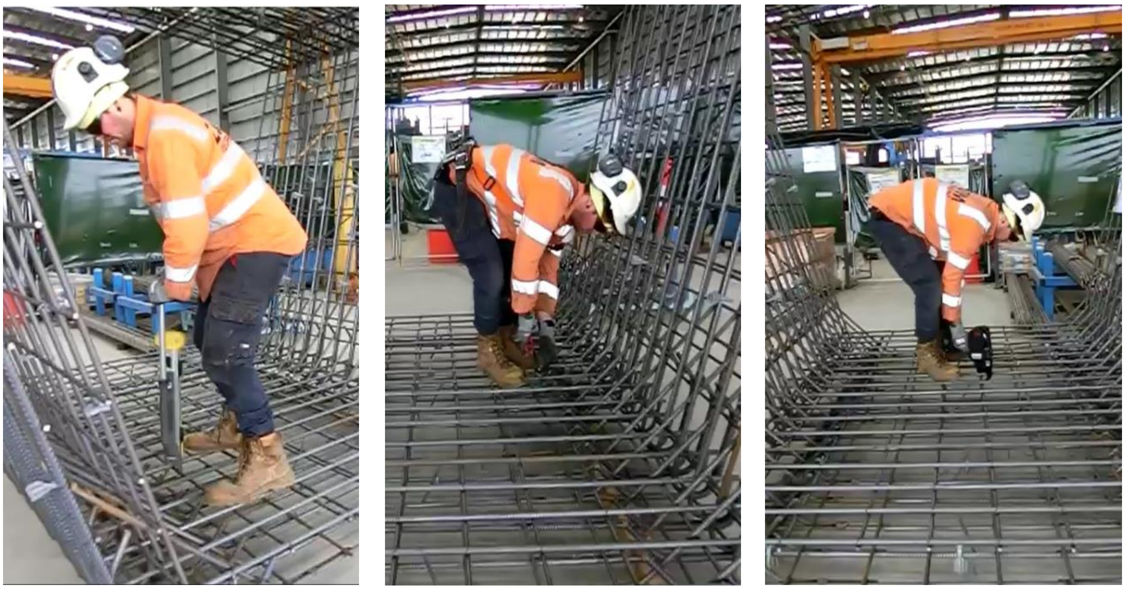


Figure 4.13: Use of the three tools at ground level.

However, when using the long-handled stapler tool between ankle and knee level, where the steel bars were at an approximate angle of 80 degrees (above horizontal), the requirement to apply the tool at a 90 degree angle to the steel bars required the participant to use a higher level of trunk inclination. The level of increased trunk inclination for the other two tools at this level was slightly greater than the preceding level, and still much higher (approximately 30%) than the mean trunk inclination for using the long-handled stapler tool.

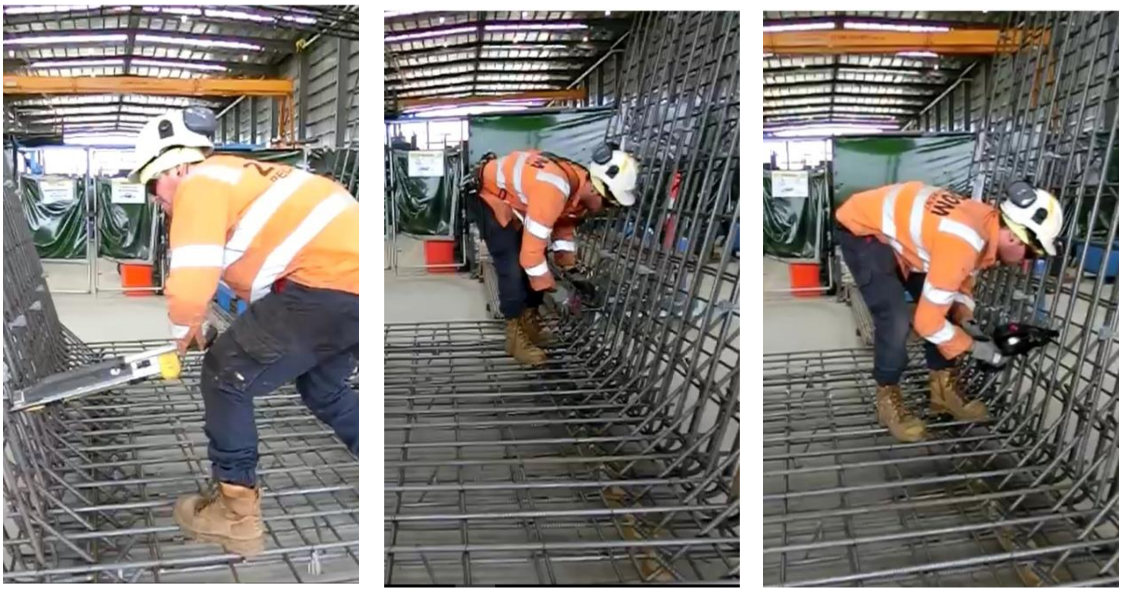


Figure 4.14: Use of the three tools at ankle to knee-level.

When the participant was working above hip height, his level of trunk forward flexion was lowest for all three tools, although the long-handled stapler tool was lowest and the power tying tool required the highest range of trunk inclination.

Figure 4.15: Use of the three tools at hip-to-shoulder level.

In summary, the long-handled stapler tool significantly reduced forward trunk flexion at all working height levels compared to the other tools. When working at ground level, the power tying tool exhibited the greatest forward trunk flexion. At the ankle-to-knee working height, the forward trunk flexion exhibited with the pincer/cutter and power tying tools were similar.

For the three work height categories above the knee (knee-to-hip, hip-to-shoulder, above-shoulder), the power tying tool exhibited the greatest trunk inclination or forward flexion, followed by the currently used pincer/cutter tool and then the long-handled stapler tool.

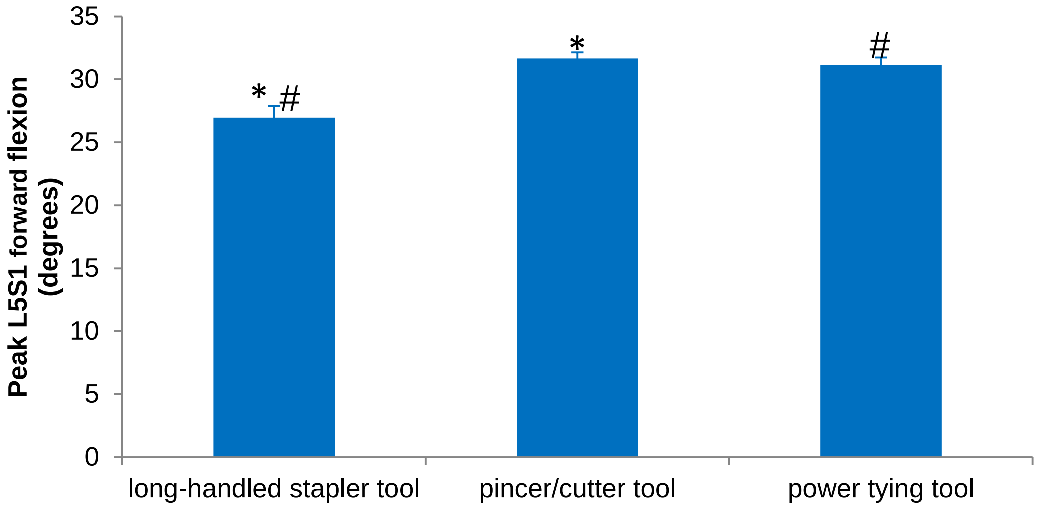
To reduce or minimise trunk inclination or forward trunk flexion, the results show the long-handled stapler tool is preferable, followed by the current manual methods of the pincer/cutter tool and then the power tying tool. However, analysis of the postures, movements and muscle activation of the right shoulder and wrist (Section 4.7) provides additional important information about using these tools during steel fixing tasks.

4.6.2 Lumbar forward flexion (L5/S1)

Lumbar (L5/S1) forward flexion were analysed for work at floor level and below only. This work height was chosen because the greatest differences in trunk inclination postures and movements were found between the work methods (the long-handled stapler tool and the other two tools). It was also chosen because the long-handled stapler tool was developed specifically for this work height.

4.6.2.1 Peak lumbar forward flexion

The mean peak forward lumbar flexion of the L5/S1 joint for the long-handled stapler tool (Figure 4.16) was significantly less ($p < 0.05$) than the pincer/cutter and power tying tools. The mean peak forward lumbar flexion for the long-handled stapler tool was approximately 4 degrees less than the other tools (long handle: 26.7°; pincer/cutter: 31.7°; power: 31.2°).



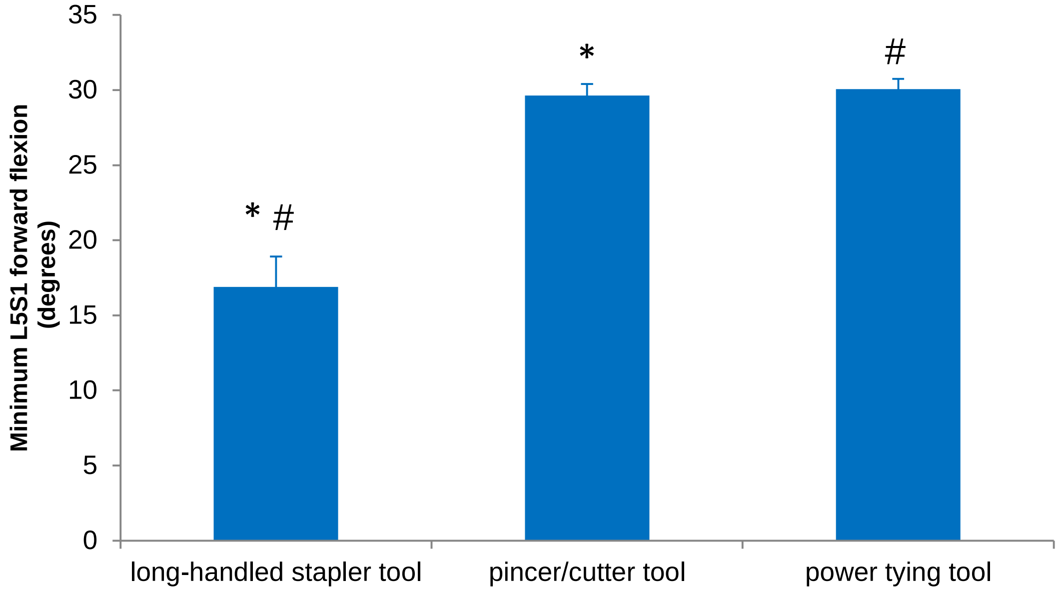
*# p < 0.05 between tools

Figure 4.16: Peak lumbar forward flexion (L5/S1) for different tools.

4.6.2.2 Minimum lumbar forward flexion

The mean minimum forward flexion of the L5/S1 joint for the long-handled stapler tool (Figure 4.17) was significantly less ($p < 0.05$) for the long-handled stapler tool compared to the other tools.

The mean minimum forward lumbar flexion for long-handled stapler tool was approximately 13 degrees less than the other tools (long handle16.8°; pincer/cutter: 29.7°; power: 30.1°).

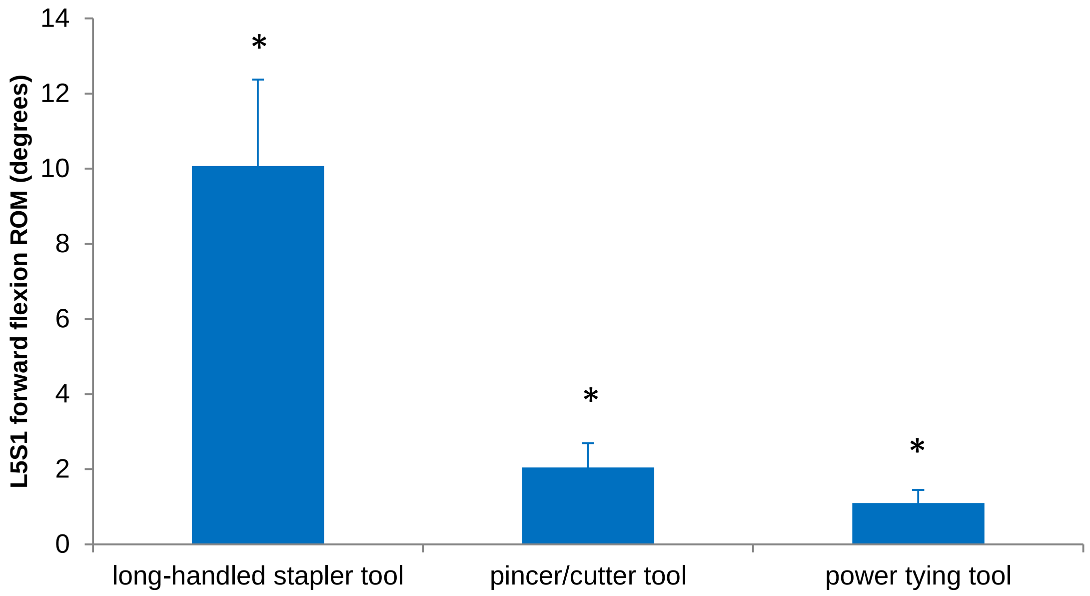


*# $p < 0.05$ between tools

Figure 4.17: Minimum lumbar forward flexion (L5/S1) for different tools.

4.6.2.3 Lumbar forward flexion range of movement

The mean range of lumbar (L5/S1) forward flexion was significantly different ($p < 0.05$) across the tools (Figure 4.18), with the long-handled stapler tool having the greatest mean range of motion (10.1°) and the power tying tool the least (1.1°).



*p < 0.05 between tools

Figure 4.18: Mean range of lumbar forward flexion (L5/S1) for different tools.

4.6.2.4 Summary of lumbar forward flexion results

L5/S1 flexion when using the long-handled stapler tool ranged from a mean minimum of 17° to a mean peak value of 27°. This indicated active lumbar movement to use this tool. Given that the tool handle had been adjusted to its maximum length, it is likely that a longer range of handle adjustment would be required to not only accommodate this participant, but taller operators.

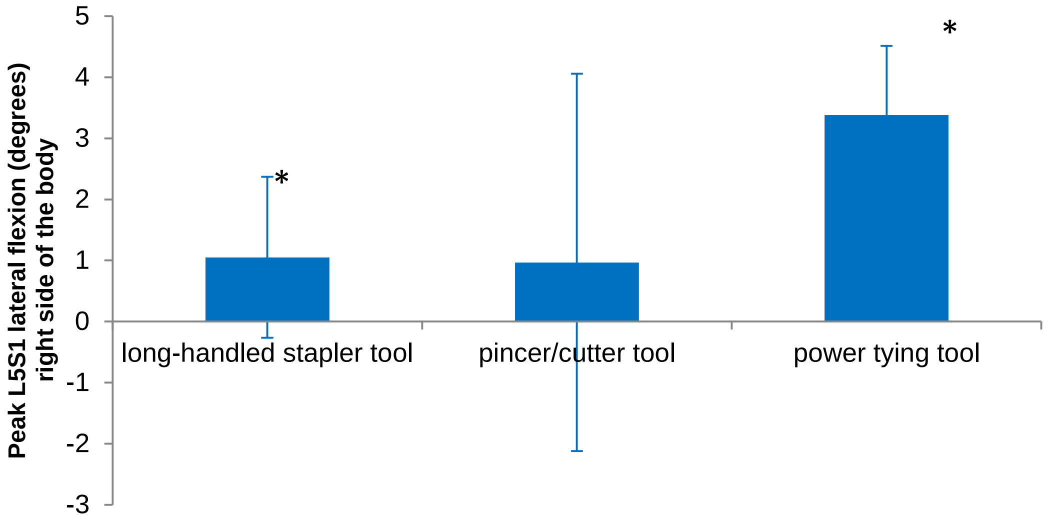
For the pincer/cutter and power tying tools the ranges or L5/S1 flexion from mean minimum to peak fell around 1 and 2 degrees respectively. This shows that, once the participant had moved to his operating position to reach down and operate each tool at floor level, he maintained this posture for all repetitions of the task.

4.6.3 Lumbar lateral flexion (L5/S1)

Lumbar (L5/S1) lateral flexion was analysed for work at floor level and below only. Again, this work height was chosen because the greatest differences in trunk inclination postures and movements were found between the work methods (the long-handled stapler tool and the other two tools). It was also chosen because the long-handled stapler tool was developed specifically for this work height.

4.6.3.1 Lumbar lateral flexion to the right side

Mean peak lateral flexion of the L5/S1 joint to the right side of the body for the power tying tool (Figure 4.19) was significantly greater ($p < 0.05$) than the long-handled stapler tool. The mean value for the power tying tool was 3.4 degrees and 1.1 degrees for the long-handled stapler tool. The difference between the power tying and pincer/cutter tools was not statistically significant.

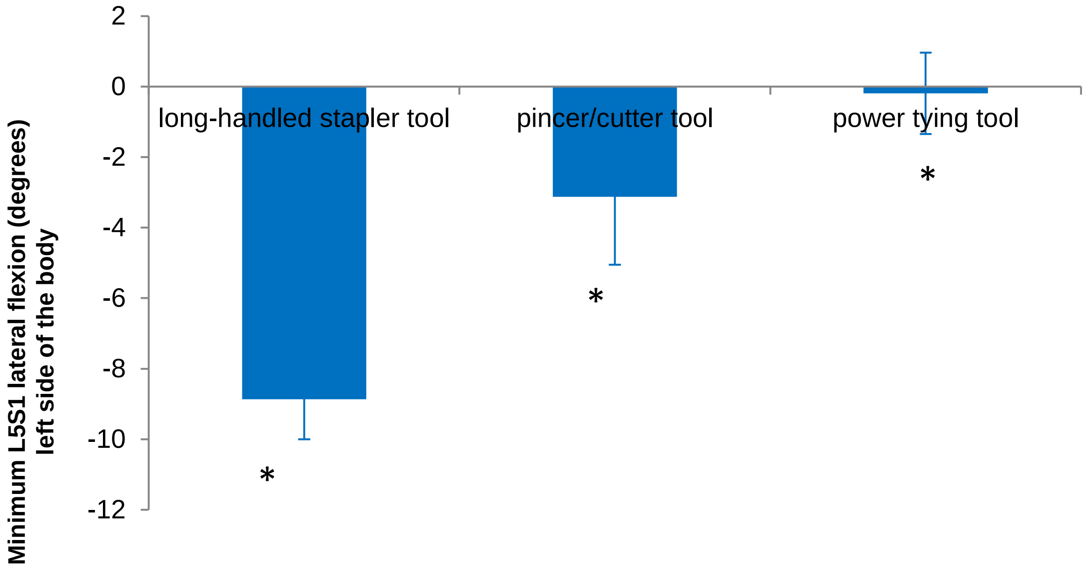


*p < 0.05 between tools

Figure 4.19: Lumbar lateral flexion (L5/S1) to the right side of the body for different tools.

4.6.3.2 Lumbar lateral flexion (to the left side)

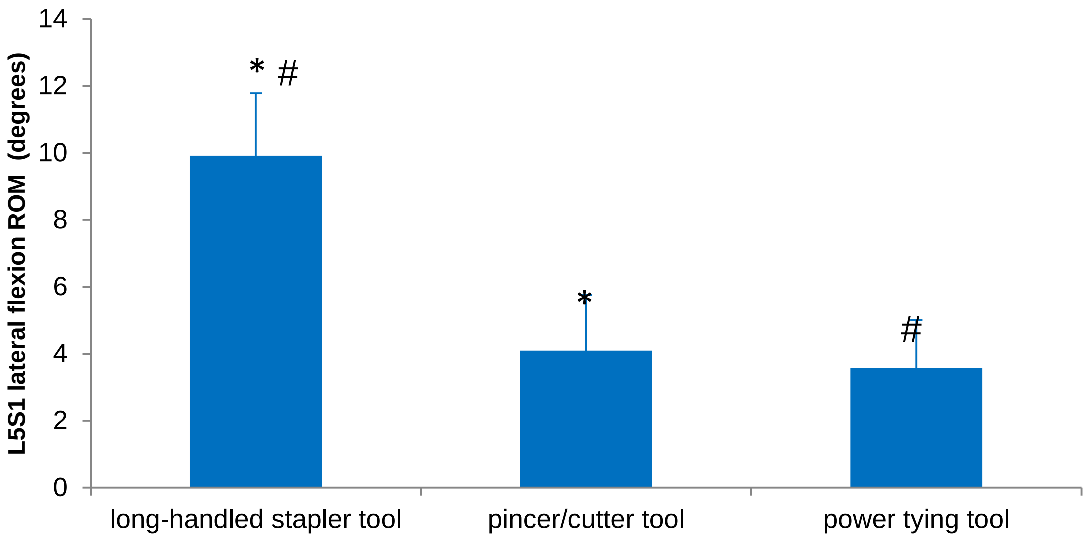
Peak lateral flexion of the L5/S1 joint to the left side of the body, was significantly greater ($p < 0.05$) for the long-handled stapler tool (8.9 degrees) compared to the pincer/cutter tool (3.1 degrees) and the power tying tool (0.2 degree).Please refer to Figure 4.20.



*   between tools

Figure 4.20: lateral lumbar flexion (L5/S1) to the left side of the body for different tools.

The average range of lumbar lateral flexion (right to left) was significantly greater ($p < 0.05$) when using the long-handled stapler tool (9.9 degrees) compared to the other two tools (≈ 3.9 degrees). Please refer to Figure 4.21.



*#p < 0.05 between tools

Figure 4.21: Range of lumbar lateral flexion (L5/S1) for different tools.

4.6.3.4 Summary of lumbar lateral flexion results

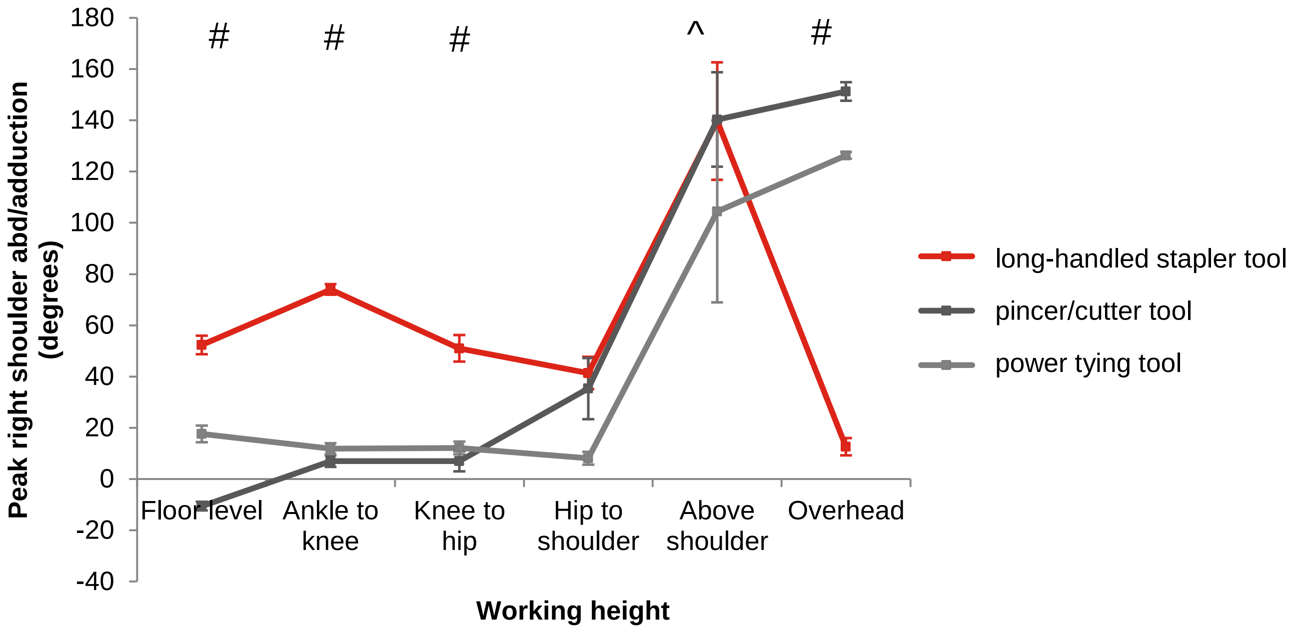
The results for the lateral lumbar flexion are similar to those for forward lumbar flexion at the L5/S1 joint where the use of the long-handled stapler tool exhibited a greater range of side-to-side movement, with most of this movement occurring to the participant's left side, even though he used the tool with both hands. The pincer/cutter tool results in minimal lateral L5/S1 movement on either side of the midline of the participant's body. The power tying tool also resulted in a similar, low range of side-to-side L5/S1 movement with most of this movement being on the participant's right side.

4.6.4 Shoulder movement (right)

4.6.4.1 Abduction – mean peak and minimum movements

The figures below (Figure 4.22 and Figure 4.23) show peak and minimum shoulder adduction/abduction data for the steel fixing tool at the different work heights. These shoulder abduction/adduction results for each tool demonstrate a very low level of right shoulder movement for the participant when using the power tying tool. This was consistent at all height categories below shoulder height, and shoulder abduction increased for the above-shoulder (Figure 4.24) and overhead (Figure 4.25) categories for this tool.

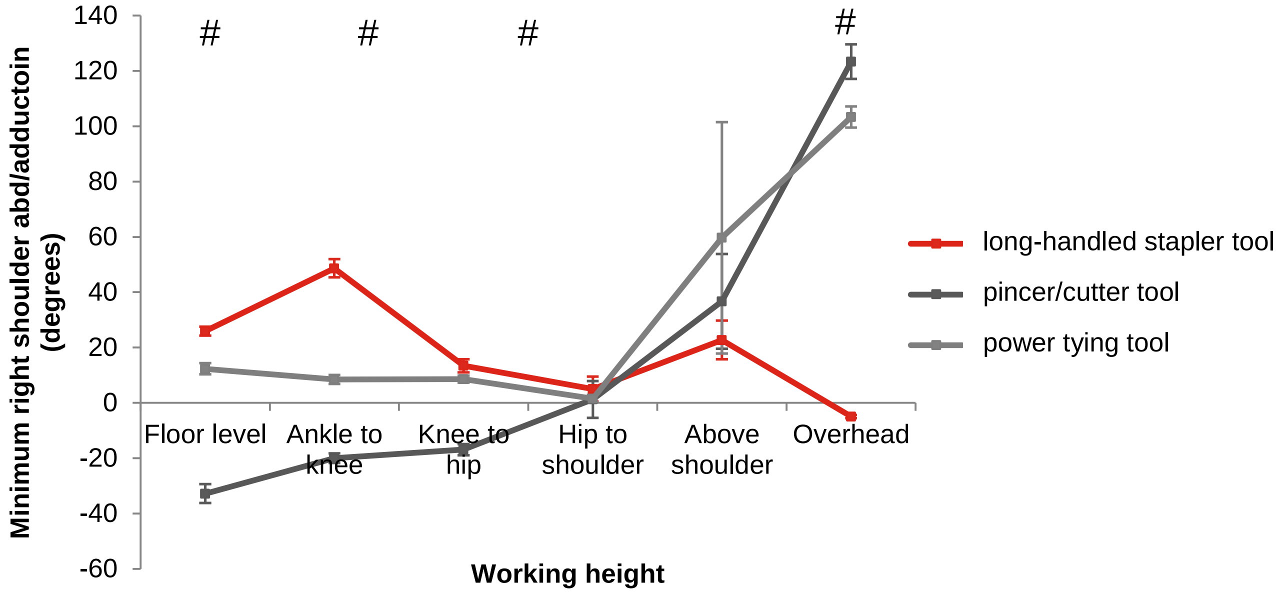
Peak right shoulder abduction



#All three tools significantly different to each other ($p < 0.05$).
^Power tying tool significantly different to pincer/cutter and long-handled stapler tool.

Figure 4.22: Peak right shoulder abduction/adduction (Mean ± SD) at each working height. Note that a positive value represents abduction whereas a negative value represents adduction.

Minimum right shoulder abduction



#All three tools significantly different to each other ($p < 0.05$).

Figure 4.23: Minimum right shoulder abduction/adduction (Mean ± SD) at each working height. Note that a positive value represents abduction whereas a negative value represents adduction.

When using the pincer/cutter tool, the participant's right hand moved to the midline or across the body to secure, twist and cut the wire. Shoulder abduction increased when working above the shoulder and overhead.

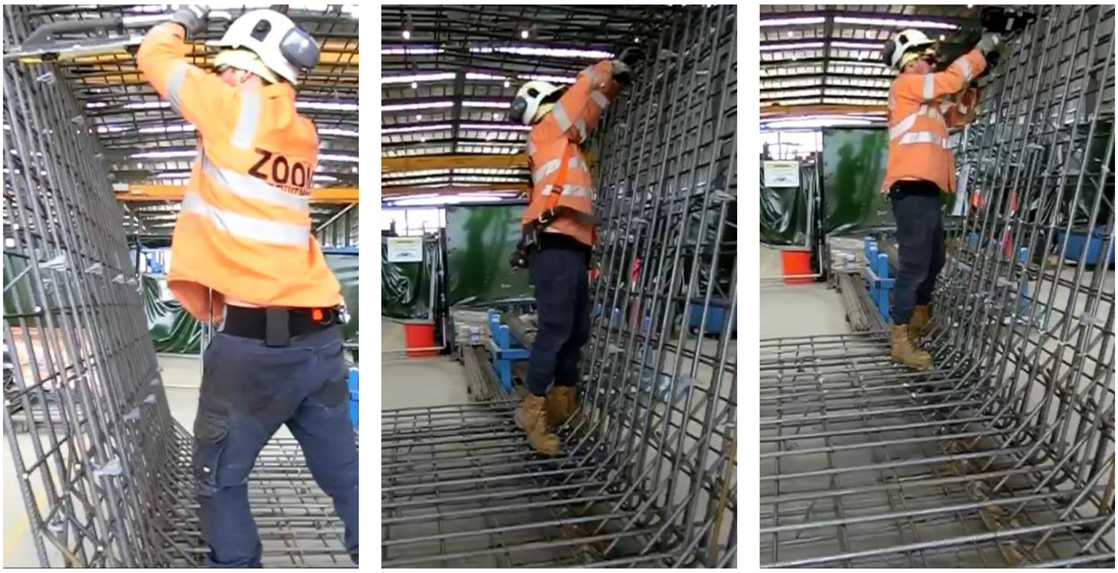


Figure 4.24: Use of the three tools above shoulder level.

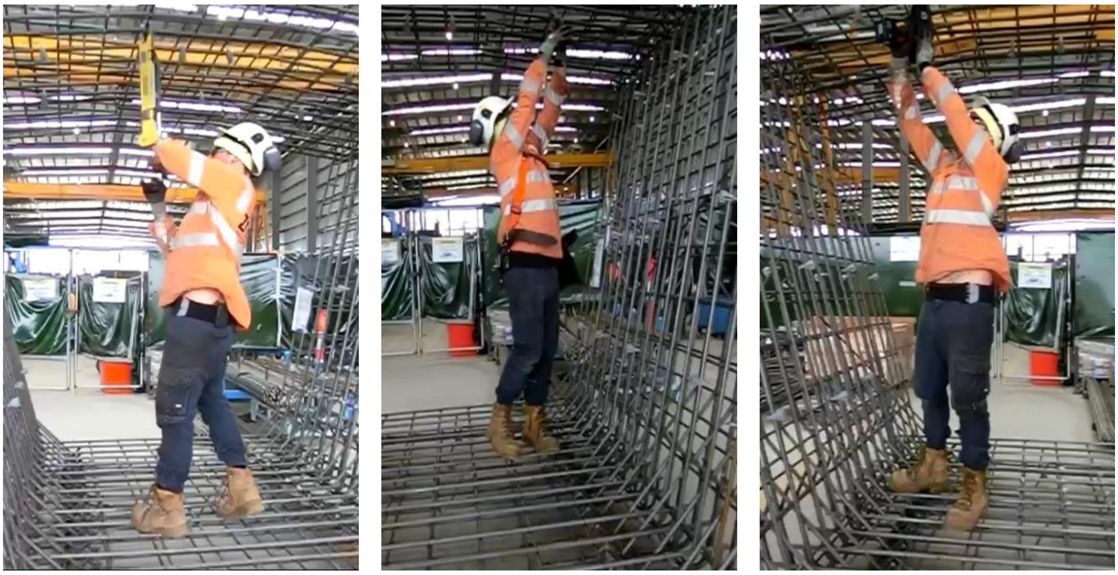


Figure 4.25: Use of three tools when working overhead.

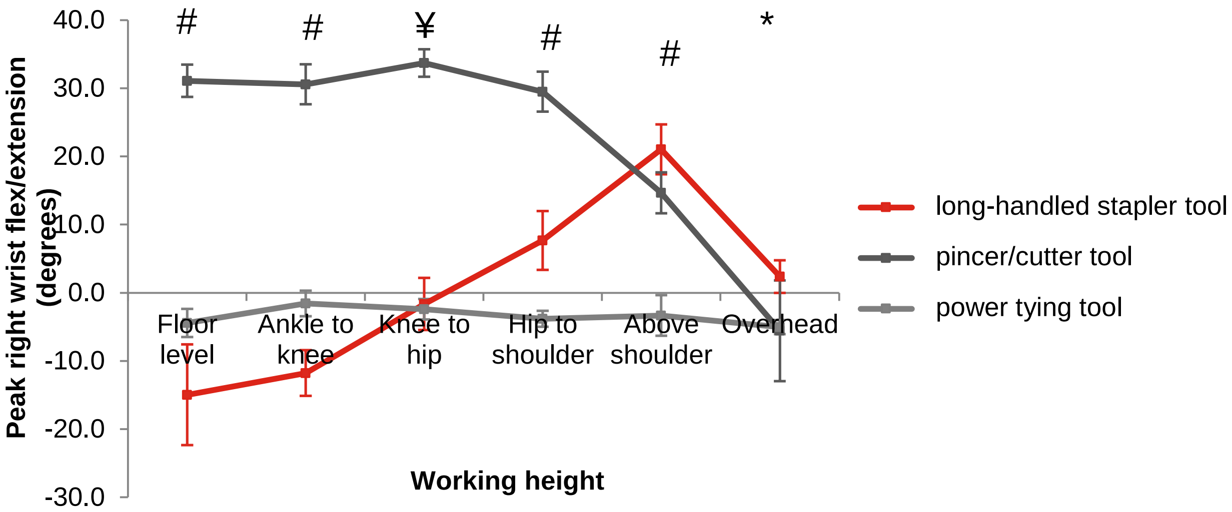
Using the long-handled stapler tool resulted in the highest level of shoulder abduction for work heights below the hip. For example, the average peak shoulder abduction at ankle-to-knee height was about 60 degrees greater when using the long-handled stapler tool compared to the other tools. When above-shoulder level, the average peak shoulder abduction for the long-handled stapler and pincer/cutter tools were similar and fell around about 140 degrees. The benefit of the long-handled stapler tool was best demonstrated at the overhead level where peak shoulder abduction was approximately 130 degrees ($p < 0.05$) less than the other tools.

4.6.5 Wrist movement (right)

4.6.5.1 Flexion and extension – mean peak and minimum movements

Peak right wrist flexion/extension

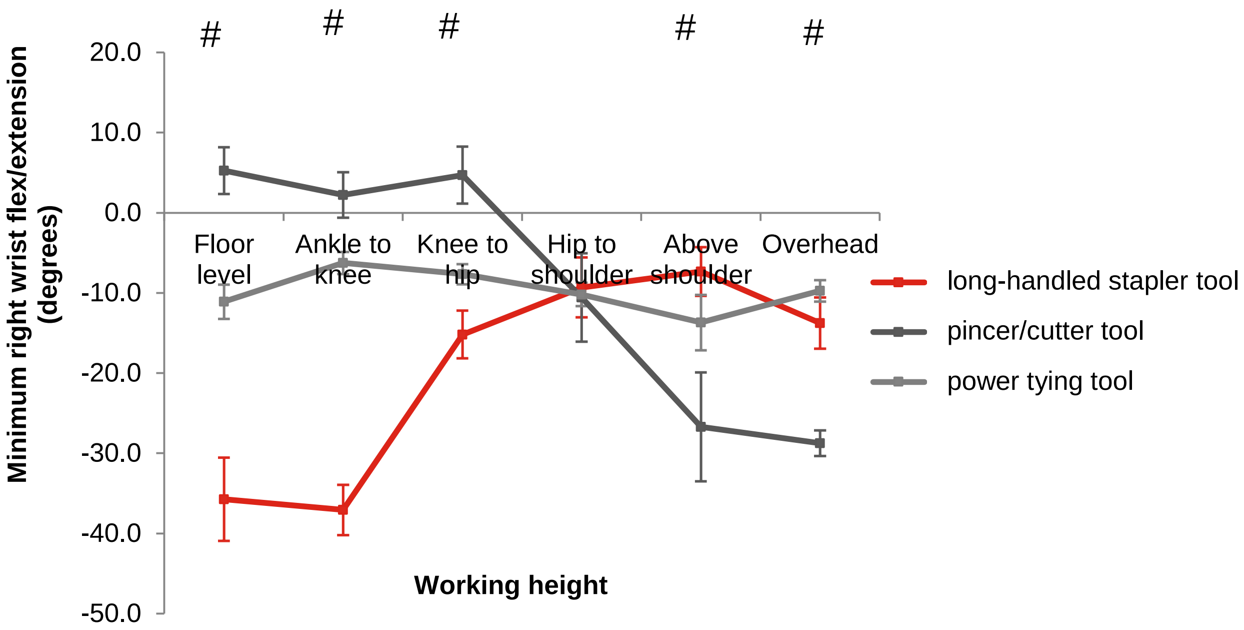
The pincer/cutter tool exhibited the greatest wrist flexion ($p < 0.05$, Figure 4.26) from floor-level to the hip-to-shoulder level. Above the shoulder the long-handled stapler tool exhibited the greatest wrist flexion ($p < 0.05$). Wrist flexion for the power tying tool remained in approximately 4 degrees of extension across the work heights (Figure 4.26).



*Long-handled stapler tool significantly different to the pincer/cutter and power tying tools.
#All three tools significantly different to each other.
^Power tying tool significantly different to the pincer/cutter and long-handled stapler tools.
¥Pincer/cutter tool significantly different to the long-handled stapler and power tying tools.

Figure 4.26: Peak right wrist flexion values (Mean ± SD) at different working heights using different tools. Note that a positive value represents flexion whereas a negative value represents extension. Minimum right wrist flexion/extension.

The results show wrist extension was greatest for the long-handled stapler tool from floor-level to the knee-to-hip level ($p < 0.05$). At the hip-to-shoulder level the minimum wrist motion was about 10 degrees of wrist extension across the three tools. The power tying tool exhibited the greatest wrist extension above the shoulder ($p < 0.05$) (Figure 4.27).



#All three tools significantly different to each other.

Figure 4.27: Minimum right wrist flex/extension values (Mean ± SD) at different working heights using different tools. Note that a positive value represents flexion whereas a negative value represents extension.

The power tying tool resulted in the lowest range of right wrist flexion/extension movement, demonstrating the intended design feature of the pistol grip used with the power tying tool. Wrist flexion/extension for the long-handled stapler tool ranged around 20 degrees (plus or minus 7 degrees). The pincer cutter tool had the highest range of wrist flexion/extension at all levels, demonstrating the dynamic action needed to use this tool by manually rotating and twisting the wire to create the required tension (Figure 4.28).

Range of right wrist flexion/extension

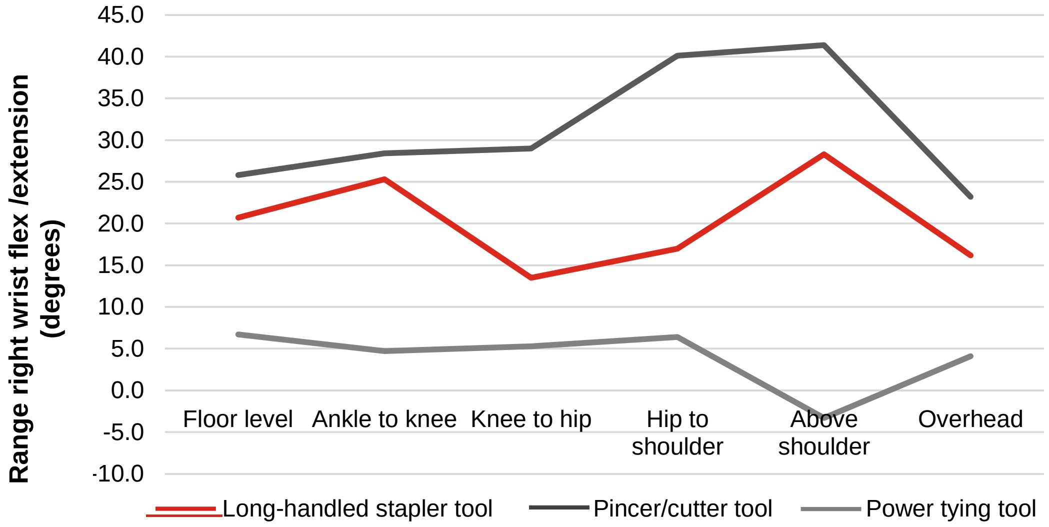
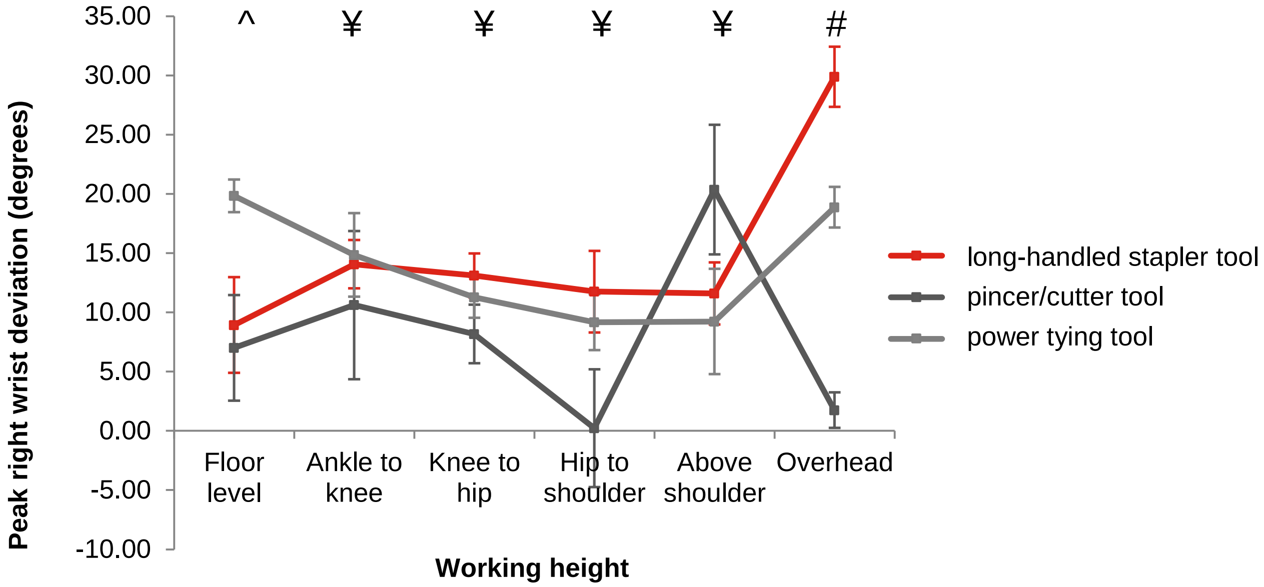


Figure 4.28: Range of right wrist flexion/extension at different working heights with different tools.

4.6.5.2 Ulnar and radial deviation

Peak right wrist deviation

Overall, the long-handled stapler tool exhibited the greatest radial deviation and reached 30 degrees when working overhead (p< 0.05) compared to values of 19 and 2 degrees for the power tying and pincer/cutter tools respectively (Figure 4.29).



#All three tools significantly different to each other.
^Power tying tool significantly different to the pincer/cutter and long-handled stapler tools.
¥ Pincer/cutter tool significantly different to the long-handled stapler and power tying tools.

Figure 4.29: Peak right wrist deviation values (Mean ± SD). Please note that radial deviation is positive and ulnar deviation is negative.

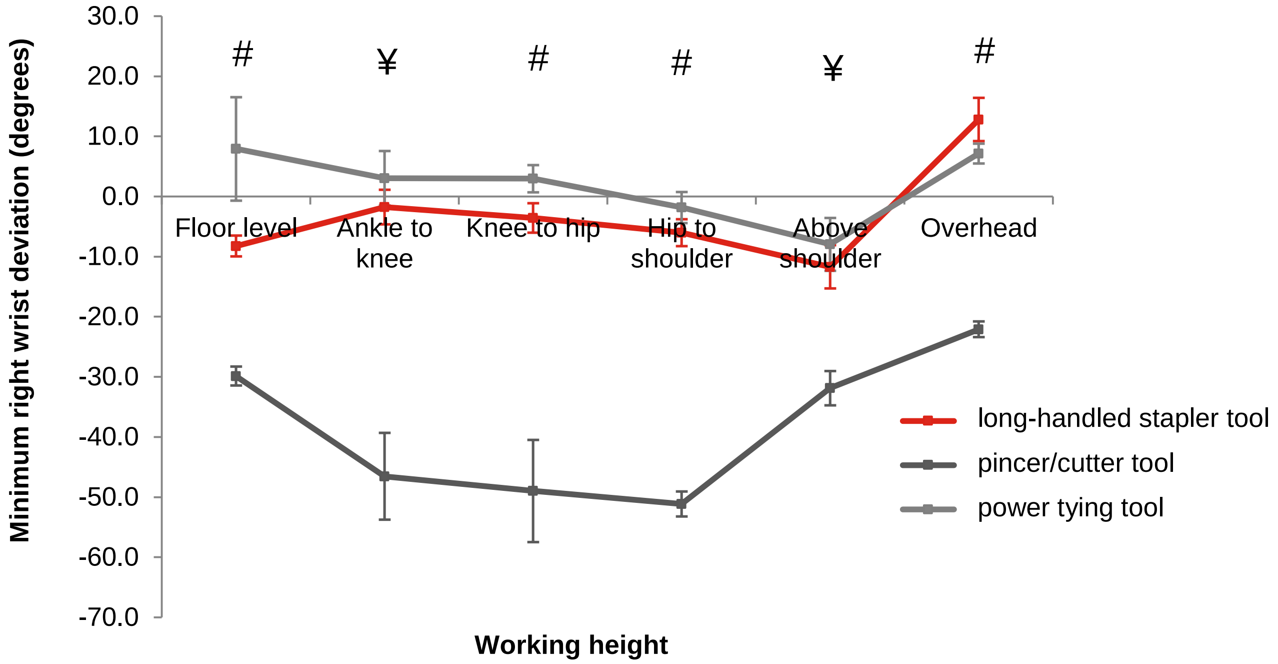
Minimum right wrist deviation

Ulnar deviation (Figure 4.30) was greatest for the pincer/cutter tool ($p < 0.05$) reaching a value of 51 degrees at the hip-to-shoulder level, whereas the other two tools exhibited a relatively neutral wrist deviation across all heights. Range of wrist deviation was greatest for the pincer/cutter tool (Figure 4.31).

The power tying tool again demonstrated the least range of right wrist movement, in this case deviation, at all height categories.

The long-handled stapler tool followed a very similar pattern of movement around a neutral wrist position, except for the overhead level where the range of radial deviation increased to the highest value of all tools, at approximately 30 degrees. While this was the highest level of radial deviation, as a mean peak value, it was not regarded to be extreme.

The pincer/cutter tool demonstrated the largest range of right wrist deviation from peak radial deviation to peak ulnar deviation. This range was attributed to the rotational aspect of this task where the tool is rotated in a clockwise direction to twist and tension the wires together. Over this range of wrist deviation movement, and the short duration of each action and the high exposure to this method, this action can be assessed to be hazardous. Compared to the other tools, the range of movement was greatest when the tool was used above shoulder height (Figure 4.31).



#All three tools significantly different to each other.

¥Pincer/cutter tool significantly different to the long-handled stapler and power tying tools.

Figure 4.30: Minimum right wrist deviation values (Mean ± SD). Please note that radial deviation is positive and ulnar deviation is negative.

Range of right wrist deviation

(Range of total deviation across ulnar and radial deviation directions)

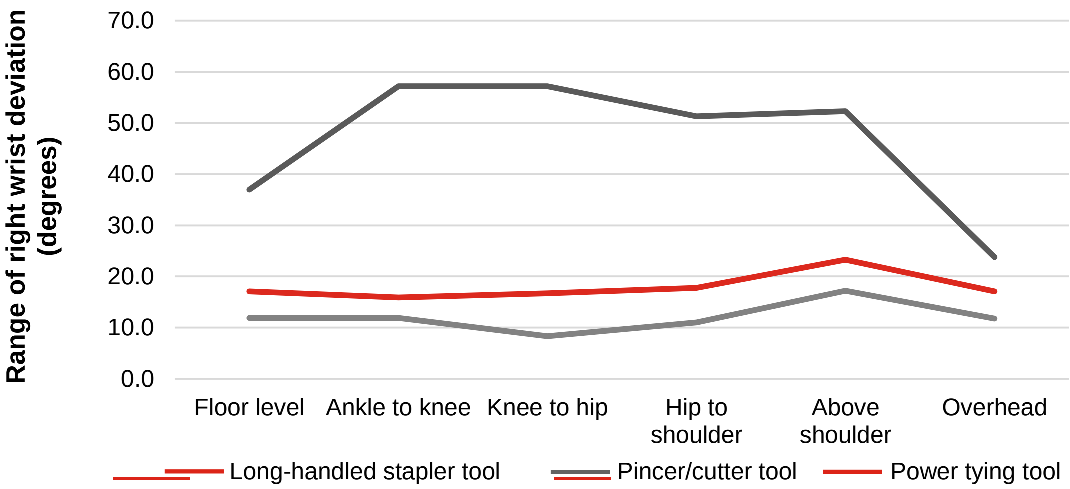


Figure 4.31: Range of right wrist deviation values.

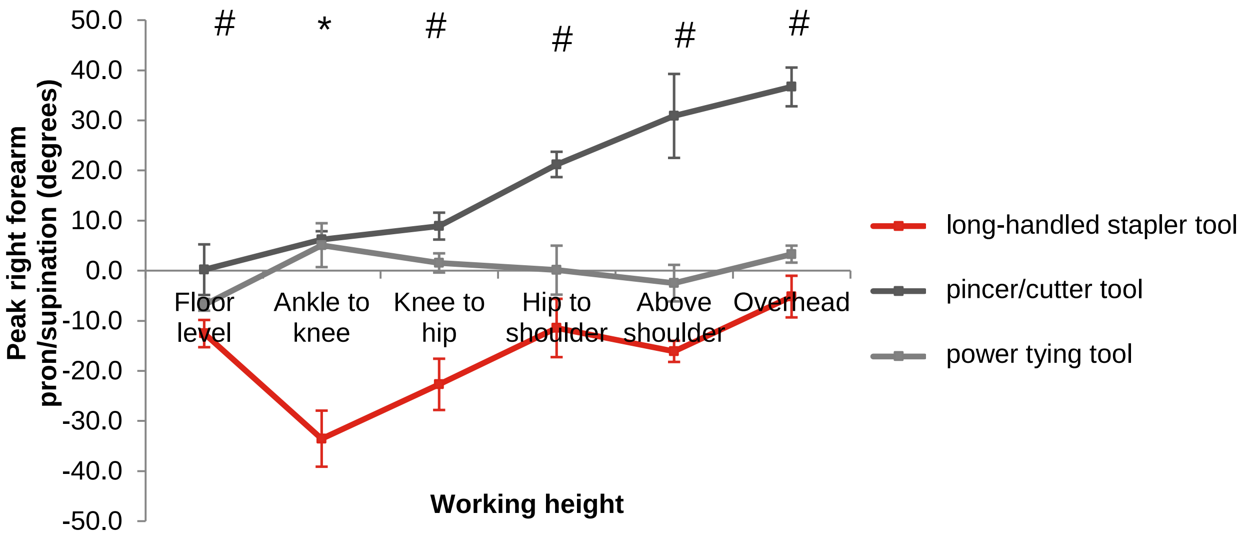
4.6.5.3 Rotation

Right wrist rotation

The power tying tool exhibited the lowest (p< 0.05) peak rotation; that is pronation or supination. The pincer/cutter tool exhibited the greatest pronation whereas the long-handled stapler tool exhibited the greatest supination. This is shown in Figure 4.32 and Figure 4.33 where positive values represent pronation and negative values represent supination.

When using the long-handled stapler tool, the participant's wrist remained in a supinated posture. This was attributed to the need to place the head of the tool at 45 degrees to the crossed steel bars for the tool to operate, and the rotational position of the curved handle relative to the fixed orientation of the head. The handle could be rotated to manipulate the rotational position of the wrist if required.

The pincer/cutter tool again demonstrated the largest range of right wrist movement; rotation in this instance. At levels below hip height, the participant rotated between approximately 20 degrees of wrist pronation to slight supination. This range of rotation increased as the work moved to higher levels with the level of supination increasing with each change in level.



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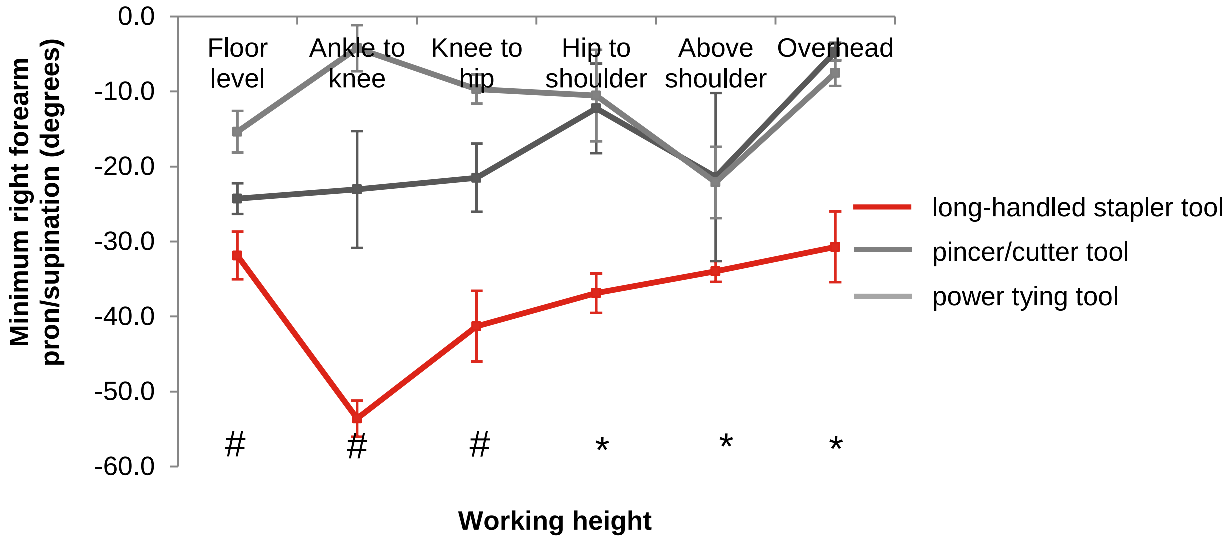
*Long-handled stapler tool significantly different to the pincer/cutter and power tying tools.
#All three tools significantly different to each other.

Figure 4.32: Maximum right wrist rotation values (Mean ± SD) at different working heights. Please note that pronation is positive and supination is negative.

Minimum



*Long handle tool significantly different to pincer/cutter and power tying tools.
#All three tools significantly different to each other.

Figure 4.33: Minimum right wrist rotation values (Mean ± SD) at different working heights. Please note that pronation is positive and supination is negative.

Range of wrist/forearm rotation

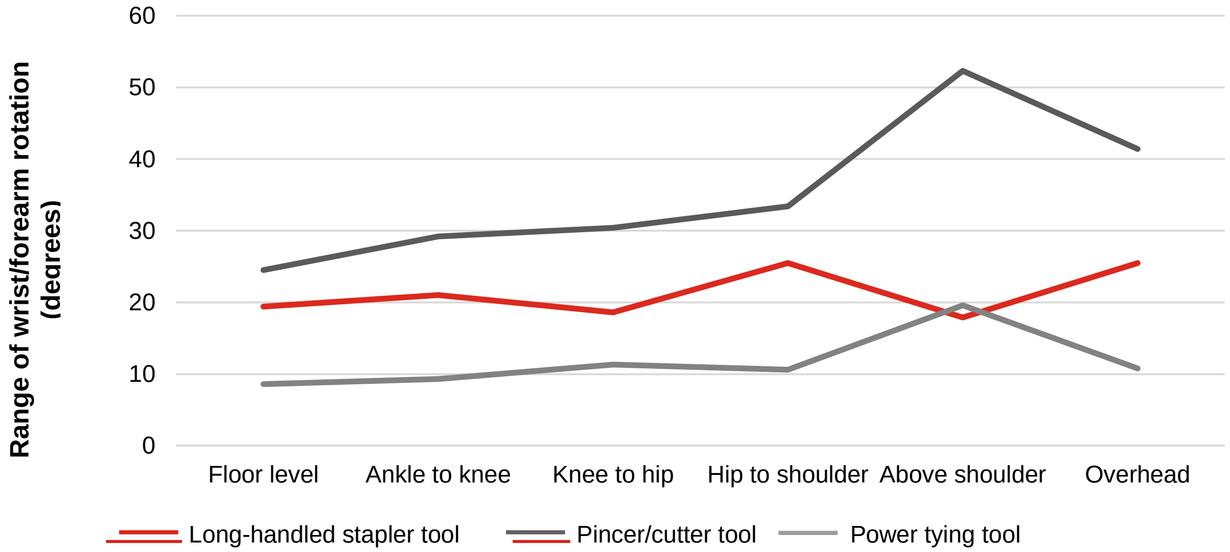


Figure 4.34: Range of right wrist rotation values.

4.6.6 EMG – muscle activity

4.6.6.1 Steel fixing at ground level

EMG for steel fixing at ground level was reviewed as this height demonstrated the greatest physical work demands for an operator's back (Table 4.1and Figure 4.35). Selected EMG results have been reported to impact on the participant's back and upper limbs. Note that EMG data for the right wrist and finger extensors was not gathered due to a sensor failure. These results are described for each tool and method. Note that each graph uses a different scale to display the percentage of MVC for each value. A reference line at 100% of MVC has been included to highlight each value relative to this benchmark value.

Long-handled stapler tool

These results indicate very high levels of muscle activity for the long-handled stapler tool (Table 4.1, Figure 4.35). The right side of the participant's back, both shoulders, forearms and biceps, demonstrated high levels of muscle activity to either directly apply the tool or to brace the body while the tool was applied.

Xsens posture and movement data showed the lowest range of trunk inclination when using this tool at ground level. However, when analysing the EMG data, it appears very high muscle activity is required to operate the ballistic, two-part action comprised of pushing down on the tool to apply the staple, and then quickly and forcefully pulling it back towards the operator to twist and tie it.

The very high levels of EMG relative to MVCs were assessed as due to the sudden stopping of the tool when first pressed down to apply and connect the staple. The participant quickly established and demonstrated competency in using this tool. However, this initial action may have been greater than that used by a highly skilled operator because the participant sought to minimise error when the staple fails to connect at the end of the action, which would then require him to stop work and free the fouled staple from the tool.

Table 4.1: Descriptive statistics (Mean ± SD) for peak EMG values for measured muscle groups.

(Note that data is reported relative to peak MVC EMG data for each muscle group.)

	Shoulders		**Mid Thoracic**		**Lumbar**		**Forearm Extensors**	**Forearm Flexors**		**Biceps**	
% MVC	Left	Right	Left	Right	Left	Right	Left (only)	Left	Right	Left	Right
Mean (%)	171.2	101.5	25.0	132.1	56.7	414.2	304.8	118.6	441.3	107.5	95.6
SD (%)	41.5	7.2	4.4	19.2	6.2	104.7	17.5	17.4	139.4	15.1	14.6

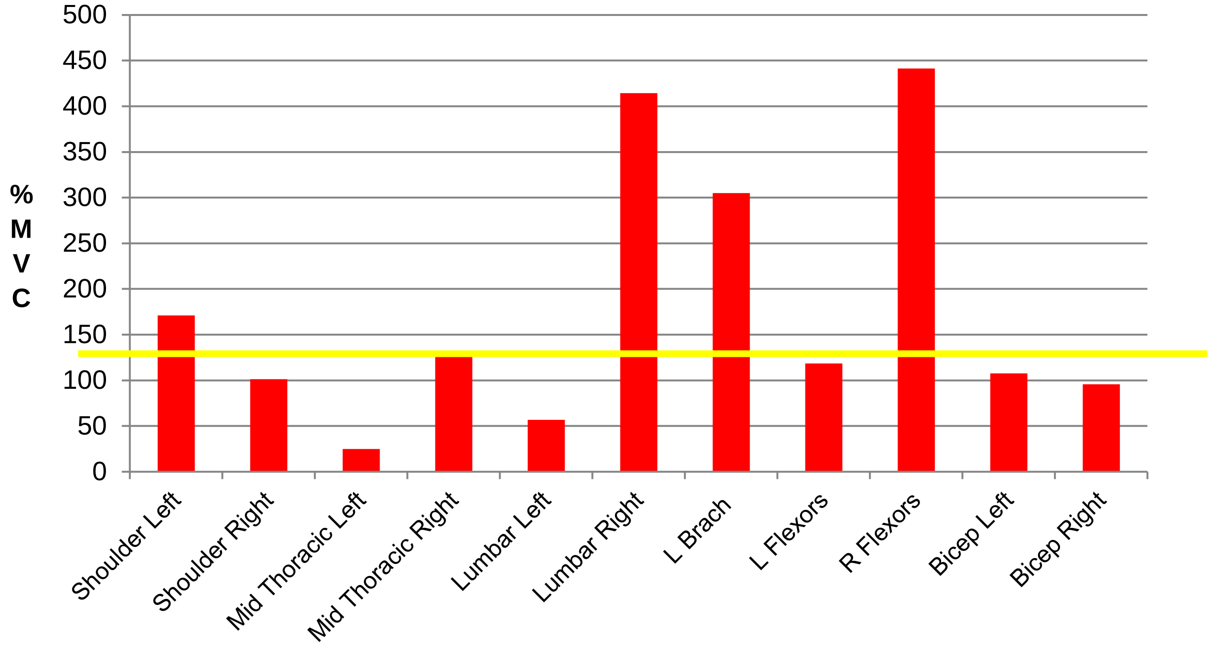


Figure 4.35: Range of EMG results when using long-handled stapler tool at ground level.

Pincer/cutter tool

These results demonstrate high levels of muscle activity for the left shoulder and wrist extensor muscles, as well as the right lumbar area and right wrist flexors. These results were attributed to the repeated actions of the participant's left upper limb to grasp the wire from the reel on his left hip, then pull it forward in combination with the continuous stabilisation of his back to bend and reach downwards and use his right upper limb to clamp, rotate and cut the wire to tie and fix the two steel rods together (Figure 4.36, Table 4.2).

Table 4.2: Descriptive statistics (Mean ± SD) for peak EMG values for measured muscle groups.

(Note that data is reported relative to peak MVC EMG data for each muscle group.)

	Shoulders		**Lumbar**		**Forearm Extensors**	**Forearm Flexors**		**Biceps**	
%MVC	Left	Right	Left	Right	*Left	Left	Right	Left	Right
Mean (%)	62.9	108.7	208.9	164.8	191.5	96.8	182.7	57.6	57.0
SD (%)	22.9	42.1	65.0	10.2	18.1	27.2	26.1	8.3	24.0

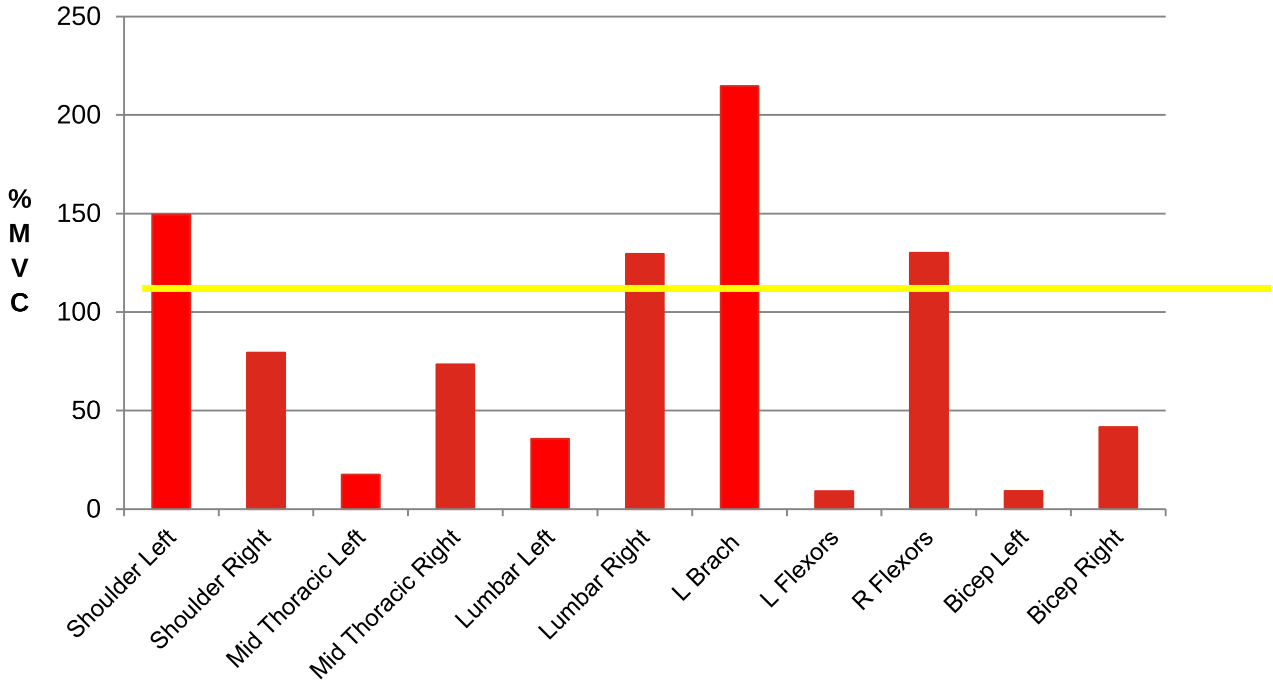


Figure 4.36: Range of EMG results when using the pincer/cutter tool at ground level.

Power tying tool

Compared to the other tools, these results show relatively low levels of muscle activity when using the power tying tool (Table 4.3, Figure 4.37). None of the sensors for the back and upper limbs exceeded 100 % MVC. This is in stark contrast to the long-handled stapler tool that required very high levels of muscle activation to use the tool and brace the body during use, even though the participant’s trunk inclination was much lower when working at this lowest operational height (ground level).

Table 4.3: Descriptive statistics (Mean ± SD) for peak EMG values for measured muscle groups.

(Note that data is reported relative to peak MVC EMG data for each muscle group.)

	Shoulders		**Mid Thoracic**		**Lumbar**		**Forearm Extensors**	**Forearm Flexors**		**Biceps**	
%MVC	Left	Right	Left	Right	Left	Right	*Left	Left	Right	Left	Right
Mean (%)	76.9	7.2	5.3	45.4	38.2	77.0	60.0	30.4	71.6	39.9	27.9
SD (%)	25.0	1.6	0.9	17.5	8.6	17.0	62.8	13.6	11.6	9.2	4.0

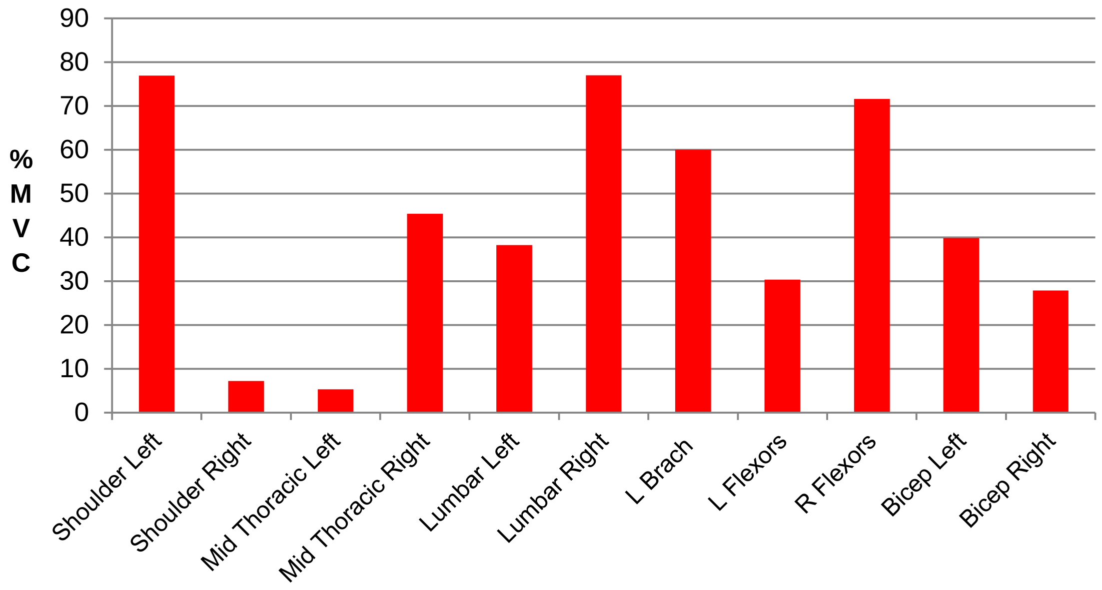


Figure 4.37: Range of EMG results when using power tying tool at ground level.

4.7 Discussion

The potential for changes to improve back postures and reduce injury risks appear to be substantial. Adopting awkward back postures for sustained periods of more than 30 minutes per session, or cumulatively for more than two hours within an 8-hour shift, are defined by WorkSafe Victoria in the *Manual Handling Code of Practice* (WorkSafe Victoria, 2000, p. 20) as being a long duration and the threshold values for hazardous exposure.

Steel fixing at low heights is regarded as common practice within the construction industry, based on operator, supervisor and industry stakeholder feedback. These results show significant improvements in operator back postures and movements could be achieved by using longer tools, such as the long-handled stapler tool, especially when operating at low heights.

However, the impact of other factors regarding the design of these types of tools need to be considered when assessing the broader benefits or limitations of alternative steel fixing tools. These other tool design factors are described below.

4.7.1 Long-handled stapler tool

The long-handled stapler tool handle was adjusted to its maximum length and the participant was 173 cm tall. The body height for the average Australian male is 175.6 cm (Australian Bureau of Statistics, 2012). It is likely taller operators would need to reach further down to grasp and use the tool which could result in them increasing their range of back movement, particularly for the two below-knee levels. This shows the tool could benefit from a longer range of adjustment to suit a broader range of body heights among operators.

Adjusting the length of the long-handled stapler tool requires the operator to loosen and screw with an Allen key, then slide the handle in or out, and then tighten the screw to hold the handle in place. A maximum length indicator was displayed on the handle. However, length settings relative to an operator's body height or for working at different heights were not available. This shows if an operator adjusts the handle length at all, it is unlikely they will adjust it for different circumstances as they arise. This represents a functional and usability limitation of the tool.

The long-handled stapler tool is oriented to single handed use only and uses a curved handle, like that of an umbrella. Given that force to operate the tool must be manually applied, an improvement in handle design to provide a more suitable handgrip shape and angle is warranted. In addition, a second handle for two handed use could be placed on either side so right and left handed operators can use both hands.

Two forceful and repeated actions are exerted to operate the tool for a single tie. These ballistic actions, and the jarring of the tool when it is pushed downwards, may introduce secondary hazards not observed in this project.

When operating at all heights, the operator has to hold the tool at 90 degrees to the rods being fixed. This becomes increasingly awkward as the operating height increases, particularly when the tool is used above shoulder height.

When the long-handled stapler tool is used overhead, the operator has to hold onto the staple cartridge to stop it from falling down, stopping the fixing movement of the cartridge.

The error rate for the long-handled stapler tool varied. The potential benefits of its use may be reduced as the staple may not properly connect after the initial pushing movement, but becomes caught within the head of the tool, requiring the operator to remove it manually.

This tool uses a two stage, forceful action to apply and secure the staple and then twist and tension it. This action was found to result in very high levels of muscle activity across the participant's back and upper limbs, either to apply the tool or brace the body as the tool is applied. These levels of muscle activity were attributed to force exertion and absorption. While this tool demonstrated a clear benefit in reducing trunk inclination and lumbar flexion, the forceful and ballistic action required to apply the tool may create secondary MSD hazards and risks.

For this tool, participant feedback was that the tension of the ties was insufficient for the steel fixing work being performed at site 4. With this work, the formed frames are lifted up by an overhead crane and moved to the next processing position. The ties were not regarded as tight enough to support the weight of the frame for this type of movement, and the participant stated that and additional half or full turn may be required.

4.7.2 Pincer/cutter tool

This tool was reported to be the current 'benchmark' within the construction industry. Participants reported a reluctance to use other devices because of simplicity and level of quality that can be achieved with this tool.

This tool requires adopting higher ranges of trunk inclination and lumbar flexion (L5/S1) when working at low levels. As work height increases, this tool required less trunk inclination than the power tying tool, but significantly more than the long-handled stapler tool.

At operational heights below shoulder level, the participant consistently moves his right hand across the midline of his body to apply the tie. This lower range of movement did not occur when using the other tools.

For heights above shoulder level, the level of shoulder abduction increases for this tool, as would be anticipated, given the short length of the tool handles.

Regarding the range of wrist movement used, this tool uses the greatest range of movement of all three tools assessed. Movement was greatest for wrist deviation and rotation. Using this tool was assessed as presenting an exposure to MSD hazards because of the highly repetitive nature of this action that can be performed approximately 30 times per minute, and for more than two hours consecutively or cumulatively during a working day.

EMG values for both wrists/forearms and the right lumbar area were high for the use of this tool when applied at ground level. This was assessed further consolidating the view that using this tool and method presents risk factors that should be controlled.

4.7.3 Power tying tool

With the power tying tool, the ‘gun’ is not well balanced in the hand of the operator. The greater weight within the upper part of the tool results in the tool generating torque or rotary forces in both forward and downward directions. The operator must continually counteract this movement by exerting greater muscular effort to hold the tool when it is not connected to a fixing position such that part of the tool’s weight and torque is transferred to the rods being fixed.

The awkward balance, and the curved upper tip of the power tying tool, requires the operator to then rotate it in the opposite direction (upwards and towards the operator) to remove it from the bars so it can be moved to the next fixing point.

This imbalance and rotational movement was noted when trialling the tool. However, of all three tools tested, the power tying tool resulted in the lowest levels of shoulder and wrist movement, and EMG for the back and upper limbs. These results demonstrated the inherently positive design features of the tool’s pistol grip design.

The tool’s key limitation was found to be the high level of trunk inclination and lumbar flexion (L5/S1) required to use the tool at low levels (that is, below hip level).

Regarding the tool’s ongoing use, the distributor reported the sensing equipment that controls the movement and tension of the wire requires regular maintenance to keep it operational.

For this tool, participant feedback was that the tension of the ties was insufficient for the steel fixing work performed at site 4. With this work, an overhead crane lifts the formed frames and moves them to the next processing position. These ties were regarded as not tight enough to support the weight of the frame for this type of movement. However, the participant did not offer any suggestions for improvement.

4.7.4 Conclusions

The assessment method enabled a comparison between the current popular method of steel fixing, using a pincer/cutter tool with two alternative tool designs readily available for purchase.

The current method of steel fixing requires repeated use of the left (non-dominant) hand to supply the wire, while the right hand repeatedly clamps, twists and cuts the wire to complete a tie. This method was assessed as presenting MSD hazards and risks because of the range of trunk and lumbar spine (L5S1) movement used to access low heights, and the range and repetitive hand and wrist actions used.

The two new tools assessed and compared with the current pincer/cutter steel fixing methods demonstrated some features that could, in part, overcome these limitations. However, neither of the new tools were found to be sufficiently advanced in design to accommodate all limitations identified within this assessment.

The long-handled stapler tool demonstrated the effectiveness in a long handle limiting back movement for low height, as well as limiting shoulder abduction when working overhead. However, the need to be able to apply the tool at a right angle to the bars being fixed introduced awkward back, shoulder and wrist movements for the ankle-to-knee and above-shoulder height categories. The main limitation with this tool, however, was identified through the analysis of EMG data, which revealed that the tool required forceful manual application. These results identified that using this tool required very high levels of muscle activity across the upper limbs and back. The assessment indicates that the tool presents new hazards not present in the two other tools and steel fixing methods.

In addition, while this tool provided a long and adjustable handle, the curved handgrip was assessed as not fit for purpose. In addition, the method and range of adjustment was too limited, making it unlikely that steel fixers would use it.

The long-handled stapler tool significantly reduced trunk inclination (forward trunk flexion) and lumbar flexion (L5S1) when operating at all levels. This improvement was greatest for operating heights considered to be most hazardous; that is, work below the operator’s knee level. This shows that long-handled, steel fixing tools have great potential to both improve work postures for steel fixers, and to significantly limit exposure to awkward and hazardous back postures. However, the long-handled stapler tool’s design tested in this assessment was not found to deliver a sufficient level of user and operational functionality for it to be widely accepted and used in its current form.

A range of improvements would be required to improve handle length and adjustment, its shape, size and angle, as well as introduce a second handle so the operator can use two hands. Also, the development of a motorised mechanism is warranted. This would ensure secondary hazards, stemming from forceful and repeated application of the tool, are not introduced with this type of tool. It would also ensure that the connection of the staple occurs more consistently and that the tie can be sufficiently tensioned.

The power tying tool demonstrated the overall effectiveness of this type of tool design. It required limited right shoulder and wrist movements, and the lowest levels of EMG for steel fixing (when operating at ground level). However, this tool offers no advantage to the user when working at very low and high levels where awkward trunk, lumbar, shoulder and wrist postures and movements were found to occur.

It was that the new tools did not tie the bars with the required level of tension for the construction work at site 4. However, for some situations, such as securing bars for a large concrete slab, they may be sufficient.

Alternative steel fixing tools demonstrated a combination of benefits and limitations for physical work demands on steel fixers and likely MSD risks. However, of the tools evaluated in this project, none were found to be sufficiently advanced to merit broad application across the construction industry. Further development work to overcome the assessed limitations is strongly indicated.

Part 5: Shotcreting

5.1 Description of work task

5.1.1 Overview of shotcreting work

Shotcreting is a construction work task that involves spraying irregular, vertical or oblique wall surfaces with concrete, without using forms to confine and define its shape. The concrete used in shotcreting has specific adhesive properties that enable it to be progressively built up from ground level to form a solid, structural wall. It is typically undertaken on a construction site that involves progressive excavation of earth and/or rock within a defined perimeter.

Shotcreting follows preparation of the site. This involves excavation to expose the wall surface to be covered, and preparation of a flat ground surface in front of the wall to accommodate shotcreting hoses and to provide a level surface for the worker (Figure 5.1). According to participants in the research, not all sites provide flat ground access to the wall being covered.

This site preparation also involves placing drainage channels vertically against the wall, at intervals of approximately 2-3 metres. These channels may extend between successive levels of excavation and shotcreting where their lower, unattached ends, may rest on the ground while the wall is concreted. This is so they can be fixed to the next section of wall to be exposed. Large pins (long steel bars) may be inserted into the wall at an oblique angle to provide structural support. If required, steel mesh can be fixed across the entire wall or sections of the wall that need a greater level of structural integrity to support the sprayed concrete.

Figure 5.1: Sites 5 (left panel) and 7 (right panel) showing construction sites and participants.

Shotcreting can be used in an excavation within rock, where the concrete may be applied directly against an exposed rock surface. It can also be applied within an earthen excavation where columns of concrete that extend vertically through the entire excavation have been poured around the perimeter prior to excavation. These columns are designed to provide structural integrity, and shotcreting is mostly applied to the exposed wall surfaces between each column.

Shotcreting is often completed after excavation. Once an area or level has been excavated, the exposed rock or earthen walls must be covered and stabilised. Participants in this investigation reported that excavated wall heights to be shotcreted can range from 1.6-3.3 metres. They also reported this work is usually conducted on walls that are up to 2.2 metres high, and that working on walls higher than this would require an extended upward reaching posture to spray the concrete upwards and as high as possible.

The thickness of the wall is determined by pre-set borders located at the upper and lower perimeters of the area to be shotcreted. The upper border is defined by either a series of long boards set in place specifically for this purpose, or the front and lowest edge of the wall surface that has previously been constructed. The lower border is defined by a series of long boards fixed at ground level along the section of the excavated area to be constructed. The wall thickness is defined by a 'line' that extends between the front edges of the upper and lower borders. The shotcreter sprays concrete within a section of the wall until they consider the depth of the concrete is sufficient to extend to, or slightly past, this line. If the shotcreter's coworkers later discover more concrete is needed when they commence smoothing the sprayed surface, they will instruct the shotcreter to quickly spray that section to add the required amount.

5.1.2 Shotcreting equipment

Shotcreting uses two hoses that extend from the concrete hopper and pump to the area of application. At site 5 the length of hose between the pump and the area being sprayed was estimated to be approximately 30-50 metres long. At site 7, a participant (#9) stated this distance can be much longer, up to 300 metres, provided a pump is powerful enough to operate at the required level of pressure.

The larger hose carrying the concrete is 50mm diameter. A hose with a narrower diameter (approximately 30 mm) carries compressed air. These hoses are tied together at their nozzle ends so their respective flows intersect. This enables compressed air to be mixed with the concrete to form a spray the operator directs across the target area to progressively build up the concrete to the required thickness.

Specially prepared concrete is used for shotcreting. It is transported to the site by a concrete delivery truck. The concrete is continuously poured into the hopper, then pumped from the hopper through the wider diameter hose to its point of application. Pumping concrete through the hose has been reported, and observed, to result in a pulsing flow that causes pulsing forces at the nozzle, rather than an even and continuous flow of concrete that would result in a continuous force. This variable flow pattern influences the holding methods and postures used by shotcreters.

The static (holding) force required to hold and manoeuvre a hose loaded with concrete was measured at site 5 and found to be 19 kilograms (approximately 186 N). This was estimated to be representative of the holding force the operator would need to lift when moving the hose vertically, as well as the force needed to hold it in position. This weight does not consider the hose reaction force where the friction of the concrete within the hose and nozzle generates a reaction force in the opposite direction to that of the flow of concrete. Section 5.3 discusses the estimated level of force exertion, and its impact on the postures used to hold a hose in place during periods of spraying.

5.1.3 Work methods

When spraying a wall section, shotcreters typically start by directing the flow in a continuous, side-to-side arc of movement slightly above ground level. In this investigation, the concrete spray at the point of contact with the wall was about 500mm wide. Shotcreters were also seen applying the concrete across wall sections approximately 1.5 metres wide. As the concrete builds up to the required thickness at the base, shotcreters typically raise the application height and continue this sequence until the target surface is fully covered to the required thickness.

Once the shotcreter finishes one section, they move to the adjacent section and continue this pattern until the job is complete, or the load delivered by the truck has been used. In this situation, the next load is then transferred into the pump for application by the next concrete truck. This process is repeated until the target area is covered. At the two sites assessed, a single load of concrete for shotcreting lasted for approximately 25 minutes.

As soon as the shotcreter commences the adjacent section, a coworker screeds the surface that has just been sprayed to finish that section. Screeding involves a coworker using the edge of a long, square edged beam to create a smooth surface at the required angle. This angle is established at the outset by using the upper and guide borders or, if these have not been used, establishing a vertical line directly in the surface using a large spirit level. All subsequent screeding is then conducted relative to these references lines.

To establish the smooth finish at the required angle, the worker slides the edge of this lightweight beam over the surface to remove any excess concrete and establish a smooth finish at the pre-established angle. If they identify there is not enough concrete within a section, they ask the shotcreter to redirect the flow and spray the area until a sufficient level of concrete is deposited. This ability to quickly redirect the flow of concrete to the adjacent area was identified as an essential quality control feature of the current manual methods of shotcreting.

When a shotcreter moves along the face of the wall from one section to the next, they drag the hoses with them and position them for the section they are about to work on. Shotcreting workers were observed to position hoses to prevent or limit the need to drag them while spraying a particular section of the wall, but still enabling them to reach all sections of the wall within that area to complete the task. Participants reported that coworkers are tasked with moving hoses for the shotcreter, but this was not consistently observed and both shotcreters were seen to drag the hose themselves on most occasions. One research participant stated that only he should handle the hose while concrete is being sprayed to avoid any sudden and unexpected movements of the hose that may cause the hose nozzle to be redirected, or cause him to stumble or fall.

When 139spraying the concrete against the wall, shotcreters were seen to either raise or lower the concrete hose and hold it in a position at the required height so the nozzle was approximately 90 degrees to the surface being sprayed. This method was seen to result in the participant holding the hose, either at the side of their body or in front of their torso. Participants reported this method would be used when spraying concrete through a steel reinforcing grid to ensure a sufficient volume of concrete is sprayed through the grid and that it is sufficiently compacted to establish the required strength.

Alternatively, a shotcreter was seen to keep the hoses and nozzles on top of his shoulder at all times. He reported that from this single, fixed position he could direct the spray to cover all height levels. This method was reported to be possible when minimal or no steel reinforcing sections were present.

5.1.4 Locations and environmental conditions

Data collection was undertaken at two construction worksites in outdoor environments. Site 5 was within the below ground level, excavation area of a large building under construction. Site 7 was within a rock cutting of a rail extension project.

At site 5, the weather was partly overcast with a light breeze. The temperature was approximately 13 degrees with no rain. At site 7, the weather was sunny with a light breeze. The temperature was approximately 19 degrees with no rain.

At site 5, the research team could work within the construction pit at an approximate distance of 15-20 metres from the participant. Data was collected via wireless transmission from the Xsens body pack (attached to the worker) to a laptop (via a modem). This method displayed the data on the computer screen as an ‘avatar image’, where the ‘avatar’ moved in real-time to match the participant’s movements.

At site 7, the team operated from above and outside the perimeter of the cutting. This was done to eliminate the team’s exposure to risks resulting from the movement of large earthwork machines within the area. Given this separation, and to minimise the risk to transmission fluctuations or errors, the method of data gathering at this site varied slightly such that the participant’s body movement data was logged onto the Xsens body pack and downloaded to a laptop after the assessment. To turn the Xsens body pack ‘on and off’ for the assessment, and to obtain video footage, the site 7 construction works Quality Supervisor operated the Xsens body pack and obtained close proximity video footage of the participant during the assessment period.

5.2 General assessment of shotcreting

The limited access to the shotcreting areas for both sites prevented detailed assessment of hoses used for shotcreting. However, observations were made regarding their design, how they are grasped, handled and positioned for use, and hazards and risks that may be present.

The first of these observations was the use of high pressure air to create the flow pattern when the air is merged with the concrete. The use of high pressure air presents an inherent hazard if the connection between the hose and the nozzle deteriorates and the hose spontaneously 'blows off'. If this occurs then the sudden, ballistic movement of the hose or nozzle could strike the operator and cause an injury. This risk would be compounded if the operator was using a holding position where the hoses were held directly in front of the torso or head – a position demonstrated by one of the participants in the research, but avoided by the other.

Another feature of hose design is that there are limited handles or grasping points for operators to obtain effective coupling with the nozzle, or lift, carry and hold the hose in the spraying position. At both sites, the air hose was seen to connect to the end of the concrete hose via a solid section tubing. At site 5, a greater gap between the air tube and the concrete hose was observed that enabled the tube to be used as a handle for general handling of the hoses. At site 7 however, this gap between the air tube and concrete hose was much less and the operator was not seen to use this tube as a handle, particularly when spraying concrete against the wall (Figure 5.2).

The absence of a defined handgrip and small clearance between the air tube and the concrete hose at site 7 required the operator to grasp the wide diameter hose to handle and move it. This limits the range of grasping options an operator can use to handle the hose across all circumstances of its use. However, it was reported by one participant that supplementary handles are not used because they would present as a blunt structure that could cause injury if the air hose suddenly separated from the nozzle, or both hoses suddenly moved and struck the operator.

Figure 5.2: Site 7 – participant holding hose to spray concrete with no handle available or used.

In addition, the operator's ability to be close to the point of contact of the concrete spray against the wall being covered was reported and observed to be a basic requirement for the operator to maintain quality control over the progressive build up and compaction of concrete. Also, the operator's ability to quickly adjust the direction of flow of concrete to or away from an area was also reported as a fundamental requirement of this work.

With regard to any mechanical devices that could be used to hold and direct the spray of a shotcrete hose, one participant indicated he was aware of only one option that had been developed. He described the use of a small excavating machine with the ends of the hoses attached to the digging bucket. The machine could be controlled by an operator to move and position the hose and nozzle for shotcreting. This participant stated the device has been used successfully to apply shotcrete to overhead structures where the application was relatively uncomplicated, and the operator was not directly exposed to the risk of falling concrete.

When asked about using this type of device for shotcreting walls, one participant stated that for that type of application it was slow and awkward to move the hose as required. This participant stated that operating the machine placed the operator too far from the area of application, making it difficult to maintain the required level of quality control. This participant also stated that while holding onto the hose during shotcreting, he can feel variations in the cyclical action of the pump and the flow of concrete through it. He stated he had learnt to modify the flow and to avoid blockages or sudden movements of the hose that could throw him off balance and possibly cause an injury.

5.3 Research methods

5.3.1 Participants

Two participants were asked to participate in the project at each site. At site 5 the participant (age – 24yrs; height – 190 cm; mass – 125 kg) was reported to be a competent member of the shotcreting team. At site 7, the participant (age – 55yrs; height – 170 cm; mass – 110 kg) was a highly experienced shotcreter with over 35 years' experience.

5.3.2 Description of work tasks

Each assessment required the participant to perform the shotcreting tasks scheduled at that time. At both sites, this involved participants performing this work for the duration of a single truck load of concrete, a period of approximately 25 minutes.

Each participant was prompted only to use their usual work methods. No specific requests or requirements were made relating to their work methods. After each assessment, the participants reported they had performed the work as they usually would have, and considered the methods to have been representative of the shotcreting work task in their particular context.

At site 5 (Figure 5.3), where participant 7 worked, the height range involved in the task was from the ground to approximately 1700mm. At site 7 (Figure 5.4), where participant 9 worked, the height of the wall to be shotcreted was estimated to also be approximately 1700mm. When applying the concrete however, participant 9 chose to construct the wall at an initial height of approximately 1200mm, and allow the concrete to set and harden, before adding concrete to it from the next load to complete coverage of that section of the exposed rock wall.

Each participant moved the spray of concrete upwards from an initially low, ground level height until they reached the maximum height for that section. Then they moved to their right to cover the next section. Handling and spraying of concrete was continuous for the assessment period.

Participant 7 moved the hose and nozzle up from a low starting height when spraying through rebar grid that was used across the entire wall section. This resulted in the nozzle being held at three identifiable levels – hip, mid chest and shoulder height. When spraying at lower levels, the shotcreter held the hose and nozzle with both hands in front of his body. At shoulder level, he either held it in front of his body or balanced the hose on top of his shoulder. To move the hose to and from his shoulder, participant 7 bent forward and slung it across his upper back or pulled it off his back and over his head. This action was repeated for each of the 8 panels completed.

Participant 9 used a different method. He placed the hose over his right shoulder at the start of the assessment period and kept it there for 25 minutes. From this position he was able to reach all heights required, although the application height was not higher than approximately 1200 mm because of the need to construct the lower section of this wall and allow it to set before adding to it.

The gathering of the Xsens movement data at site 5 involved the torso and upper limbs. Data for the lower limbs was not gathered because of faulty equipment and the need to replace one of the sensors on the occasion of the assessment.[2]

Figure 5.3: Site 5 showing the environment and participant shotcreting, and different levels.

The site 7 assessment involved shotcreting an exposed wall of rock within the cutting of a corridor being developed for a new rail corridor. Because the wall was being set against rock, only small grids of steel reinforcement were around the end of each pin that extended into the wall. This enabled the shotcreter to spray at all times with the hose resting on his right shoulder. There was no requirement to hold the hose at a lower level for this wall.

[2] Owing to the required distance between the activity and the research team, this was not identified until after the assessment period.

The movement pattern of this shotcreter was observed to be as follows. He rested and moved to an upright standing posture during the brief pauses, and then leaned forward as the next cycle commenced. He used his body to counterbalance the increased rearward force generated by the hoses.

It was not possible to measure the hose force during this assessment. However, a static weight of 19 kilograms was measured at site 5 at the point at which the participant was seen to grasp and hold the hose to lift and lower it.

The site 7 participant stated he considered he was exerting a very high level of force that he estimated to be approximately 70 kilograms (equivalent to 687 N) to hold and direct the flow of concrete from this hose. He stated this was based on his previous experience at handling loads of this weight and performing this work for more than 35 years. It was not possible to validate this estimation of force exertion. However, field-based observation of the task also revealed that a consistent part of shotcreting involves the operator using their body weight to repeatedly ‘lean’ against the hose to apply the force required to hold it and direct the flow. This requirement is an unusual feature of the shotcreting task and was consistent for both participants, particularly when the hose was held over the top of their shoulders. Even if participant 9’s estimate of force exerted was halved (35 kilograms), it would still be regarded as very high force exertion. In the absence of being able to measure hose reaction forces, the RMIT researchers determined it is likely that very high forces can be exerted during shotcreting and this consideration should be incorporated into the task analysis.

To control the hose, participant 9 was seen to hold the hose in place on his shoulder by placing his right hand over the top of the hose and leaning forward with each pumping cycle. He would then move his right arm and shoulder to change the direction of flow. These observations of a forward leaning movement when the flow of concrete was greatest were demonstrated in the Xsens data and avatar motions.

Figure 5.4: Site 7 showing high and low flow forward leaning, and upright trunk postures respectively.

This pattern of repeated forward leaning movements was also reported by participant 9 and was regarded to be indicative of the operator exerting a high level of force using his right upper limb and trunk for this job. Movement of the participant’s whole body was used to exert the required level of sustained force to hold and direct the hoses and the flow of concrete. This trunk movement pattern was performed repeatedly for the duration of each shotcreting period.

5.4 Data analysis

Four types of back posture and movement data (joint angular motion) were recorded by the Xsens system. These were trunk inclination (T12/S1), and lumbar joint motions at three levels of the lumbar region (T12/L1, L3/4 and L5/S1). The three lumbar joint motions were found to be small, falling around 2-3 degrees. Due to the low range of joint motion, these data were not considered relevant to this project. Accordingly, these results are not reported. Only trunk inclination results are reported.

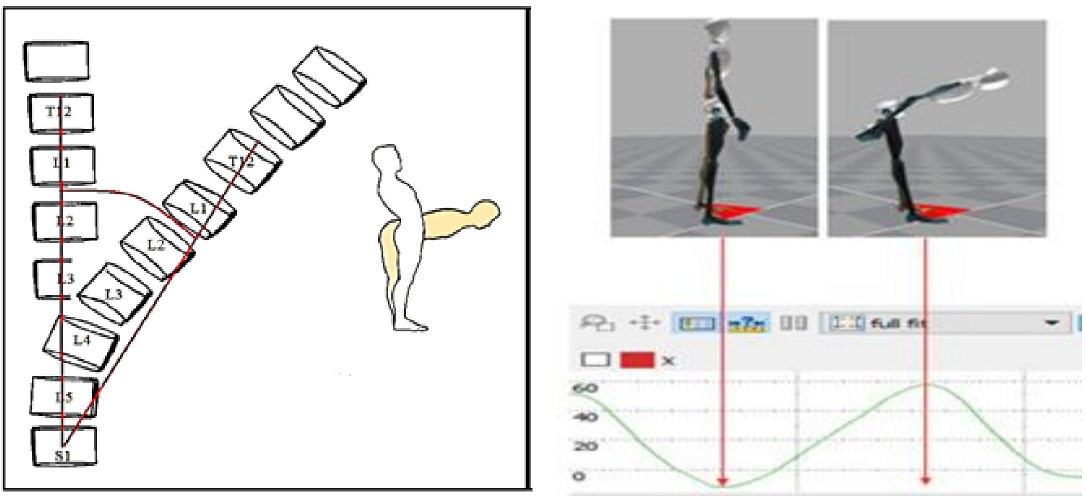
Data on the participant's dominant, right upper limb, in particular shoulder and wrist, were reviewed and found to be pertinent. These data were extracted for the results.

5.4.1 Trunk inclination

Trunk inclination data (trunk forward flex/extension in the sagittal plane) were extracted by using the positions of the T12 and S1 vertebrae (Left panel Right panel

Figure 5.5). This level was chosen as the data best matched a visual representation of the participant's trunk movements in this plane. A higher level vertebral, such as T8 within the back, was not used as angles from this level were greater than the apparent angle of the trunk, most likely reflecting greater mobility of the mid thoracic spine.

For trunk inclination, forward flexion is positive (+ve) or greater than zero. Rearward extension is negative (-ve) or less than zero.



Left panel **Right panel**

Figure 5.5: Left panel: schematic representation of trunk inclination angle (forward flexion in sagittal plane ≈ 30°). Right panel: avatar image of participant showing a standing

position (trunk inclination ≈ -18 degrees extension) and forward flexed position (trunk inclination ≈ 60 degrees).

5.4.2 EMG – muscle activity

EMG data for shotcreting was reviewed. The focus of EMG consideration was to better understand muscle activity relative to the RMIT researchers' assumptions that holding the hose and directing the spray onto a wall requires high levels of force exertion.

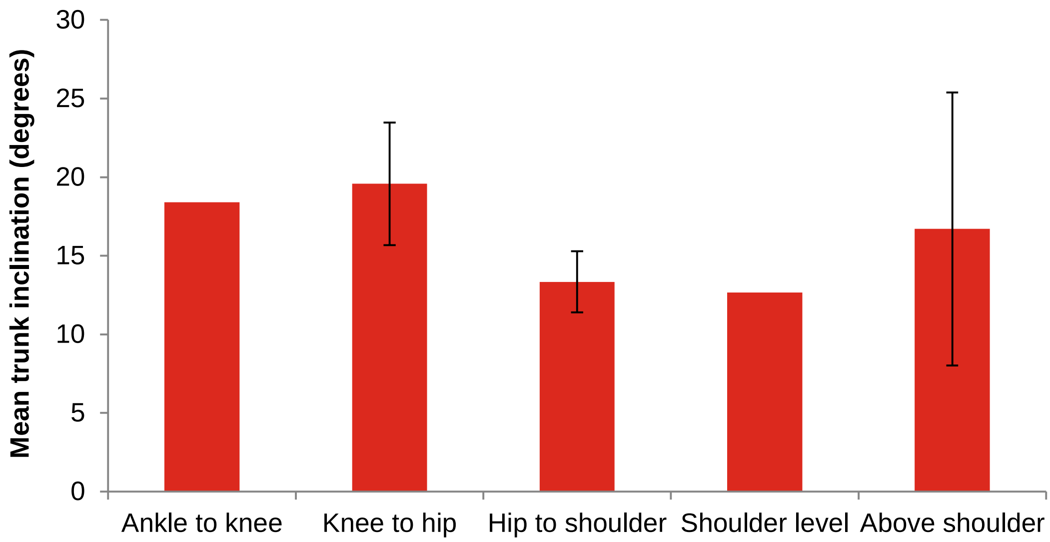
5.5 Results

5.5.1 Trunk inclination

5.5.1.1 Mean trunk inclination

Mean trunk inclination was measured for each trial at the knee-to-hip, hip-to-shoulder and above-shoulder levels. Each trial lasted about 5 minutes. Descriptive statistics (mean ± SD) were then generated from these data and are shown in Figure 5.6. For ankle-to-knee and shoulder-levels, the task was performed only for one trial (over a period of about 5 minutes). Hence, the data shown in Figure 5.6 is the mean for one trial (no standard deviation values are reported).

Mean trunk inclination was similar across all five working heights during shotcreting. This value fell between 12 degrees and 20 degrees.



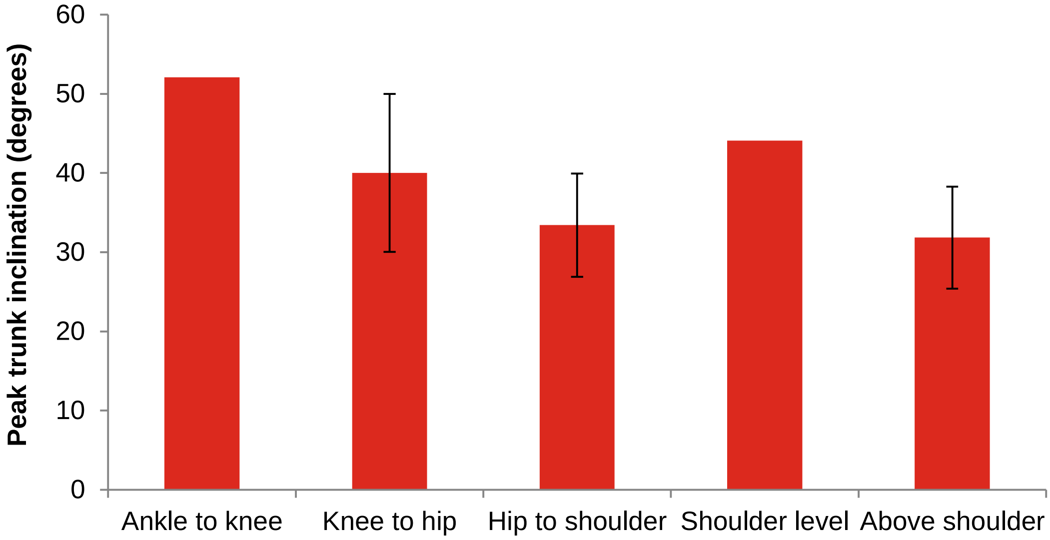
(Note that sixth value at ground level was not used because width of spray that resulted in the area of application was always higher than ground level.)

Figure 5.6: Mean trunk inclination values (Mean ± SD) for different levels of application of concrete.

5.5.1.2 Peak and minimum trunk inclination

Peak and minimum trunk inclination were measured for each trial at the knee-to-hip, hip-to-shoulder and above-shoulder levels. Descriptive statistics (mean ± SD) were then generated from these data and are shown in Figure 5.7. For the ankle-to-knee and shoulder-levels, the task was performed only for one trial. Hence, the data shown in Figure 5.7 is the mean for one trial (no standard deviation values are reported).

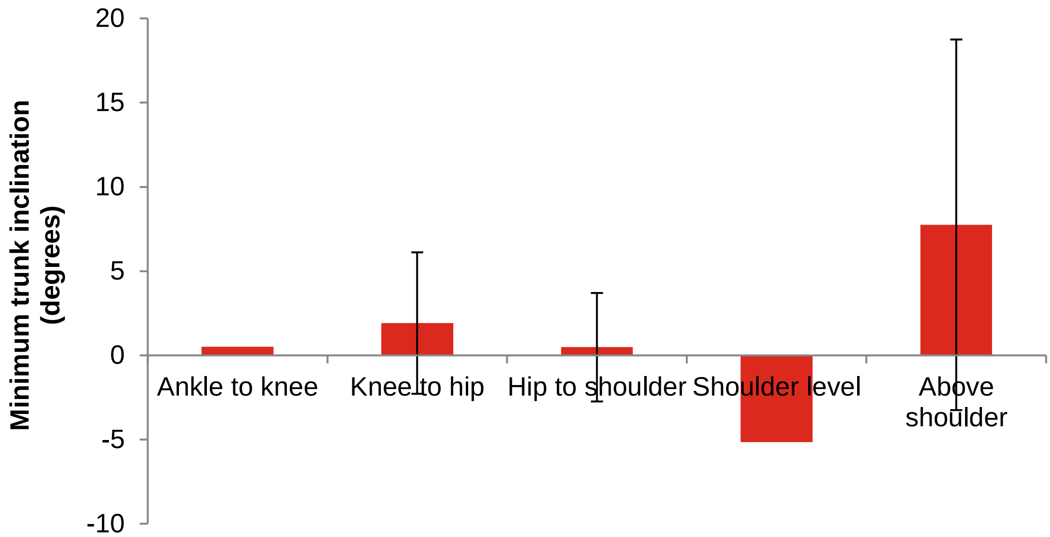
There was a reduction in peak trunk inclination as the height at which the spray of concrete was applied increased from ankle-to-knee to hip-to-shoulder working heights. Peak trunk inclination was above 40 degrees and occurred at the ankle-to-knee and shoulder level working heights.



(Note that sixth value at ground level was not used because width of spray that resulted in area of application was always higher than ground level.)

Figure 5.7: Peak trunk inclination values (mean ± SD) for the different levels of application of concrete.

The average minimum trunk inclination was similar across the heights below shoulder level, ranging from 0.5 degrees to 2 degrees (Figure 5.8). However, the average minimum trunk inclination during shotcreting at shoulder level was about -5 degrees of trunk extension, and about 8 degrees of trunk flexion above the shoulder.



(Note that sixth value at ground level was not used as width of spray that resulted in area of application was always higher than ground level.)

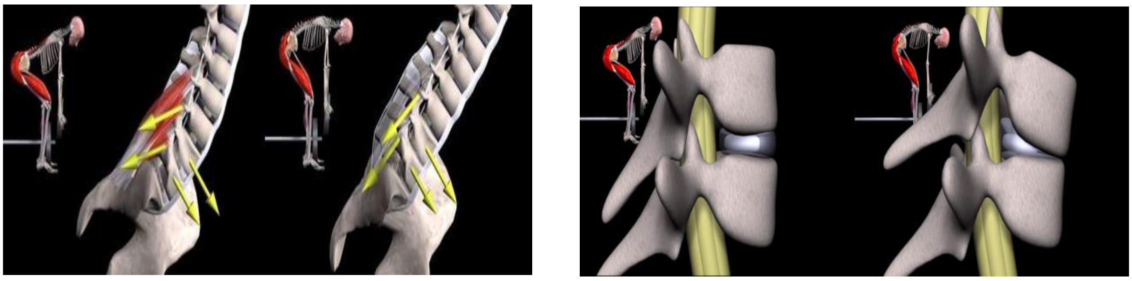
Figure 5.8: Minimum trunk inclination values (Mean ± SD) for the different levels of application of concrete.

5.5.1.3 Time duration above 40 degree trunk inclination

Another way of reflecting on the impact of work postures and movements, in particular a participant's back posture and movements, is to consider what proportion of their total work cycle time was spent within each postural category, or above postural thresholds. WorkSafe Victoria's *Manual Handling Code of Practice* (WorkSafe Victoria, 2000, page 17) indicates trunk postures and movements greater than 20 degrees inclination present a higher risk to workers than lower postures and movements.

However, considering trunk inclination data above or below this value as being hazardous or safe is simplistic and provides little sensitivity regarding postures and movements greater than 20 degrees. This approach is not consistent with biomechanical models. These models show that the net anterior shearing force (horizontal force) acting on the intervertebral discs within the spine significantly increases with trunk inclination and lumbar flexion. This is due to reduced capacity of back extensor musculature (for example, longissimus thoracis and iliocostalis lumborum) to generate posterior shearing forces within the vertebral column Left **panel** **Right panel**

Figure 5.9). Accordingly, using 20 degrees of trunk inclination as a single threshold value could result in underestimating physical work demands and injury risks.



Left panel Right panel

Figure 5.9: Left panel: schematic representation of anterior and posterior shearing forces within vertebral column. Posterior shearing force, generated by back extensors, counters anterior shearing force generated by trunk inclination and lumbar flexion. Right panel: combination of trunk inclination and lumbar flexion can lead to disc rupture where anterior portion of disc is squeezed.

Source: Muscle and Motion Ltd (2017)

Consideration of trunk inclination in categories greater than 20 degrees can provide a more descriptive understanding of the nature of the task. This type of analysis is now possible with movement sensing technologies (for example, Xsens system). It provides an objective way of investigating work exposures to awkward or hazardous postures and movements for occupational tasks.

A threshold value of 40 degrees is used for all construction tasks assessed within this project, thus providing common means for comparing this factor between each task. An investigation of the proportion of total work cycle time spent in the higher range of trunk inclination (that is, above 40 degrees) provides critical insight into the inherent requirement of the task. The figures below show the per cent of time spent in a trunk inclination posture of more than 40 degrees.

Only a very small percentage of task time (3%; 1.8 seconds) was spent at more than 40 degrees trunk inclination when directing the spray at the lowest height of ankle-to-knee. The percentage of task time spent at more than 40 degrees trunk inclination for the other shotcreting heights is considered to be insignificant, falling below 0.6%. This shows that for a significant time period (97% or more) the participants' trunk postures were not extreme. The mean trunk inclination value interval of 12-20 degrees would be regarded as most representative of the nature of back and trunk movement for shotcreting.

The video images obtained in conjunction with the data indicate participants can adopt a static work posture for a sustained period of a cycle of shotcreting to direct the spray of concrete to one or more height levels. For example, participant 9 demonstrated very limited trunk movement over the 25 minute (approximate) duration. However, participant 1 was observed to bend mostly more than 40 degrees of trunk inclination to grasp and manipulate the hoses. This participant did not adopt trunk inclination above 40 degrees while holding the hose to spray concrete at any level.

5.5.2 EMG – muscle activity

5.5.2.1 Holding the hose and spraying the wall

EMG for shotcreting was reviewed. The period analysed was when the participant held the hose, moved forward with the hose pressurised, and directed the spray, and then moved back to an upright posture as the hose pressure reduced.

Selected EMG results have been reported to describe the impact on the participant's back and upper limbs. A reference line at 100 % of MVC has been included to highlight each value relative to this benchmark value (Table 5.1, Figure 5.10).

Table 5.1: Representative peak EMG values for measured muscle groups.

	Shoulder	Mid Thoracic		Lumbar		Wrist Extensors	Wrist Flexors	Bicep
%MVC	Right	Left	Right	Left	Right	Right	Right	Right
Representative %	44.2	15.6	124.4	101.7	173.3	69.1	59.9	24.5

(Note that the data has been reported relative to the peak MVC EMG data for each muscle group)

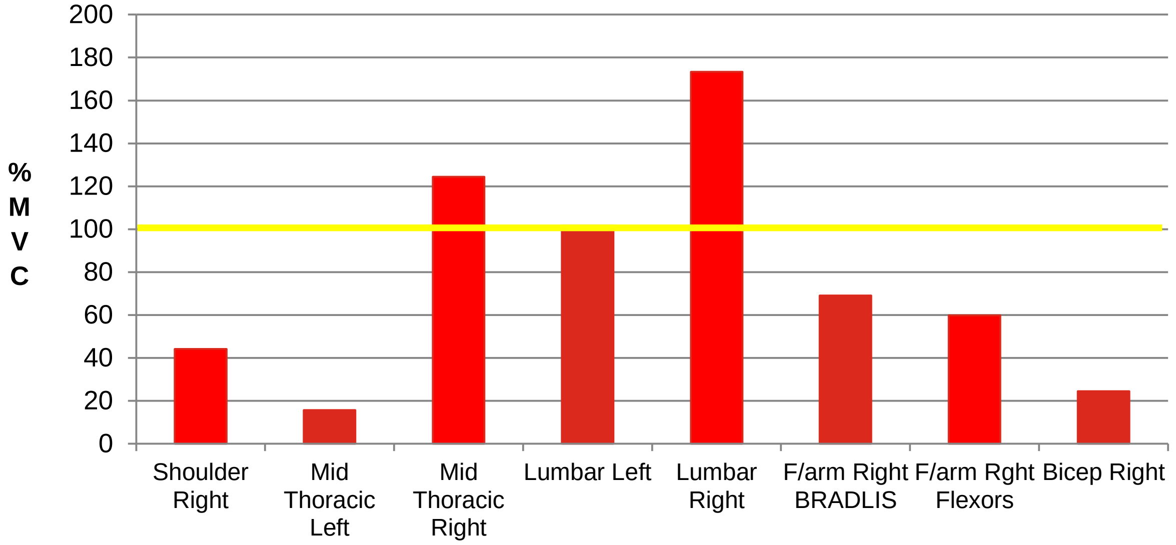


Figure 5.10: Plot of EMG results for a period of sustained shotcreting.

These results demonstrate high levels of bilateral lumbar, and right mid thoracic back muscle, activity to stabilise the participant during this sample of shotcreting. Moderate levels of right forearm muscle activities were also seen.

These EMG findings were considered as representative of this task where the highly experienced participant was likely to be very efficient with the timing of his movements and the avoidance of unnecessary or inefficient movements. Nonetheless, these EMG values are high, particularly those for the middle and lower back. They demonstrate a high level of physical exertion to maintain the hose on the shoulder to spray the wall.

It should be noted that these mid and low back EMG values were exerted as the participant adopted a relatively static posture, while remaining in an almost neutral upright, standing posture with minimal variation or movement. There were no sudden or ballistic movements to create a sudden peak force. The high EMG values obtained were representative of the sustained force exerted to hold the hose in place and direct it during periods of peak flow.

5.6 Discussion

5.6.1 Implications of the results

Considering the trunk inclination data described in Section 5.3, it is apparent that shotcreting mostly involves adopting relatively fixed and upright back and trunk postures. Participant 9 consistently demonstrated these postures. His trunk inclination varied only slightly within 40 degrees during the 25 minute assessment period of his shotcreting. That is, participant 9 only occasionally and momentarily moved to a 40 degree trunk inclination position when he was adjusting his overall position. He did not apply concrete while in this position.

Participant 7 adopted greater variety in his trunk movement as he used three specific holding positions at hip, mid-chest and shoulder-level. He also used a greater range of movement to place the hose over his shoulder and remove it when he needed to move the spray at a lower level. However, his range of trunk inclination for the sustained postures used to apply the concrete was limited, with minimal time spent with a trunk inclination angle greater than 40 degrees. Participant 7 demonstrated the greatest trunk inclination angles when applying the concrete at lower heights.

Limited trunk inclination was found for both participants when using their body weight to lean against the hose to maintain its position for spraying, particularly when the hose was supported on the participants' shoulders. This is an irregular work posture, particularly when sustained or repeated over a working day. It raises the issue that in performing their work, shotcreters apply awkward, and probably very high force, exertion. The magnitude and duration of forces exerted by each shotcreting participant which cause them to adopt these work postures, as well as the forces exerted to move the hoses, requires further investigation.

Measuring forces applied by shotcreters to handle and hold hoses to perform their work was not within the scope of this project. However, the static weight of the loaded hose used by participant 7 at site 5 was measured at the point at which he held it. This measurement was 19 kilograms weight force (186 N), indicating the consistent vertical load handled by shotcreter to lift, move and hold the hose would be at least of this magnitude. Dragging the hose along the ground and lifting it up to place it over a shotcreter's shoulder is likely to involve a higher level of force than 19 kilograms because of friction of the hose on the ground as it moves or the increased speed of movement to move the hose up or down.

This level of force exertion would be regarded as moderate to high where 27 kilograms (265 Newtons) of lifting force exertion is regarded to be a maximum acceptable level of force because of joint compression forces (Mital et al., 1993).

When discussing force exertion with participant 9, he put forward that the force he exerts when leaning on the hose to hold it and direct its flow is about a 70 kilogram weight force (687 N). He made this estimate based on his extensive experience at handling loads of this weight over his working career.

This level of force exertion would be regarded as very high and inherently hazardous. Both participants demonstrated conservative postures when performing this work. However, it is apparent that they work on ground surfaces of variable condition. Any sudden or unintended movement could cause them to become unbalanced and result in changing their body position and posture to a position from which they may be unable to continue to exert this level of force to hold the hose. In this situation, any sudden movement of the worker or the hose could result in them having to suddenly exert high forces to prevent themselves from letting go of the hose. This would increase their risk of a musculoskeletal injury and create exposure to a secondary hazard of the hose 'whipping' about and striking anyone within its proximity.

The nature and magnitude of this force exertion for shotcreting is a key finding of the assessment. Direct measurement of forces exerted could not be conducted. However, the EMG data reviewed supports this assumption as high levels of back muscle activity occurred to maintain the participant's static and upright body posture while he controlled the hose to spray concrete against the wall.

The range of trunk and back postures was found to be moderate. However, adopting sustained and high level of force for periods of more than 30 minutes per session, or cumulatively for more than two hours within an 8-hour shift, are defined by WorkSafe Victoria in the *Manual Handling Code of Practice* (WorkSafe Victoria, 2000, p. 20) as being a long duration and the threshold values for hazardous exposure.

5.6.2 Task redesign considerations

Shotcreting work requires moderate to very high force exertion on hoses to move and hold them for the full duration of the task. Given this, adaptive devices to improve grip and posture are unlikely to be sufficient to prevent or reduce the nature of sustained force exertion.

Accordingly, options to eliminate sustained exertion of moderate to high forces when performing shotcreting work is considered a more viable and effective task redesign option.

5.6.3 Shotcreting redesign objectives

Based on this assessment of shotcreting, the following objectives for design of a mechanical shotcreting device have been identified, but would not be limited to:

1. Eliminate sustained, awkward and moderate to very high force exertion by the operator when manually carrying, holding and directing a loaded hose of concrete while the contents are sprayed onto the target surface. Pursue elimination, or limit awkward, sustained postures and movements, while simultaneously maintaining at a minimum level (and where possible improving) the full and usual range of operational and quality provisions for shotcreting. These provisions would include:

- Ability to direct the flow to a vertical or oblique wall from low and high positions at a range of different angles, at least replicating those currently performed by a person. The lowest and highest settings should be at least 700mm and 1800mm respectively. These dimensions are from the ground to the mid point of the concrete hose outlet.
- Move the hose and flow of concrete from side to side, over a range of approximately 1500mm, so that it is applied as required.
- Ability to quickly direct the flow back to the adjacent area most recently covered when requested by operators who are screeding the surface and require more material to establish a consistently flat finish.
- Maintain visual control over the area of application of the concrete to ensure the required volume and quality of coverage and compaction is achieved.
- With minimal or no manual force exertion, ability to move the entire hose and mechanical device to one side, by up to 2 metres per time, so the device can commence shotcreting on the next, and usually adjacent, area requiring application.

2. Ability to perform shotcreting over the usual range of ground surfaces for this activity. To achieve this, standards for ground surfaces may need to be adopted to ensure a consistent and functional surface of a specific depth, angle and surface finish is provided to maximise operational effectiveness, and to eliminate tripping and other hazards.

3. Ability to operate so that nearby team members can perform their work smoothing and screeding the surface. This will require maintaining the supply of concrete through the hose without team members being adversely affected by the shotcreting operator or operation, or being exposed to any new hazards.

4. Ensure the level of noise emitted by the device is within, and preferably below, existing noise exposure standards.

5. Ensure the device presents no electrical, mechanical or plant safety hazards for shotcreters or others involved in preparing, transporting, maintaining, cleaning or general operation of the device.

6. Ensure there is no exposure to hazardous substances for the shotcreting operator, others working nearby, or those who might otherwise need to use or service this device.

5.6.4 Prospective design concept and features

To satisfy the proposed design criteria outlined in Section 5.6.3, general design features are proposed for a mechanical shotcreting device (Figure 5.11, Figure 5.12, Figure 5.13). These features listed below could also be used to develop a robotic device, an initiative that is strongly indicated. A pathway of progressive mechanisation may support a process of identifying and overcoming subtle design criteria and functions of a mechanised shotcreting device, initially retaining an element of human control in operating the device. The proposed design concepts and features include:

1. Use a mobile device, such as a platform trolley, that can support a structure, such as a pillar, onto which shotcreting hoses (concrete and air) are connected.

2. Enable the operator to vertically raise and lower this support structure and the attached hoses over the height range usually performed when shotcreting a wall.

3. To achieve vertical tilting of the hose, an independent ‘head’ on top of the pillar or similar support structure may be required.

4. Potentially design the handles and spraying head as robotic devices (exoskeletal force and assistance movement systems) so any movement or force exertion by the operator is enhanced.

5. Power the device mechanically so an operator can move it to, from and within an area, without the need to push or pull it manually.

6. Enable the operator to easily activate controls to move the device, while eliminating or minimising any hazards or risks such as the operator driving the device into themselves or over their foot.

7. Enable the device to move over the range of ground surfaces usually found within building or rail construction sites that require shotcreting to be performed.

8. Ensure the overall structure has the smallest possible footprint.

9. Ensure the device provides inherent stability during shotcreting, able to resist the force of the hose and prevent the device from tipping over. Counterbalancing devices activated for operational use, like those used with cranes, may be required so the device is stable and balanced when transported and set up. Ensure this balance can be changed to offset the tipping force exerted through the hose once the flow of concrete commences.

10. Enable the operator to control horizontal (side to side) and vertical (height and hose spray angle) activity with minimal physical effort, and ensure controls are at least as effective as an operator manually holding and moving the hose to apply concrete.

11. Install two level indicators at right angles so they display the trolley’s position lengthways and side to side. The trolley should only be used when the level markers are within a defined ‘safe’ zone, or include a facility to tilt the trolley platform to achieve this balance so the platform can be adjusted so it is within this zone before the device is used. Indicators should be positioned and large enough so they can be seen by the operator from their usual operational position.

12. The trolley should use four, large diameter wheels or tracks.

13. Two vertical handles are recommended to enable the operator to control the angular movement of the ‘head’ and direction of the flow and spray of concrete.

14. The handles should provide the following features:

    - 1000mm long.
    - 30mm diameter.
    - Vertically oriented.

- Coated a yellow/orange colour for optimum visibility.
- Have no sharp edges, protrusions, prominences, catching, pinching or jamming points.
- When set to their lowest position, the lower ends of the handles should not present a foot jamming or trapping hazard for the operator. To maintain toe clearance for the operator, a minimum clearance of 100mm is required below the lowest point of the handle.

This handle design should enable most users to work with their hand(s) approximately at elbow height, regardless of the height at which the concrete is being sprayed within its overall height range.

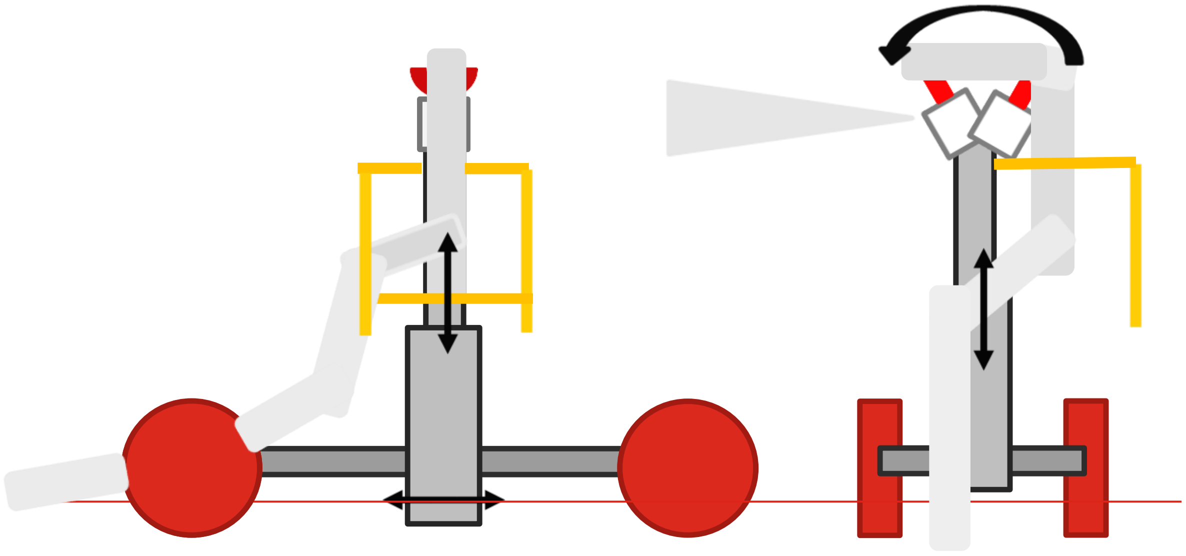


Figure 5.11: Front and end views of a proposed mechanical shotcreting device.

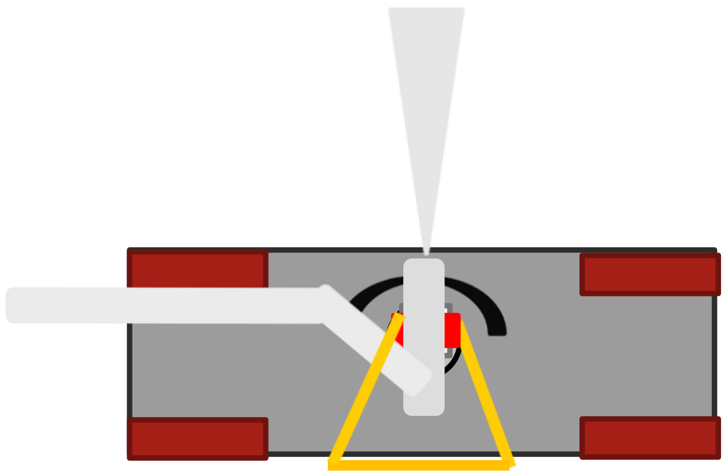


Figure 5.12: Plan view of a proposed mechanical shotcreting device.

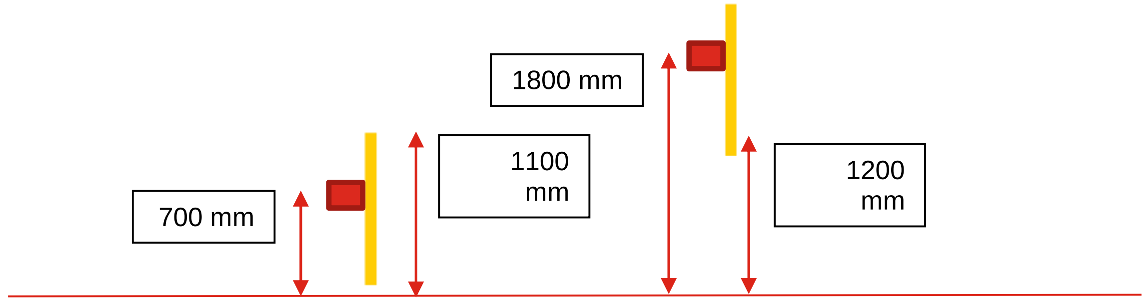


Figure 5.13: Device handle dimensions and height ranges, relative to suggested spray head height range, for maintain grasping point at approximate elbow height for shotcreter operator.

5.6.5 Conclusions

This assessment found limited levels of trunk movement for shotcreting tasks. It also highlights the sustained nature of these tasks and the need for shotcreters to exert moderate to very high forces for extended periods within a shift. This drew the focus of the assessment to the nature of this force exertion and its likely impact on shotcreters.

Consideration of alternative methods for manually handling and holding shotcreting hoses was made but no obvious improvements were identified. This led the researchers to consider options of eliminating or substantially reducing the nature and duration of this force exertion.

Initial design considerations and criteria were proposed for a portable, mobile device that supports the hose and enables it to be directed with at least the same level of accuracy afforded by currently used manual methods. This design considers the environment in which shotcreting occurs and incorporates feedback from discussions with research participants and contractors engaged in shotcreting work.

Part 6: Cable pulling

6.1 Description of work task

6.1.1 Overview of cable pulling work

Cable pulling work investigated in this project involved work crews setting cables in place along the rail corridor for new signalling equipment. From direct observation, this work involved feeding cables from large, vehicle-mounted reels through underground conduits on a point-to-point basis. The conduits are connected by circular, vertical pits. Upper edges of the pits were at ground level and the depth of each pit was approximately 1500mm. Each pit was covered by a large lid or cover, and the diameters of the pits and covers were approximately 800mm. They are wide enough for a person to be lowered into. Even though the pits are covered, they are not water or pest proof. Water in a pit may have to be pumped out, or pests, such as snakes or rats, removed before entering the pit.

Prior to the cable pulling, another work group feeds a series of ropes through each conduit. The ropes protrude from each end of the conduit and are accessible within the pits. These ropes match the number of different cables to be pulled through.

The cables to be set in place are stored on large rotating drums at the rear of a truck. More than one type of cable can be pulled through at the same time. Initially, the cables to be laid are manually pulled from the truck and then the ends of these cables are bound together with tape (Figure 6.1). The bound cables are then pulled to the pit and tied to the designated pulling ropes. The tied ends are then fed into the opening of the conduit to position them for the pull through. The crew then moves to the next pit and a member is lowered into the pit. This person grasps the pull rope and brings it to the upper edge of the pit where it is accessible. Another member then grasps the rope and commences to pull it through the conduit and pit. Once the end of the cable is pulled through the conduit and up to the edge of the pit, the cable is then pulled through until the required length is achieved. Drag on the cable increases with the length of the conduit. Long conduits require crew members to exert very large pulling forces. Crews have the option to use a vehicle-mounted, mechanical cable pulling machine. However, vehicle access, a suitable ground surface, and clearance around the pit, are necessary for this mechanism to be used.

Figure 6.1: Commencing the cable pulling tasks using a standing position only.

6.1.2 Cable pulling equipment

The task of cable pulling is mainly performed without mechanical assistance (Figure 6.2). However, on the day of our assessment a mechanical cable pulling device was reported to be available if required. The crew members observed stated they usually use the device to pull the cables through longer conduit distances due to the high pulling force required to drag cables through the conduit.

Figure 6.2: Guidance and protective devices used for ropes and cables within and on upper edge of pit.

Two devices were observed being used for guiding and protecting ropes and cables as they are pulled over sharp edges at the end of a conduit and the edge of a pit, and to reduce drag forces.

One device was a 90 degree, curved component inserted to the end of the conduit through which the rope and cables were being pulled. To insert and remove this item, a worker climbed into the pit after it had been drained (if required), and checked for vermin or other hazards. Inserting and removing this guide at the end of the inlet conduit was observed to require the worker to reach and bend down slightly. The size and weight of the device was low, and this task was performed quickly and infrequently. While space within the pit was limited, this task was not observed or reported to be hazardous or require controls or improvements.

The second device had small rollers and guides. It was positioned on the ground at the edge of the pit with the cable running over the top of it. The device was applied by a worker standing on the ground next to the edge of the pit. A pit lid removal lever was used to remove and replace the pit lid, while a small submersible, mechanical pump was used to empty one of the pits that filled with water to a depth of approximately 500mm.

6.1.3 Work methods

Cable pulling was observed to involve the crew member first bending and reaching to ground level to grasp the rope or cable. He then moved to an upright standing position, pulling the rope or cable upwards during this movement (Figure 6.3).

Pulling the rope or cable through a relatively short distance is generally performed by one crew member. As the cable is pulled through, another crew member positions the sections of cables on the ground. This method was seen at site 8 where the cable was pulled approximately 25 metres under railway tracks from one side of the rail corridor to the other side.

For this method, a second crew member stood directly behind the member pulling the cable. The second crew member held the lower sides of the cable puller's outer safety vest. This was a risk control strategy to limit the likelihood of the puller losing their footing or stumbling and falling forward into the pit. This strategy was not endorsed but has been described in this report as its use is a form of acknowledgement by current operators that there is some form of risk of the participant stepping or falling into the pit for which a control strategy is required. A strategy such as a robust physical barrier would be more effective and is described later in this section.

To pull the rope over longer distances, several crew members pull on the rope together. Alternatively, a mechanical pulling device is used, but this was not seen during either assessment.

Figure 6.3: Sequence of cable pulling movements.

The method of several crew members pulling on the rope and cable was seen at site 6. This location was also next to rail tracks, within the rail corridor. The pull distance was approximately 80 metres. This method involved the first crew member (the participant in this investigation) reaching and bending down to grasp the rope and pulling it up as he moved to an upright position. He then turned to face away from the pit in the direction the rope and cable were to be pulled, which was parallel to the train tracks. As he turned, he raised the rope and placed it over his shoulder. He then held the rope with both hands in front of his torso and began to walk away from the pit. As his distance from the pit increased, he began to lean forward while continuing to walk, using his body weight to help exert the force needed to keep pulling the rope and keep the cable moving. As the distance from the pit increased, more pulling force was required. To increase the force, the participant increased his forward lean. Once resistance became too high he stopped walking, let the rope or cable drop to the ground, and walked back to the pit to recommence this cycle.

At the point when resistance forces became too high for the crew member, he would ask for assistance from other crew members. Alternatively, other crew members joined in the cable pull when it became clear the crew member was struggling. Sometimes, this involved members successively assisting with the task. This involved positioning themselves approximately 10 metres apart so, at its peak, there were either three crew members pulling the cable, or two members pulling the cable and one walking back to the pit to re-establish his grasp.

Once the cable had been pulled out to a sufficient length, all crew members stopped pulling and proceeded to the next step of the process. The next step was either to prepare to pull the cable through the next section of conduit, or to coil the cable up and leave it in the pit for the next stage of the signalling construction process.

6.2 Pilot work to refine assessment method

6.2.1 First cable pulling assessment

This first cable pulling assessment was conducted at site 6 on 25 August 2017. At this location, the crew was required to pull the lead rope and attached cable through an underground conduit approximately 100 metres long. The rope had previously been fed through the conduit. The cable pulling involved the participant initially pulling the rope through the conduit until the rope was completely pulled through and the end of the signalling cable was brought through at the end of the rope. The cable was then grasped and pulled through until there was sufficient length to run it through another conduit leading from the same pit to another pit closer to the railway line. The cable was then pulled through the second conduit to the point at which the cable would later be connected to rail signalling equipment.

Initially, the participant pulled the rope through by himself. Once the cable was available to pull, the participant started to pull it through the conduit but was then assisted by his coworkers until the required length of cable had been pulled through.

Work group members reported this method was representative of their usual work task, except they would usually assist earlier than they had in this instance. For demonstration purposes, they delayed their assistance to maximise the period the participant spent pulling the rope through.

The workers subjectively reported that the forces exerted by the team pulling method were reasonable and safe. They also reported that if the level of force being exerted was judged to be too high, the vehicle mounted mechanical cable pulling device would be used. The criteria used by group members for deciding on use of a mechanical pulling device were not explained.

Review of the Xsens data, coupled with the video footage, revealed a distinct downward reaching action, every time the participant re-established his grasp over the cable. Without having measured the pull forces involved, as this was not within the scope of the method for this project, it was apparent that a peak level of force to pull cables occurred at this point. This was determined when the participant at both site assessments was the only person pulling the cable, because he leaned and reached forward and used the rearward movement of this body as a cantilever to initiate the force required to move the cable. At the first site 6 assessment, and when the participant was being assisted by three coworkers to pull the cable through, similar initial pulling movements of these cables was also observed and recorded, even though additional force was being applied to the cable by the other workers.

With this in mind, future design considerations should seek to reduce the impact of this combination of high forward trunk inclination and apparent high force exertion. A reduction in trunk inclination to exert these forces should reduce shearing forces in the back.

6.2.2 Development of a trestle to raise the access height of cables

To address the considerations described above, a simple design was developed to raise the height of the rope and cable at the edge of the pit to reduce forward trunk inclination of those crew members pulling them. This involved fixing a PVC pipe to the top of a timber trestle (see Figure 6.4). The trestle dimensions were: 90mm diameter of PVC pipe, pipe length of 500mm, and a trestle height of 770mm. Corner sections and short vertical barriers using the same material were installed at each end of the pipe to prevent a rope or cable from sliding off either of the ends.

This device was tested and it was determined that members of the cable pulling and research team could hold the trestle down when being used by placing a foot on each end of the lower part of the trestle.

Figure 6.4: Trestle design and its features.

The works supervisor approved the trial of this device to evaluate its possible impact on cable pulling, on proviso there were no catch points and the device did not pose any threat of damage to the cables being pulled over it. This device was assessed in the subsequent assessment at site 8.

6.3 Research methods

6.3.1 Participant

The same participant was involved in the initial and subsequent redesign of the cable pulling task. The participant (age – 28yrs; height – 171 cm; mass – 71 kg) was reported to be able to competently perform all elements of the job, which he demonstrated during the assessment.

6.3.2 Description of work tasks

6.3.2.1 First cable pulling assessment

Data from the first assessment of this task was reviewed. Awkward back postures were reported within the Xsens data, in combination with likely high or very high levels of force. These results led to consideration of design options that could be easily and consistently applied to this work to reduce the impact of these hazardous factors.

6.3.2.2 Development of a device to improve postures for cable pulling

A method of reducing the range of back movement for the participant was considered as one strategy to reduce the physical demands of this work, and possible injury risks. A simple solution was developed that involved a trestle system (Figure 6.5). A 90mm diameter plastic pipe was fixed to the upper part of the trestle and vertical risers fixed at each end. The large diameter pipe provided a surface to pull the cable over. The risers prevented the cable from slipping off either end and falling to the ground when it might be damaged.

The second assessment at site 8 involved the same participant who performed the two methods of cable pulling: the usual method, and the other with the trestle in place just in front of the participant's static pulling location. At this site, only relatively short lengths of cable (approximately 30 metres) were to be pulled through.

Task one was to pull two types of cable from the reels on the truck and place them on the ground so there was sufficient length to feed through a conduit that extended under the rail tracks (Figure 6.6).

Figure 6.5: Task one, with and without the trestle.

Figure 6.6: Task two, with and without the trestle.

Task two involved pulling the rope and cable through the conduit on the other side of the tracks until approximately 20 metres of cable was available (Figure 6.6) that eventually could be extended to a signalling connection.

These tasks were of relatively brief duration. When these tasks were considered to be approximately 50 per cent complete, the trestle was introduced and the cables fed across the top of the trestle. The participant then continued to pull the cables until each task was complete, with the trestle remaining in place. Two members of the research team placed a foot at the base of the trestle on each side to hold it in place during testing for each task.

6.4 Data analysis

Four types of back posture and movement data (joint angular motion) were recorded by the Xsens system. These were trunk inclination (T12/S1), and lumbar joint motions at three levels of the lumbar region (T12/L1, L3/4 and L5/S1). The three lumbar joint motions were found to be small, falling around 2-3 degrees. Due to the low range of motion for these joints, only the L5/S1 results are described.

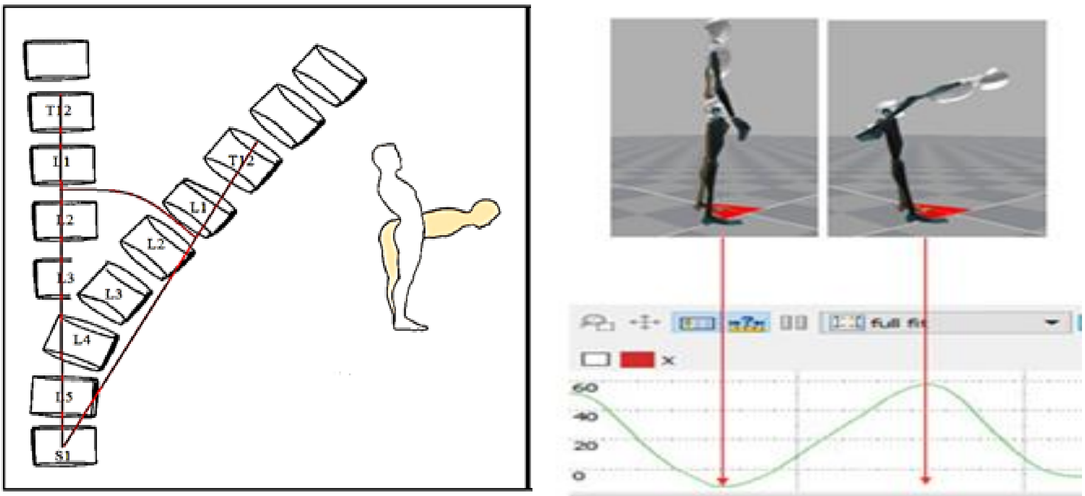
In addition, after initially observing high force exertion, EMG data was evaluated from the first cable pulling assessment that involved pulling cable through a longer conduit. This was done to evaluate and test the RMIT researchers' assumption that this task required high to very high force exertion.

6.4.1 Trunk inclination

Trunk inclination data (trunk forward flex/extension in the sagittal plane) were extracted by using the positions of the T12 and S1 vertebrae Left panel Right panel

Figure 6.7). This level was chosen as the data best matched a visual representation of the participant's trunk movements in this plane. A higher level vertebral, such as T8 within the back, was not used as angles from this level were greater than the apparent angle of the trunk, most likely reflecting greater mobility of the mid thoracic spine.

For trunk inclination, forward flexion is positive (+ve) or greater than zero. Rearward extension is negative (-ve) or less than zero.



Left panel **Right panel**

Figure 6.7: Left panel: schematic representation of trunk inclination angle (forward flexion in sagittal plane ≈ 30°). Right panel: avatar image of participant showing a standing position (trunk inclination ≈ -18° extension) and forward flexed position (trunk inclination ≈ 60°).

6.4.2 Lumbar flexion

Lumbar flexion data (Figure 6.8) were calculated within the Xsens system at three levels of the lumbar spine (low back), T12/L1, L3/L4 and L5/S1. The range of overall lumber flexion is determined by the relative position of the Xsens shoulder and pelvic sensors. This value is divided by the number of spine represented within these movements and then allocated to the different levels of the lumbar spine according to previously established proportions.

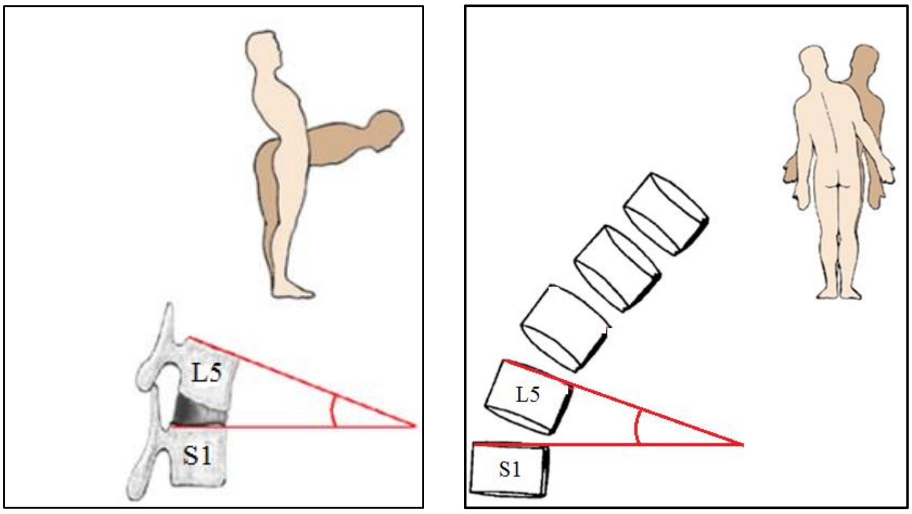


Figure 6.8: L5/S1 forward and lateral flexion.

These data at all three lumbar levels were reviewed and data at the L5/S1 level only was selected for reporting. This was because the range of movement at this level, relative to the two levels above, was much greater and more likely to represent any changes between different tools and work methods. Also, this level is the base of the spine where high levels of leverage and disc compression can occur and is commonly referred to the location within workplaces.

Lumbar flexion data at the L5/S1 level was analysed and reported for forward and lateral (side to side) flexion. Lumbar forward flexion has positive values while extension uses negative values. For lateral flexion, movement to the person's right side is positive while movement to their left side is shown with negative values.

6.4.3 EMG - muscle activity

EMG data for cable pulling was reviewed to investigate muscle activation relative to the RMIT researchers' observations that this task involved exerting high forces to pull cable through the conduit. In the absence of being able to measure these forces directly, an approach not defined in the original research method, EMG data can be used to provide some insight into the level of muscle contraction or intensity.

6.5 Cable pulling results

6.5.1 Trunk inclination

This section reports trunk inclination data (Figure 6.9) for the two cable pulling tasks at site 8, which involved participant 8 standing in a fixed position to pull rope and cables. These results are based on testing during these pulling tasks where, when approximately 10 metres of rope or cables had been pulled through, the trestle was positioned for the remaining duration of that task.

This provided two trials of the two different rope and cable pulling conditions where the participant remained standing in the same position while pulling cable from large drums mounted on the rear of the truck. The first trial involved the participant using the usual method for 20 seconds and using ten sequential pulling actions. The first trial with the trestle method extended for 15 seconds and nine pulling actions.

The second trial was conducted on the other side of the railway line. The participant used the usual method of bending and reaching down to the edge of the pit for 20 seconds and exerted ten pulling actions. The second method with trestle in place went for 23 seconds and involved 13 pulling actions.

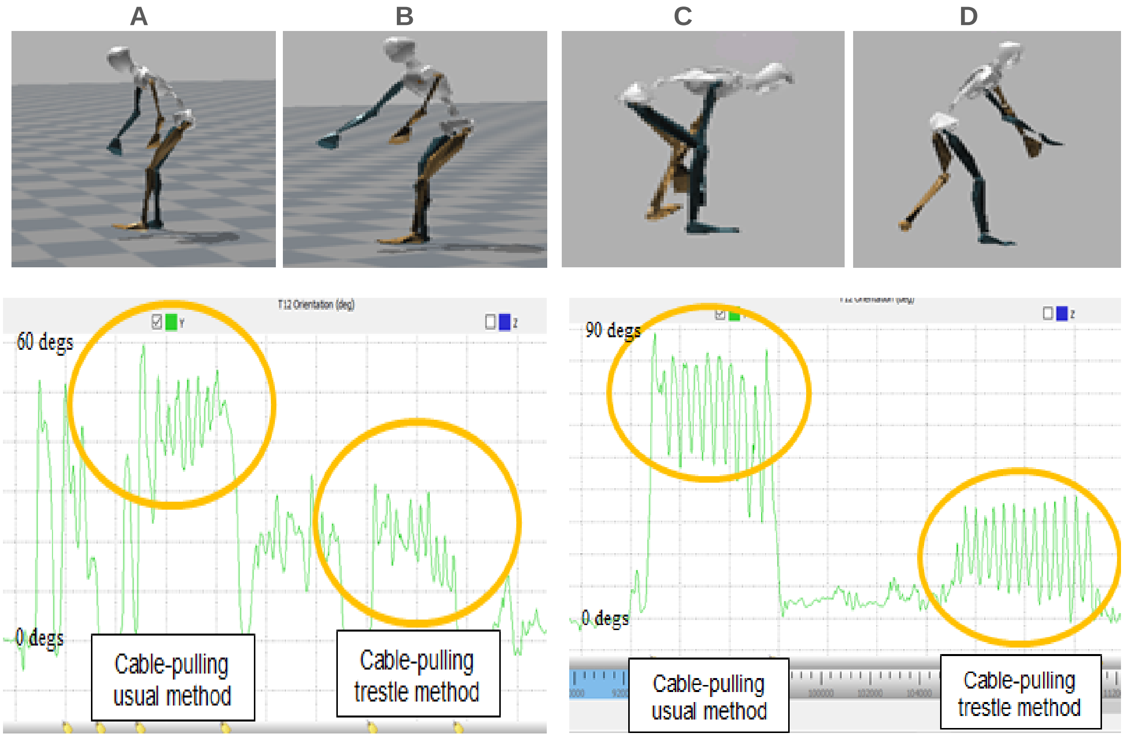


Figure 6.9: Xsens avatar screen images and trunk inclination graphs showing repeated pulling actions.

6.5.1.1 Mean trunk inclination

Mean trunk inclination for the usual method of cable pulling, when standing in a fixed position, would be regarded as high (42.9 ± 21.3 degrees). Introducing the trestle led to a reduction in the mean trunk inclination of approximately 50 per cent (mean 21.3 ± 0.03 degrees). This is much closer to the preferred threshold value of 20 degrees (Figure 6.10).

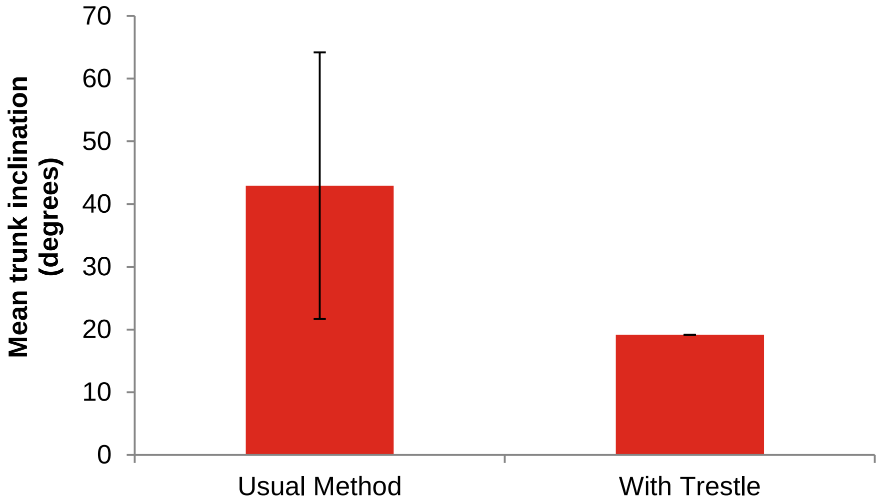


Figure 6.10: Trunk inclination (Mean ± SD) values for the usual and trestle methods.

6.5.1.2 Peak and minimum trunk inclination

Peak trunk inclination for the usual method of cable pulling (62.1 ± 20.5 degrees), when standing in a fixed position, can be classified as high. On average, the introduction of the trestle reduced peak trunk inclination by 27 degrees (34.9 ± 4.7 degrees) (Figure 6.11). Minimum trunk inclination also reduced from 16.9 degrees of forward flexion to a backward extension value of 1.5 degrees (Figure 6.12)

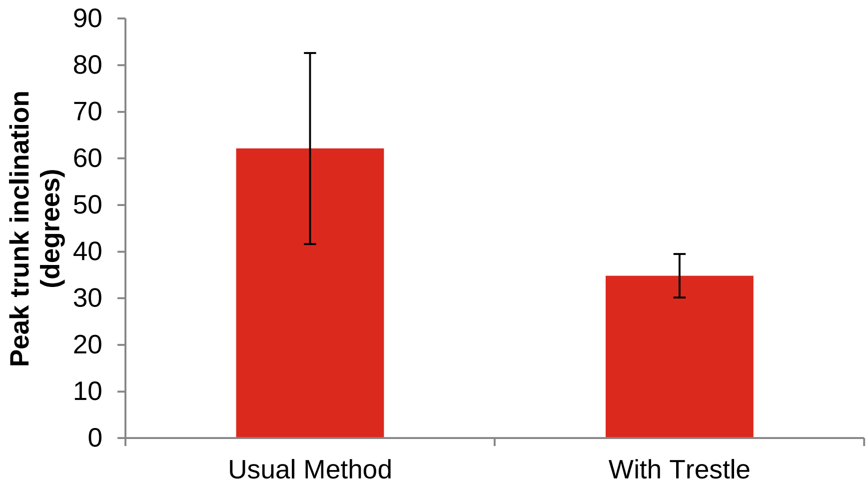


Figure 6.11: Peak trunk inclination (Mean ± SD) values for usual and trestle methods.

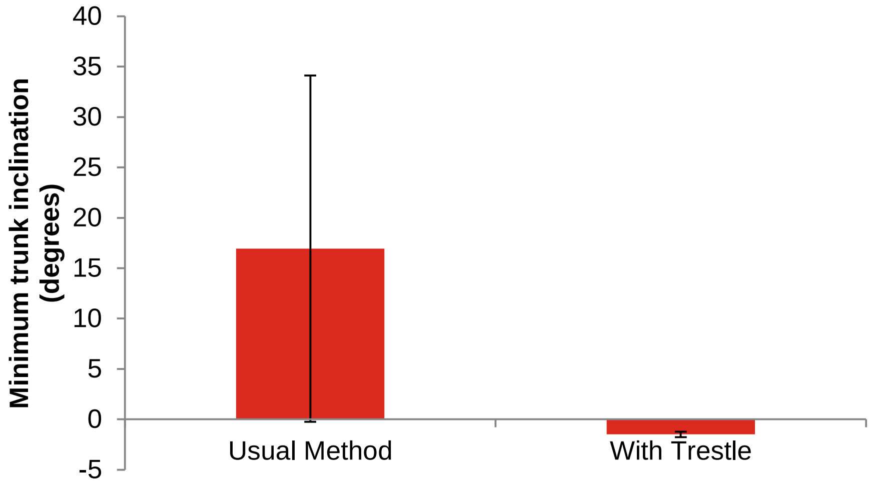


Figure 6.12: Minimum trunk inclination (Mean ± SD) for usual and trestle methods. Note that a positive value represents forward flexion whereas a negative value represents backward extension.

6.5.1.3 Per cent time duration above 40 degree trunk inclination

Another way of reflecting on the impact of work postures and movements, in particular a participant's back posture and movements, is to consider what proportion of their total work cycle time was spent within each postural category or above postural thresholds. WorkSafe Victoria's *Manual Handling Code of Practice* (WorkSafe Victoria, 2000, p. 17) indicates trunk postures and movements greater than 20 degrees inclination present a higher risk to workers than lower postures and movements.

However, considering trunk inclination data above or below this value as being hazardous or safe is simplistic. It provides little sensitivity regarding postures and movements greater than 20 degrees. This approach is not consistent with biomechanical models showing that net anterior shearing force (horizontal force) acting on the intervertebral discs within the spine *significantly increases* with trunk inclination and lumbar flexion. This is due to reduced capacity of the back extensor musculature (for example, longissimus thoracis and iliocostalis lumborum) to generate posterior shearing forces within the vertebral column (Figure 6.13).

Accordingly, using 20 degrees of trunk inclination as a single threshold value could result in underestimating physical work demands and injury risks.

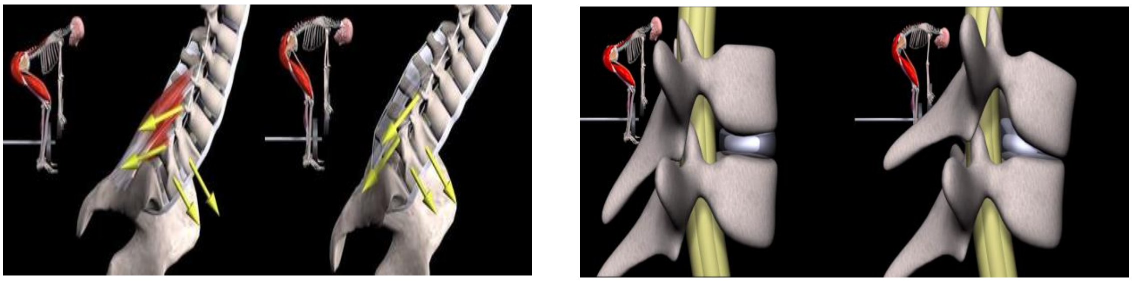


Figure 6.13: Left panel: schematic representation of anterior and posterior shearing forces within vertebral column. Posterior shearing force, generated by back extensors, counters anterior shearing force generated by trunk inclination and lumbar flexion. Right panel: combination of trunk inclination and lumbar flexion can lead to disc rupture where anterior portion of disc is squeezed.

Source: Muscle and Motion Ltd (2017)

Considering trunk inclination in categories greater than 20 degrees can provide a more descriptive understanding of the nature of the task. This type of analysis is now possible with movement sensing technologies (for example, Xsens system). It provides an objective way of investigating work exposures to awkward or hazardous postures, and movements for occupational tasks.

A threshold value of 40 degrees is used for all construction tasks assessed within this project, providing a common means of comparing this factor between each task. An investigation of the proportion of total work cycle time spent in the higher range of trunk inclination (that is, above 40 degrees) provides critical insight into the inherent requirement of the task. Figure 6.14 shows the percentage of time spent in a trunk inclination posture of more than 40 degrees. This figure represents a combination of data for tasks 1 and 2.

For the usual method of cable pulling, when the participant was standing in a fixed position, 56.0% of task time was spent with a trunk inclination greater than 40 degrees (Figure 6.14). After the trestle was introduced, the participant's forward inclination did not extend beyond 40 degrees at any time at either of the two cable pulling locations on this site.

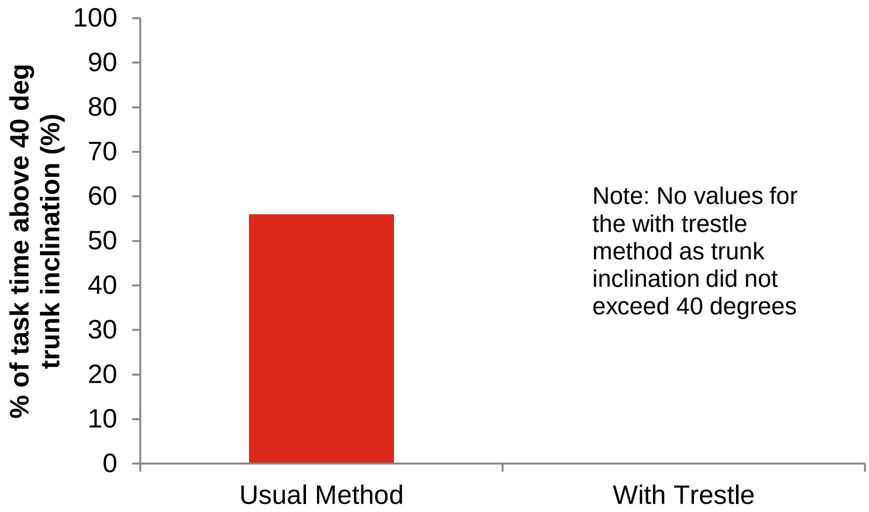


Figure 6.14: Per cent of total task performance time (Mean value) for both tasks, with the participant's trunk inclination greater than 40 degrees of forward flexion.

This value does not represent other elements of cable pulling involving the participant and crew members walking away from a pit with the rope or cable over their shoulder to pull it through the conduit. However, cable pulling from a fixed position was reported to be commonly performed and is consistent with the initial part of other cable pulling tasks where the person reaches to ground level to grasp the rope or cable to then pull it.

6.5.2 Lumbar forward flexion (L5/S1)

Peak and minimum forward flexion of the lumbar spine at the L5/S1 level was reduced when cable pulling was performed with the trestle, compared to without the trestle (usual method). The range of L5/S1 movement used to perform these tasks was similar between the two methods (usual method: 11.3 degrees, compared to with trestle: 12.3 degrees) (Figure 6.15).

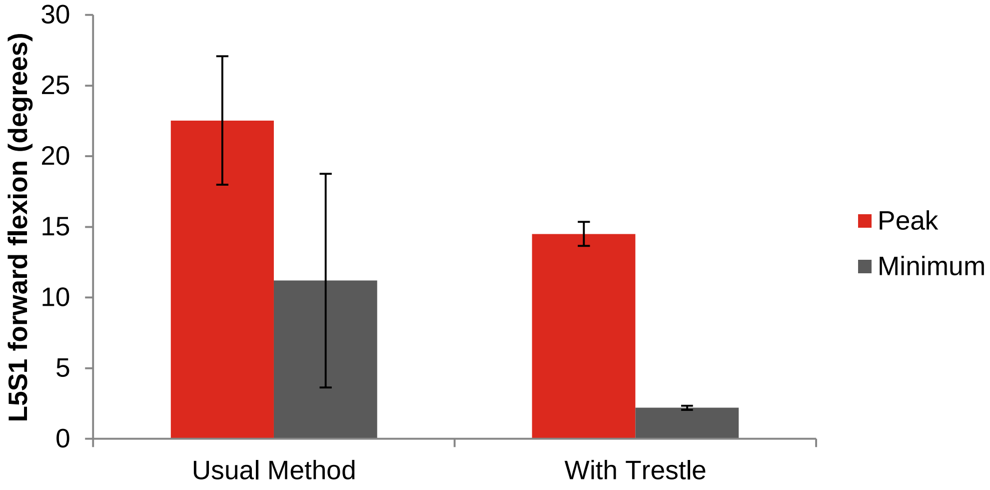


Figure 6.15: Peak and minimum L5/S1 forward flexion (Mean ± SD) values to indicate differences between usual and trestle methods.

6.5.3 Lumbar lateral flexion (L5/S1)

Minimum lateral flexion of the lumbar spine at L5/S1 level (Figure 6.16) was also reduced when cable pulling was performed with the trestle, compared to without the trestle (usual method). However, peak lateral flexion increased from 1.2 to 4.1 degrees. Note that range of movement in lateral flexion (peak minus minimum joint angle) was slightly less with the trestle (7.7 degrees) compared to the usual method (10.5 degrees).

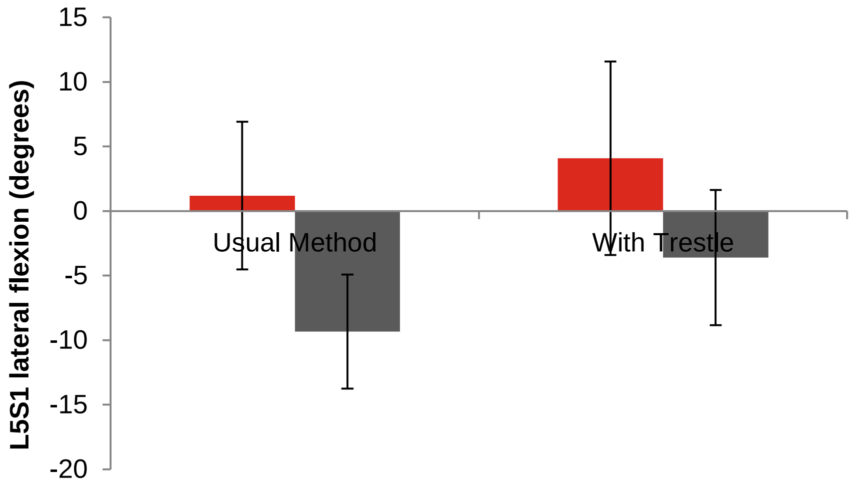


Figure 6.16: Mean peak (red) and minimum (grey) L5/S1 lateral flexion values showing differences between usual and trestle methods. Please note that right lateral flexion is positive and left lateral flexion is negative.

6.5.4 EMG - muscle activity

Two high force exertion periods were observed. First, when the participant was located at the edge of the pit to pull the cable through (Figure 6.17). Second, when he turned and walked away from the pit, pulling the cable as he walked with the cable anchored over his left shoulder (see Figure 6.18).

Figure 6.17: Participant 8 reaching down and then pulling upwards to pull the cable through the conduit, with observed high force exertion.

Figure 6.18: Participant 8 pulling the cable by placing it over his left shoulder and walking away from the pit, while others assist.

It was considered appropriate to validate the RMIT researchers' assumptions of high force exertion for cable pulling by reviewing the EMG data obtained at the first assessment. These data were not reviewed for the second assessment because the lengths of cable pulled at the second assessment were much shorter and the forces assessed to be less.

The EMG data reviewed for cable pulling included data captured from the shoulders, mid thoracic (mid back), mid lumbar (low back) and biceps (upper arm) musculature. These muscles were selected as they were considered most suitable to describe force exertion for this task.

EMG results were reviewed for two sample periods when the participant had grasped the cable with both hands and pulled it towards his body so the cable would be close to his right hip. The participant repeated this action until a sufficient length of cable had been pulled through for him to turn away from the pit, place the cable over his right shoulder, and start walking away from the pit and pulling the cable with him. Once the area in front of the pit was clear, a coworker stepped in, pulled the cable though several times before turning, securing the cable and walking away. Two other coworkers also assisted in this way so that once the participant had pulled the first section of cable through by himself, others were assisting simultaneously because it was not possible or safe for only one person to pull the cable through.

Once the participant had walked a distance where he was no longer able to move forward because of the high level of force being exerted, he dropped the cable and walked back to perform his next cycle of pulling the cable with his coworkers. This ‘leapfrogging’ approach was repeated until the required length of cable had been pulled through. Two samples of this walking and pulling task were also reviewed to assess EMG data.

Cable pulling with two hands

<u>First sample</u>

The peak EMG data for two repetitions of this method of pulling the cable were investigated for the arm pulling phase of this task. Peak EMG data were extracted for six arm pulls of the cable. Because the focus was on seeking to evaluate if high to very high forces had been used, the muscle groups most affected by this method were evaluated. The Mean ± SD values for the peak EMG data, expressed as a percentage of the MVC, are shown below (Table 6.1 and Figure 6.19, Figure 6.20, Figure 6.21, Figure 6.22).

Table 6.1: Peak EMG (Mean ± SD) values, expressed as percentage of MVC, for first two handed cable pulling task.

%MVC	Shoulder Left	Shoulder Right	Mid Thoracic Left	Mid Thoracic Right	Lumbar Left	Lumbar Right	Bicep Left	Bicep Right
Mean (%)	12.1	143.0	65.3	89.9	196.8	143.2	7.6	62.6
SD (%)	5.2	53.1	15.4	11.4	40.2	20.2	0.9	9.0

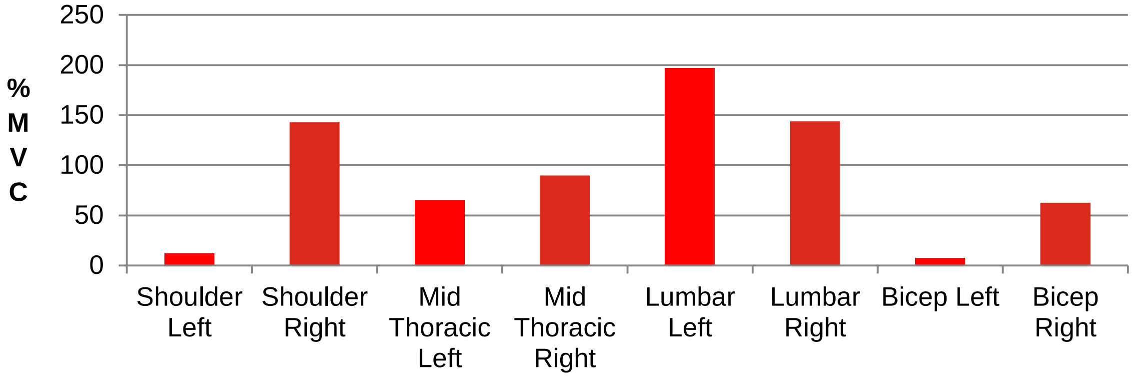


Figure 6.19: EMG values, Mean ± SD, expressed as a percentage of the MVC, for the first two handed cable pulling task.

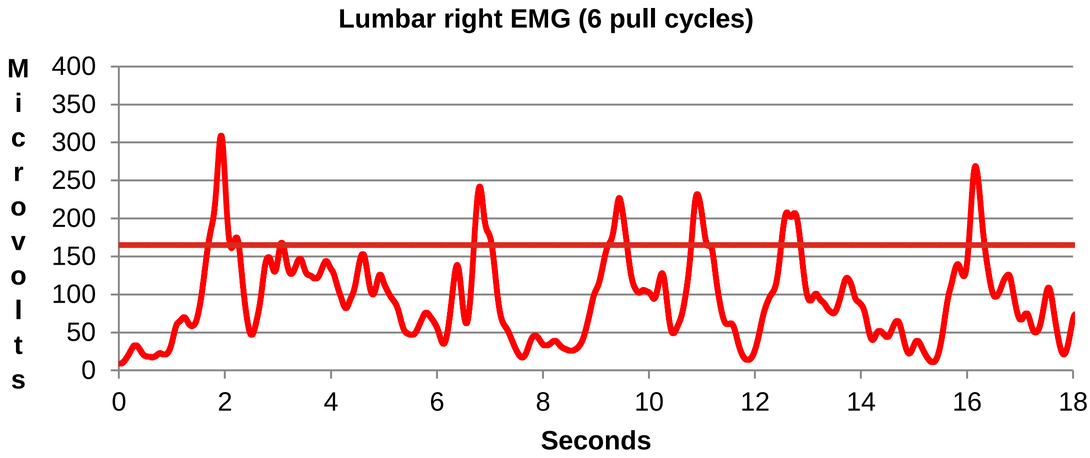


Figure 6.20: Time line plot of right lumbar EMG data showing six pull peaks above MVC level (represented by the red horizontal line) for the first two handed cable pulling task.

<u>Second sample</u>

Table 6.2: Peak EMG (Mean ± SD) values, expressed as percentage of MVC, for second two handed cable pulling task.

%MVC	Shoulder Left	Shoulder Right	Mid Thoracic Left	Mid Thoracic Right	Lumbar Left	Lumbar Right	Bicep Left	Bicep Right
Mean (%)	10.4	152.1	64.6	91.9	175.5	134.6	16.8	61.3
SD (%)	4.4	49.9	12.2	12.3	50.1	18.9	21.7	8.9

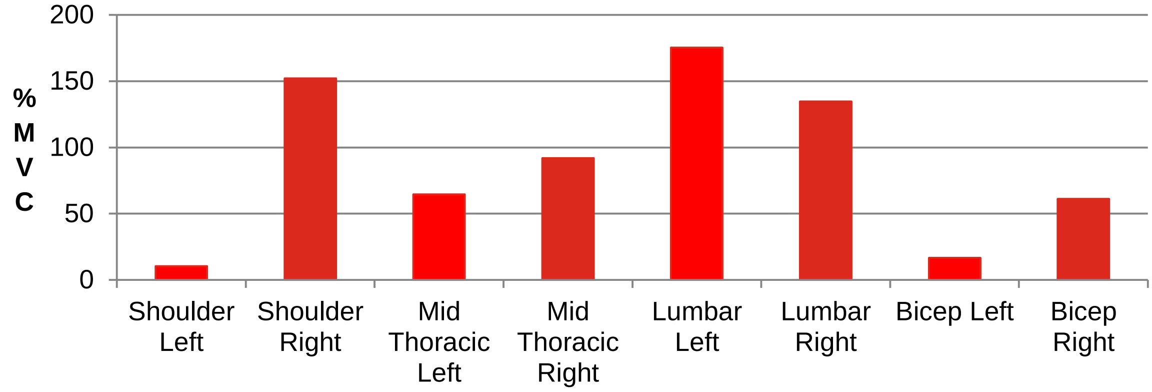


Figure 6.21: EMG values, Mean ± SD, expressed as a percentage of the MVC, for the second two handed cable pulling task.

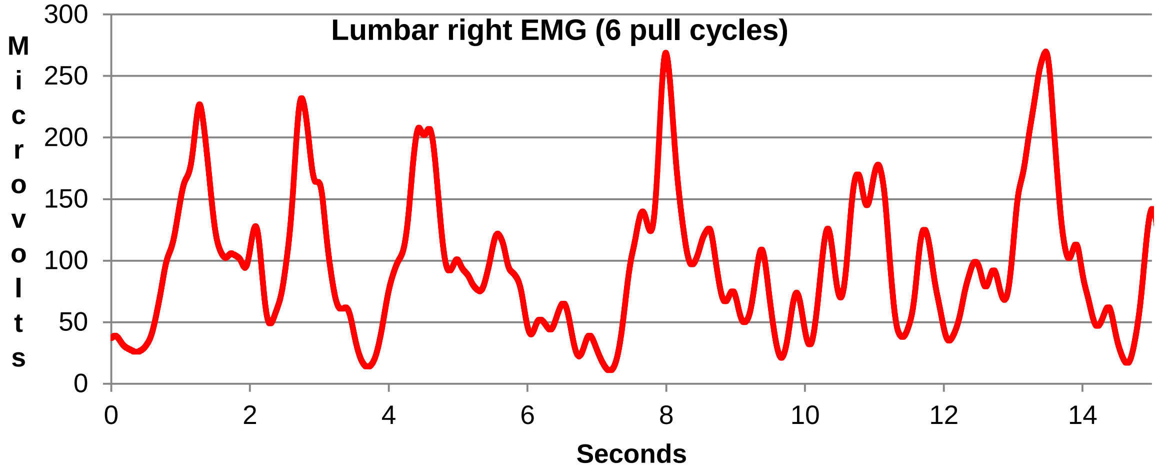


Figure 6.22: Time line plot of right lumbar EMG data showing six pull peaks above MVC level (represented by red horizontal line) for the second two handed cable pulling task.

These data demonstrate very high levels of lumbar and right shoulder muscle activity to pull the cable through. During the two repetitions of this task, these muscles consistently exceeded the 100% MVC values, showing very high levels of force exertion by the participant to pull the cable through.

Cable pulling with the cable over the shoulder

The peak EMG data for two repetitions of this method of pulling the cable were investigated for the stepping-pull phase of this task. Peak EMG data were extracted for seven stepping pulls of the cable. Because the focus was on seeking to evaluate if high to very high forces had been used, the muscle groups most affected by this method were evaluated. The Mean ± SD values for the peak EMG data, expressed as a percentage of the MVC, are shown below.

Table 6.3 and Table 6.4, and Figure 6.23 to Figure 6.26 show peak mean values for EMG for the selected muscles for two samples of the task which were: pulling the cable away from the pit while holding the cable in place over the participant's left shoulder; and walking away from the pit to keep the cable moving through the conduit. These results describe the first and second repetitions of this task, in the same order of their performance during the assessment.

First sample

Table 6.3: Peak EMG (Mean ± SD) values, expressed as percentage of MVC, for first over shoulder cable pulling task.

%MVC	Shoulder Left	Shoulder Right	Mid Thoracic Left	Mid Thoracic Right	Lumbar Left	Lumbar Right	Bicep Left	Bicep Right
Mean (%)	15.1	74.9	22.4	40.2	29.6	134.1	19.8	39.2
SD (%)	2.7	11.9	2.1	8.1	13.8	37.1	4.6	5.7

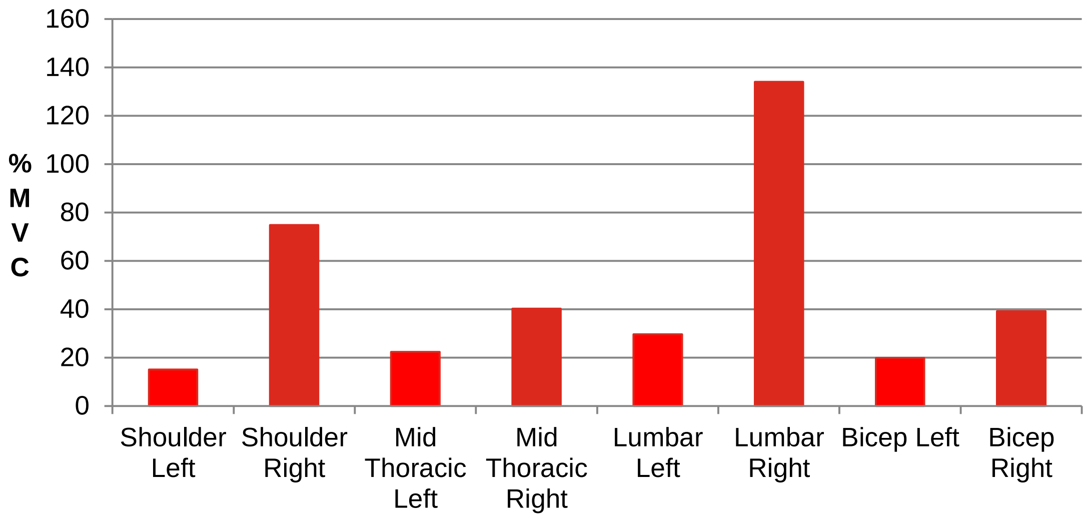


Figure 6.23: EMG values, Mean ± SD, expressed as a percentage of the MVC, for the first over the shoulder cable pulling task.

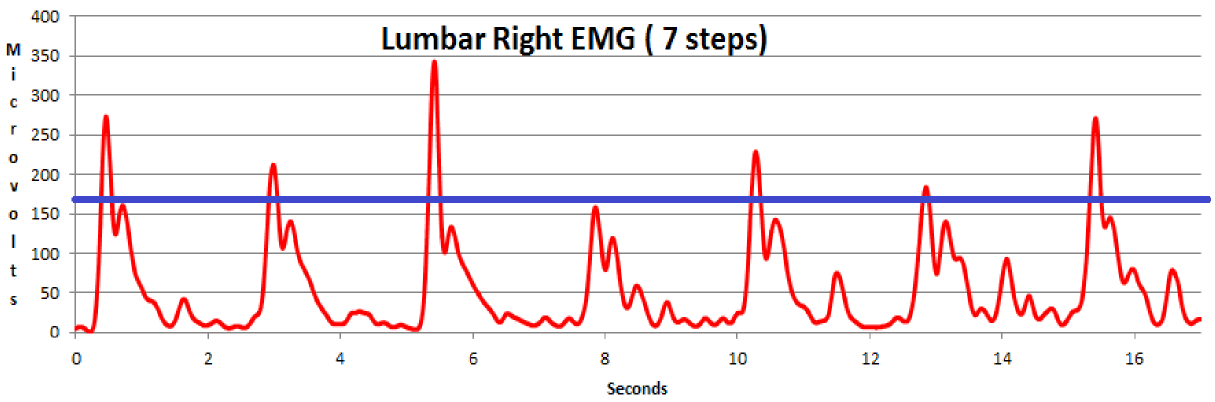


Figure 6.24: Time line plot of right lumbar EMG data showing six pull peaks above MVC level (represented by blue horizontal line) for the second two handed cable pulling task.

<u>Second sample</u>

Table 6.4: Peak EMG (Mean ± SD) values, expressed as percentage of MVC, for second over shoulder cable pulling task.

%MVC	Shoulder Left	Shoulder Right	Mid Thoracic Left	Mid Thoracic Right	Lumbar Left	Lumbar Right	Bicep Left	Bicep Right
Mean (%)	43.3	49.6	69.6	100.2	222.0	148.5	6.6	63.4
SD (%)	16.4	27.6	15.2	13.1	58.9	23.0	1.2	9.0

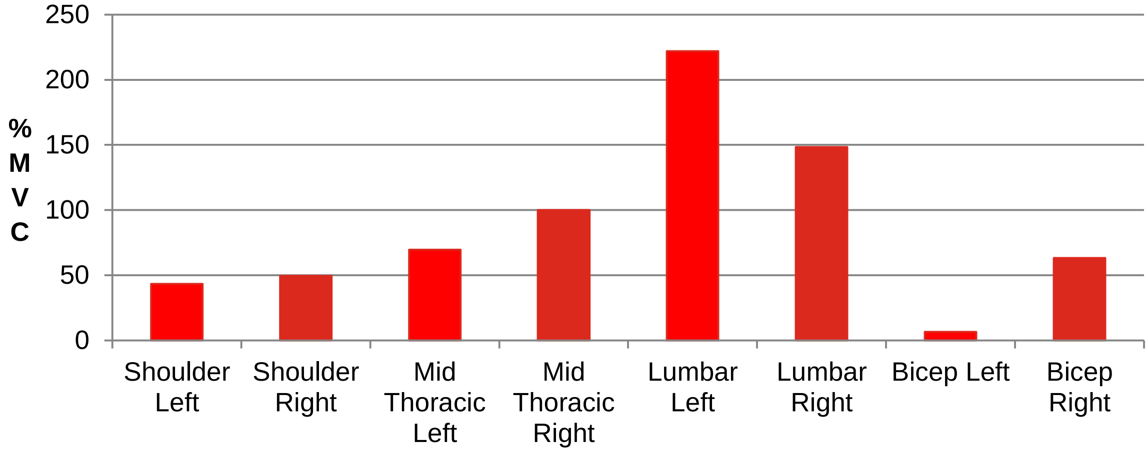


Figure 6.25: values, Mean ± SD EMG, expressed as a percentage of the MVC, for the second over the shoulder cable pulling task.

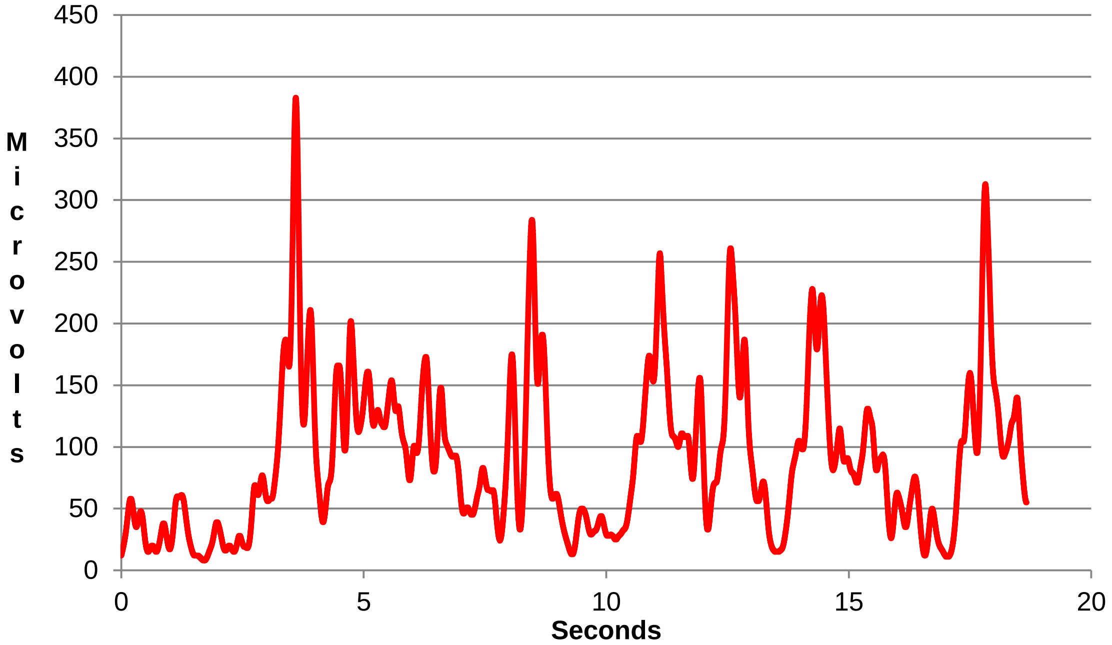


Figure 6.26: Time line plot of right lumbar EMG data showing six pull peaks above MVC level (represented by red horizontal line) for second over shoulder cable pulling task.

These data demonstrate that the participant uses very high levels of lumbar muscle activity to stabilise his back/trunk while anchoring the cable over his left shoulder to pull it along while he walks away from the pit pulling the cable out. During the two repetitions of this task, these muscles consistently exceeded 100% MVC values, indicating very high levels of force exertion by the participant to pull the cable through while it was held over is left shoulder. This supports the RMIT researchers' assumptions during the first assessment of cable pulling. It should be noted that high muscle activity levels and force exertion occurred while his coworkers provided assistance to limit the level of force he exerted.

Summary of EMG findings for cable pulling

While lumbar muscle activity for the two handed and over the shoulder pulling tasks were very high, right shoulder data for the over shoulder method was less than for the two handed task. This can be explained by the two very different methods used. The two handed task required active shoulder stabilisation to pull the cable through. The over the shoulder method relied on the participant holding the cable over his shoulder to create a lever where he could utilise his lower limb muscles and back stabilisation to maximise his ability to exert a pulling force on the cable. He continued to apply this force until it exceeded his capacity to keep moving forward with the cable.

In the firefighting industry, the method of pulling a fire hose forward by anchoring over the firefighter's shoulder is not recommended. While this method increases leverage to pull the hose forward, if the hose becomes caught or stuck then the firefighter will abruptly stop and may fall or injure their shoulder. If a cable or hose pulling task requires this method to pull it along, then it is likely the forces exerted, along with secondary hazards if the item becomes caught, are too high. Other strategies or methods to eliminate or reduce these levels of force should be investigated and implemented.

6.6 Discussion

6.6.1 Implications of the results

The trunk inclination and lumbar flexion (L5/S1) data described earlier demonstrates that cable pullers use high levels of trunk inclination and lumbar flexion, as demonstrated by the mean and peak values. Higher levels of trunk inclination and lumbar flexion (L5/S1) occur at the start of a rope or cable pulling cycle where the worker reaches to a position slightly higher than ground level to obtain their grasp. They then pull back with their shoulders, as well as extending their legs, to pull the cable through.

In addition to adopting these high levels of back movement, force exertion for cable pulling is most likely highest at this point of the cycle. This was demonstrated with analysis of EMG data.

Force exertion to pull the rope or cable along, once the participant was upright, was also identified as problematic. Even with multiple coworkers assisting, the participant was seen and measured to adopt high levels of muscle exertion, and an overall forward body inclination to maximise his leverage over the cable and achieve the level of force needed to keep moving forward.

6.6.2 Task redesign considerations

This pulling action and force exertion occurs at the start of a pulling cycle where the crew members need, and are able, to pull the rope and cable by walking away from the pit or cable drum. It also occurs when they perform these pulling actions while remaining in a fixed position.

Introducing the trestle design raised the height of the cable to 770mm above the ground. This substantially reduced trunk inclination and lumbar flexion (L5/S1) compared to the usual method deployed. These results indicate that introducing this type of device can improve cable puller work postures, particularly at a time within the work cycle when the operator is exerting high to very high levels of force.

It is apparent that crews already use rope and cable guidance devices at the end of the conduit and at the upper edge of the pit. An additional improvement could involve introducing one more such item, such as the trestle tested in this evaluation that contributes to cable management and improved work postures. This device could also provide an important barrier to the pit, for reducing the risk of the operators stepping into the pit. However, if this device was to serve this purpose it would need to be sufficiently stable to remain in place if a horizontal force of 550 Newtons was applied horizontally at the upper border, and the upper edge should be not less than 900mm above the ground (Australian Standard:1657, 2013).

This assessment also found that even with multiple workers performing cable pulling tasks, the level of force manually exerted can become excessive. Methods of eliminating or reducing this level of force are strongly indicated. This would require mechanical or powered cable pulling devices that can be located near a pit with limited space around it or which may be difficult to access. The current larger vehicles that provide this feature may be too big to gain access to a higher proportion of cable pulling sites, particularly within rail infrastructure projects.

6.6.3 Conclusions

This assessment demonstrated and quantified trunk inclination, lumbar flexion (L5/S1) movement and EMG values for the usual method of cable pulling. It also provided preliminary evidence on the likely impact of a trestle device to raise the cable when pulling it close to a pit, thus improving operator back postures and movements. This would be a technology solution, consistent with other devices already used to protect and guide ropes and cables in outdoor work environments.

Improving trunk inclination and lumbar flexion (L5/S1) for this task should both enhance the capacity of crews to perform this work, and reduce manual handling risks.

However, this solution should be considered in the context of greater and desirable use of mechanical cable pulling devices. Such devices would mean manual cable pulling is eliminated or substantially reduced, particularly for scenarios where access to the site is limited or where cable pulling over longer distances is required. The design of such a device should enable it to be rapidly deployed and operated by a minimal number of operators. This would maximise its use, effectiveness and contribution to efficiency.

Part 7: Jackhammering

7.1 Description of work task

7.1.1 Overview of jackhammering work

Jackhammering is a common construction work task. It involves using a mechanical jackhammer tool to chisel at solid material, such as concrete, to break it up.

Jackhammers were originally designed to break up solid ground or floor level surfaces. For this type of work, the chisel end of the tool is rested on the target surface, and the tool held in a vertical or slightly oblique position relative to the ground. The operator activates the tool to progressively break the surface down, then moves to an adjacent area to repeat this cycle. As the chisel tool bites into the target surface, the operator may choose to lower the handle to increase the angle of the tool to either target the material at a different angle, or use the chisel end as a lever to dislodge pieces that have been broken up.

Besides the manual use of a jackhammer, a range of different sized vehicles with mechanical jackhammers were observed at several participating sites. These machines were used to excavate a large rock cutting for a railway line extension (see Figure 7.1).

Figure 7.1: Assessment equipment test at site 1 – jackhammering demonstration using bluestone blocks.

The jackhammering tasks assessed in this project involved constructing large foundation columns to form the support base for a larger slab base structure onto which pillars were to be constructed to support an elevated structure. This required participants to use the tool at heights ranging from approximately 50mm to 1700mm.

7.1.2 Jackhammering equipment

A jackhammer tool was reported to weigh approximately 45 kilograms. It has a T-shaped handle at its upper end and lever controls that can be operated while holding onto the handle. A chisel is connected to the lower end of the tool. The device is powered by air pressure so that when activated, the chisel quickly moves in and out. When the handle is held and braced by an operator, this repeated and forceful movement of the chisel against the targeted surface results in it breaking down.

The jackhammer is driven by pneumatic pressure. An air supply hose extends from a nearby compressor to the target area and the tool. In our observed jackhammering activity, the hose was approximately 25 metres long. In the three jackhammering assessments conducted for this project, there did not appear to be any pattern of managing the air supply hose relative to the work position. At times, this resulted in the hose being in the way and presenting a tripping hazard for the operator. In addition, it presented a risk of the hose being punctured if the tool was dropped or misdirected.

There were no supplementary handles on the jackhammering tools assessed. However, at assessment site 3, a small curved metal section at the junction of the lower body of the tool and the chisel was used as a handle by both operators to lift the tool to heights greater than knee-level.

7.1.3 Work methods

The conventional method of using a jackhammer was initially demonstrated through a pilot study. This method typically involves working with the chisel at ground level where the tool is held in vertical or slightly oblique position relative to the ground.

The work undertaken by the two participants, and observed, in this research project differed from this conventional method and positioning. The job requirement was to clear concrete around vertical steel sections housed within large concrete columns. The columns had been previously constructed by deep holes being drilled, a steel core inserted, and then concrete poured to form the structural column. The upper part of the columns (approximately 1.8 metres) were later exposed by excavating the earth around them to form a wide trench. The exposed sections of these concrete columns were described as ‘end caps’. Selected end caps within a group of these columns were tested for strength (compression). Once the columns’ integrity was confirmed, the exposed concrete sections were removed so that only the internal steel bars were exposed. These bars would later be integrated with the steel bars of the large pad that would be constructed on top of these columns. This pad would, in turn, support the above ground pillars on which an elevated structure would subsequently be placed.

Two methods of exposing and removing the end caps were described and observed during the assessments.

The method developed for this construction project involved placing lagging (foam tubing) around the upper vertical sections (approximately 1.8 metres) of the steel core that was inserted into each foundation hole before the concrete was poured. If the lagging was applied correctly, jackhammering work required to expose the steel rods (as the first stage of removing the entire end caps) is minimal. Participants reported this could take less than one hour. Once the rods were exposed, a horizontal hole is drilled through the cap close to the excavated ground level. An expanding tool, such as the ‘jaws of life’ used in road rescue operations, is then inserted into the hole and activated. This causes the concrete column to split across the base at the level of the hole. Once the vertical steel rods are cleared, a crane lifts the separated part of the concrete column up and away to expose the rods for integration with the next stage of steel work.

A second method of removing end caps and exposing the steel rods is necessary if the steel frame within each concrete column had not been properly prepared with lagging, or if the lagging had not been put in place at all. In this situation, the participants reported it can take up to five hours, mostly of jackhammering, to expose the steel rods around the edge of a single column, drill the lower core hole, and crack the column for removal.

The key difference between the two methods is the height-level and duration of jackhammering. The height of the columns, and the need to expose the rods fully, required the use of non-typical jackhammering methods; that is, lifting the end of the chisel to heights of 1700mm (approximate) with long work duration periods and associated increased physical demands.

Further, problems with the placement of lagging were exacerbated because one contracting company prepares and pours the columns, while a different contracting company removes the end caps and exposes the steel rods.

7.1.4 Locations and environmental conditions

Data collection was undertaken at a single construction site (site 3) on two occasions (see Figure 7.2). The site-based work assessed involved preparatory tasks required for constructing and installing structural columns. Six site visits were made, but only two assessments could be completed due to the outdoor nature of the work, winter conditions and other environmental factors, such as needing to pump water out of the work area to enable participants to operate safely within it.

For the first assessment at site 3, the weather was partly overcast and the temperature was approximately 8 degrees Celsius with no rain. At the second assessment, which occurred approximately two months later in early spring, the weather was sunny and the temperature was approximately 21 degrees with no rain.

Figure 7.2: Site 3 excavations and columns on each side of the rail corridor.

At this site, for both assessments, the research team could only work from the perimeter of a large trench or pit in which the exposed columns were located. Access was restricted to reduce the team's exposure to health and safety risks resulting from the jackhammering activities being performed. These pits were approximately 3-4 metres wide and 8-15 metres long.

In relation to participant 4, data were collected via wireless transmission from the Xsens body pack (attached to the worker) to a laptop (via a modem). This method displayed the data on the computer screen as an avatar image, where the avatar moved in real-time to match the participant's movements. For participant 10, data were collected using the Xsens body pack as a data logger. This method was used to avoid any wireless interference that had been experienced in earlier assessments conducted during the project. These data were downloaded to a laptop after the assessment.

7.1.5 General assessment of jackhammering

The jackhammering tool was designed to break up ground level surfaces and structures. The handles are designed for the operator to hold and stabilise the tool while pressing downwards to generate the action force needed to penetrate and break up the target surface with the oscillating chisel. The tool's heavy weight, combined with the body weight of a worker, favours this action. The tool's length also significantly reduces shoulder movement but allows the worker to brace their shoulders and lean over the top of the tool to help exert action force necessary for the chisel to be effective. The tool's handles cannot be moved so different body positions can be employed by workers of different stature when working at the same height.

Using jackhammers to break up the concrete surface of the structural foundation columns at site 3 was effective in exposing the internal steel frame and bars for end cap removal. However, this method of using a jackhammer is inconsistent with the tool's inherent design and presents an ergonomic hazard.

Figure 7.3: Site 3 – examples of jackhammering above ground level.

Above ground level use requires these tools to be lifted up repeatedly and operated from heights

ranging from ankle to above-shoulder levels (

Figure 7.3, Figure 7.4). Handling the tool in this manner would be assessed to present hazardous manual handling – even without the need to physically measure operators' postures and movements, as was done in this project.

With regard to other aspects of jackhammer design and use, the tool's continuous vibration, and the requirement for the operator to maintain their grip to stabilise the tool, creates a secondary hazard of exposure to hand/arm and whole-body vibration.

Exposure to other hazards, such as concrete dust and airborne chips of concrete, were also increased when using the jackhammer at higher levels. Silica is a natural substance found in rocks, sand and clay, and in products such as bricks and concrete aggregates. Work processes, such as cutting, grinding, or breaking materials containing silica can generate respirable crystalline silica (RCS) dust particles so small they cannot be seen under ordinary lighting and can be inhaled deep into the lungs (Workplace Health and Safety Queensland, 2017). While the workers we observed wore protective face masks, it would be preferable to change the work process to eliminate or reduce the need to break concrete columns in this way.

Finally, the absence of an apparent, deliberate coordination of the placement of air hoses was seen during this project. This was found to present tripping hazards and required operators to regularly move hoses with their feet to create the required clearance around their work position.

7.2 Research methods

7.2.1 Participants

Two jackhammer operators at site 3 were asked to participate in the project. Each participants' work methods were assessed at different times, approximately two months apart. Both participants (Participant 4: age – 25yrs; height – 180 cm; mass – 82 kg; Participant 10: age – 40yrs; height: – 188 cm; mass – 102 kg) were reported to be highly competent. They worked each day as a team, performing jackhammering work at this and other construction sites.

7.2.2 Description of work tasks

Each assessment required the participant to perform jackhammering tasks scheduled at that time. However, the representative samples involved each participant performing this work for 20-30 minutes per assessment.

Each participant was prompted to use only their usual work methods. No specific requests or requirements were made relating to their work methods. After each assessment, the participants reported they had performed the work as they usually would, and considered the methods to have been representative of the jackhammering work task for this particular site and the requirement to prepare each end cap for removal.

Both participants worked with the end of the chisel between their ankles and above their shoulders. At no time did either participant actively use their jackhammer at ground level to break up material. Their only application of the tool at ground level was to insert the chisel so they could 'park' the tool in an upright position, rather than lean it against a column or lie it flat on the ground, while they assessed the next step within their process.

A commonly observed pattern of use was for the operator to lift the jackhammer and apply the chisel at the highest position (approximate 1600-1700 mm) and then commence operating the tool. To raise the tool to this level, each participant was observed to reach down and grasp the tool at a small, unidentified, protruding component at the junction of the body and chisel. They then moved to an upright posture, lifting up the tool. Usually the end of the chisel was lifted to a position slightly higher than the target height, and would be lowered to the target height when the chisel came in contact with the side of the column.

As material broke away the participants allowed the chisel and tool to slide down the face of the column to the next level to be broken up. They would repeat this action until the chisel reached the level of their knees (approximately).

Figure 7.4: Site 3 showing participant 4's movements to lift tool to highest jackhammering level.

To chisel at the surface between ankle and knee-height (Figure 7.4 and Figure 7.5), both participants used similar methods. They started with the tool in a resting vertical position next to the target area. They then positioned the tool over one thigh and, while holding on to the handles, leaned backward to bring the tool onto their thigh. From this position they commenced jackhammering to break up the surface. They were observed to maintain this posture to support the weight of the tool until it moved to a lower position closer to the ground when they would move back to a more upright standing posture.

Figure 7.5: Site 3 showing handling of jackhammer tool to operate between knee and ankle height.

A secondary part of this operation required a core drill to drill a 40mm diameter (approximate) hole through the column close to ground level. This task was performed exclusively by participant 4 using a core drill suspended from the side of a column. This allowed the participant to maintain a consistently horizontal straight drill direction to achieve the required quality outcome. However, this method of reducing manual effort was in stark contrast to the high level of manual effort demonstrated to expose the internal steel structures.

Operating the column separation tool was not seen during these assessments. Participant 4 reported it to be relatively straightforward and did not believe it posed any physical demands or risks.

7.3 Data analysis

Jackhammering at site 3 involved participant 4 working on a section of a column until the required level of exposure of the internal steel rods was achieved. This process was repeated around a column until all rods were exposed and then he would move to the next column and commence work on that. Participant 10 demonstrated his usual operational jackhammering work in the second pit area, but this was a slightly different set up to participant 4's assessment. His exposure of the internal steel columns was not a requirement for the work being conducted on that day. However, he reported this work represented his usual work task.

Four types of back posture and movement data (joint angular motion) were recorded by the Xsens system. These were trunk inclination (T12/S1), and lumbar joint motions at three levels of the lumbar region (T12/L1, L3/4 and L5/S1). The three lumbar joint motions were found to be small, falling around 2-3 degrees. Due to the low range of joint motion, these data were not considered relevant to this project. Accordingly, these results are not reported. Only trunk inclination results are reported.

7.3.1 Trunk inclination

Trunk inclination data (trunk forward flex/extension in the sagittal plane) were extracted by using the positions of the T12 and S1 vertebrae (Figure 7.6). This level was chosen as the data best matched a visual representation of the participant's trunk movements in this plane. A higher level vertebrae, such as T8 within the back, was not used as angles from this level were greater than the apparent angle of the trunk, most likely reflecting greater mobility or curvature of the mid thoracic spine.

For trunk inclination, forward flexion is positive (+ve) or greater than zero. Rearward extension is negative (-ve) or less than zero.

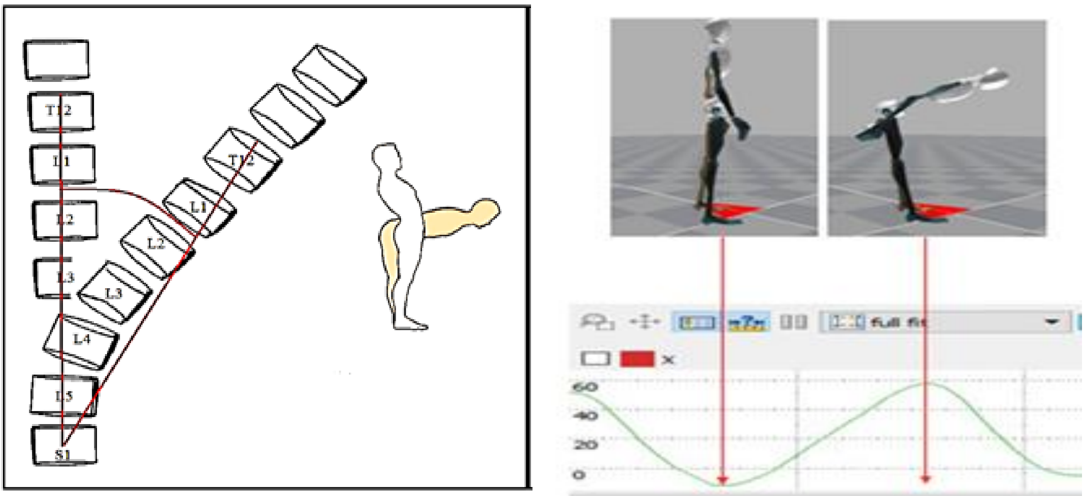


Figure 7.6: Left panel: schematic representation of trunk inclination angle (forward flexion in sagittal plane ≈ 30°). Right panel: avatar image of participant showing a standing position (trunk inclination ≈ -18° extension) and forward flexed position (trunk inclination ≈ 60°).

7.3.2 Lumbar flexion

Lumbar flexion data (Figure 7.7) was calculated within the Xsens system at three levels of the lumbar spine (low back), T12/L1, L3/L4 and L5/S1. The range of overall lumber flexion is determined by the relative position of the Xsens shoulder and pelvic sensors. This value is divided by the number of spine represented within these movements and then allocated to the different levels of the lumbar spine according to previously established proportions.

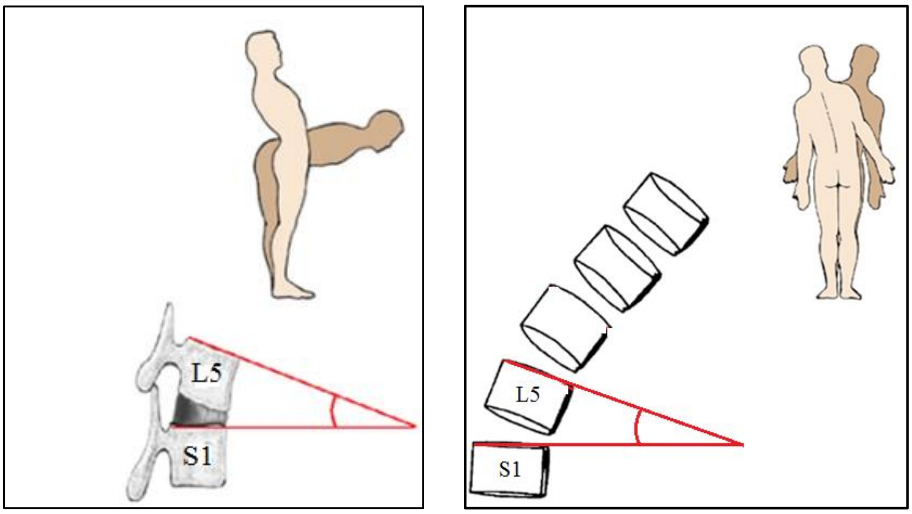


Figure 7.7: L5/S1 forward and lateral flexion.

These data at all three lumbar levels were reviewed and data at the L5/S1 level only was selected for reporting. This was because the range of movement at this level, relative to the two levels above, was much greater and more likely to represent any changes between different tools and work methods. Also, this level is the base of the spine where high levels of leverage and disc compression can occur and is commonly referred to the location within workplaces.

Lumbar flexion data at the L5/S1 level was analysed and reported for forward and lateral (side to side) flexion. Lumbar forward flexion has positive values while extension uses negative values. For lateral flexion, movement to the person's right side is positive while movements to their left side is shown with negative values.

7.3.3 EMG – muscle activity

EMG data for jackhammering was reviewed to investigate muscle activation relative to the RMIT researchers' observations that this task involved exerting high forces to lift the jackhammer up and use it with the chisel end approximately at shoulder height. In addition, the activation of a range of back, shoulder and arm muscles during jackhammering at these higher levels was also of interest to understand muscle use during the static holding periods of this work where the operator needs to absorb vibration from the tool.

7.4 Jackhammering results

7.4.1 Trunk inclination

7.4.1.1 Mean, peak and minimum trunk inclination

Descriptive statistics (mean ± SD) are shown in Figure 7.8 and Figure 7.10. The mean trunk inclinations for both participants' combined results for jackhammering across different work heights were: 15 degrees (SD 4.7 degrees) for ankle-to-knee; 33 degrees (SD 8.5 degrees) for knee-to-hip; 26 degrees (SD 5.4 degrees) for hip-to-shoulder; and 10 degrees (SD 7.1 degrees) above shoulder.

Peak trunk inclinations for both participants' combined results for jackhammering across different work heights were: 52 degrees (SD 23.8 degrees) for ankle-to-knee; 61 degrees (SD 2.4 degrees) for knee-to-hip; 52 degrees (SD 8.4 degrees) for hip-to-shoulder; and 53 degrees (SD 8.3 degrees) above shoulder. These results show a high measure of trunk inclination for work performed at all levels. Review of trunk inclination graphs and video footage indicated these peak values could be attributed to participants' movements of the jackhammers within these ranges because actual jackhammering work requires the tool to remain in the same position, and in this case height, for the chisel to be able to effectively break down the concrete.

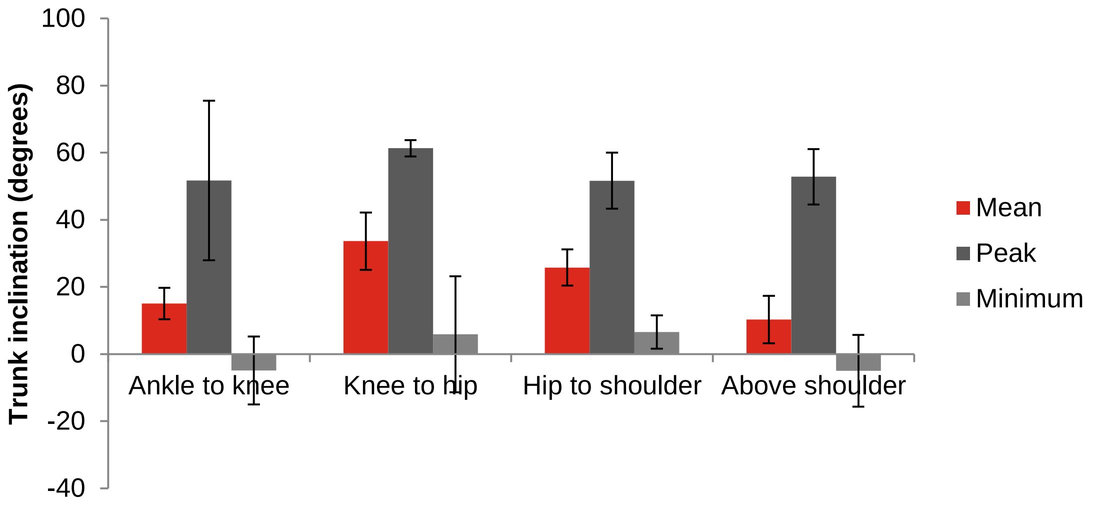


Figure 7.8: Combined mean, peak and minimum trunk inclination values for the different levels of application of jackhammers for both participants.

Minimum trunk inclinations for both participants' combined results for jackhammering across the different work heights were: 15 degrees (SD 4.7 degrees) for ankle-to-knee; -5 degrees (SD 10.1 degrees) for knee-to-hip; 7 degrees (SD 5.0 degrees) for hip-to-shoulder; and -5 degrees (SD 10.7 degrees) above shoulder. These results indicate the adoption of upright postures by both participants when working within each height category.

7.4.1.2 Time duration above 40 degree trunk inclination

Another way of reflecting on the impact of work postures and movements, in particular a participant's back posture and movements, is to consider what proportion of their total work cycle time was spent within each postural category or above postural thresholds. WorkSafe Victoria's *Manual Handling Code of Practice* (WorkSafe Victoria, 2000, p. 17) indicates trunk postures and movements greater than 20 degrees inclination present a higher risk to workers than lower postures and movements.

However, considering trunk inclination data above or below this value as being hazardous or safe is simplistic. It provides little sensitivity regarding postures and movements greater than 20 degrees. This approach is inconsistent with biomechanical models showing that net anterior shearing force (horizontal force) acting on the intervertebral discs within the spine significantly increases with trunk inclination and lumbar flexion. This is due to reduced capacity of the back extensor musculature (for example, longissimus thoracis and iliocostalis lumborum) to generate posterior shearing forces within the vertebral column (Figure 7.9).

The posterior shearing force, generated by back extensors, counters the anterior shearing force generated by trunk inclination and lumbar flexion. The combination of trunk inclination and lumbar flexion, as seen in Figure 7.9 below, can lead to disc rupture where the anterior portion of the disc is squeezed.

Accordingly, using 20 degree trunk inclination as a single threshold value could result in underestimating physical work demands and injury risks.

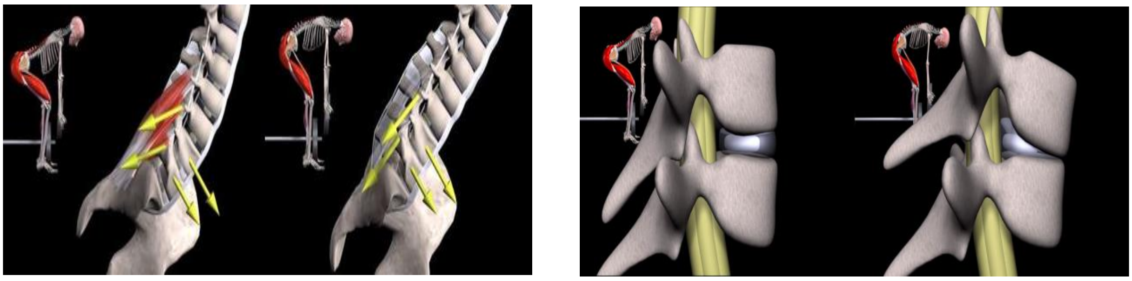


Figure 7.9: Schematic representation of anterior and posterior shearing forces within the vertebral column.

Source: Muscle and Motion Ltd (2017)

Considering trunk inclination in categories greater than 20 degrees can provide a more descriptive understanding of the nature of the task. This type of analysis is now possible with movement sensing technologies (for example, Xsens system). It provides an objective way of investigating work exposures to awkward or hazardous postures, and movements for occupational tasks.

A threshold value of 40 degrees is used for all construction tasks assessed within this project to provide common means of comparing this factor between each task. An investigation of the proportion of total work cycle time spent in the higher range of trunk inclination (that is, above 40 degrees) provides critical insight into the inherent requirement of the task. Figure 7.10 shows the per cent of time spent in a trunk inclination posture of more than 40 degrees.

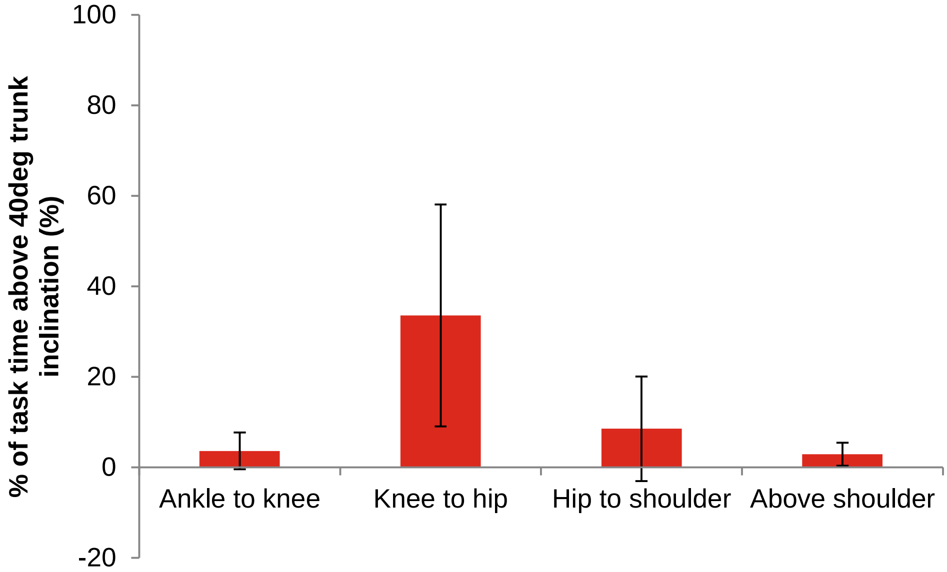


Figure 7.10: Combined percentage of total jackhammering assessment time both participants spent with trunk inclination greater than 40 degrees.

The percentage of total jackhammering assessment time for both participants with trunk inclination greater than 40 degrees within the four height categories measured were: 3.7% for ankle-to-knee; 33.6% for knee-to-hip; 8.6% for hip-to-shoulder; and 2.9% for above shoulder. The remaining 51.3% of assessment time was spent performing tasks other than jackhammering, such as moving the tool to a new position or reviewing and planning the work.

These results highlight that the greatest proportion of active jackhammering work with trunk inclination more than 40 degrees was conducted between knee-to-hip level. This result is consistent with the mean trunk inclination angle of 33 degrees (SD 8.5 degrees) for work performed at this level, highlighting the awkward trunk postures exhibited when operating at this level.

The proportion of total jackhammering time for each participant with trunk inclination greater than 40 degrees when working at the other three height categories was regarded as low. However, any trunk inclination greater than 40 degrees, particularly if combined with awkward force exertion, as was observed with the handling the jackhammer tools, could be regarded as hazardous when using WorkSafe Victoria's Manual Handling Code of Practice guide (WorkSafe Victoria, 2000, p. 17).

These results indicate the lowest range and proportion of work time for trunk inclination occurred for the lowest and highest work height categories. However, considering these data and the impact on other joints of a participant's body is warranted to understand if this is due to an increase in the range of movement and physical work demands experienced by these other body locations.

7.4.1.3 Lifting and holding the jackhammer

These results provide a valuable insight into the nature of jackhammering work performed at site 3 with regard to trunk inclinations used when jackhammering. However, they do not reveal the specific physical demands of lifting the jackhammer tool to various heights for use.

Figure 7.11 below shows the avatar generated from the Xsens capture of participant 4 lifting the jackhammer from ground level to apply the chisel above shoulder height. Figure 7.12 shows trunk inclination for this action and the preceding period of jackhammering work.

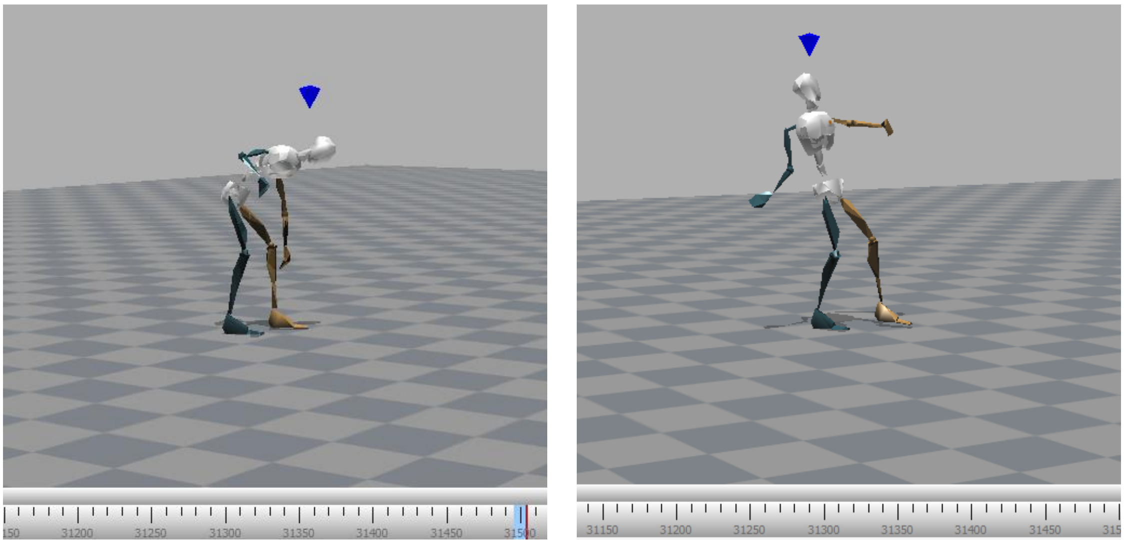


Figure 7.11: Screen images of participant 4 about to lift the jackhammer and then holding it to apply the chisel above shoulder height, as displayed on the Xsens MVN program.

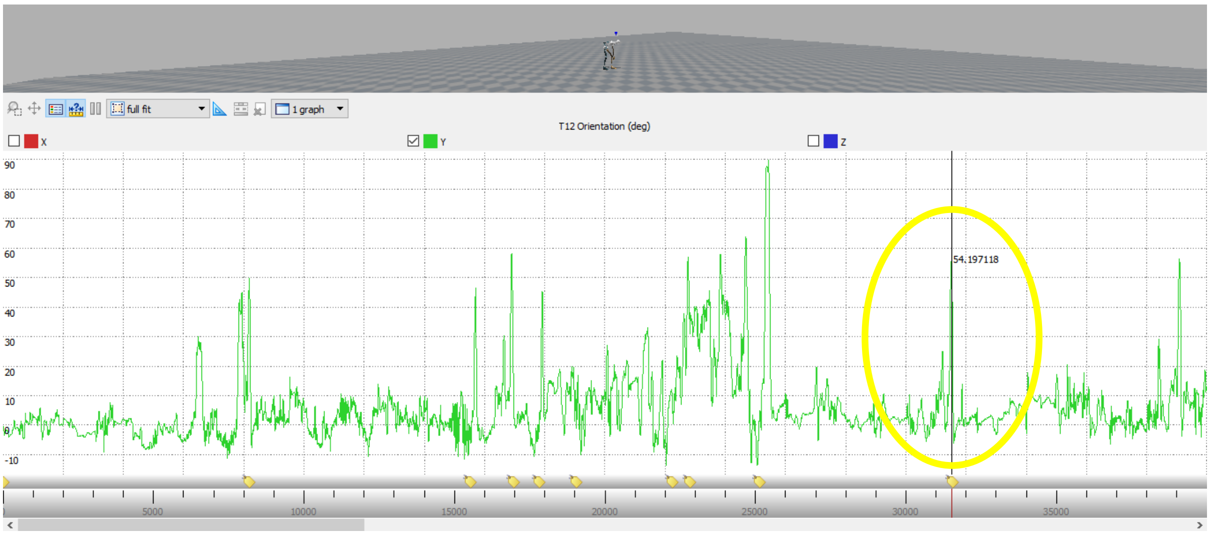


Figure 7.12: Screen image of trunk inclination time line graph, calculated at T12 level, for same work period displayed in Figure 7.11, indicated by vertical line and inclination value.

When bending down to lift the jackhammer, in the example described above, trunk inclination peaks at 54.2 degrees. The tool's full weight of 45 kilograms (approximate) is not lifted because the handles remain pressed against the participants' lower torso so the tool pivots around this point as the chisel end is raised. Even so, this movement in combination with exertion of force to raise the tool every time it moves upwards in this way presents a manual handling hazard.

7.4.2 Lumbar forward flexion (L5/S1)

Peak and minimum forward flexion of the lumbar spine at the L5/S1 level increases once the chisel end of the tool is raised above knee height to break material from the side of the concrete cap (column) to expose steel bars (Figure 7.13). The ranges of L5/S1 movement were similar for all three height categories above knee height. This was attributed to the lifting component of handling the jackhammer for these three tasks. Initially, the participant reached forward and downward to the lower end of the tool and grasped it with his left hand so as to lift it to the required operational level. A different method of positioning the jackhammer was used for ankle-to-knee height where the participants kept both hands on the upper handles and flexed their right hip under the tool to lift it and establish a slight (downward) angle to operate the device.

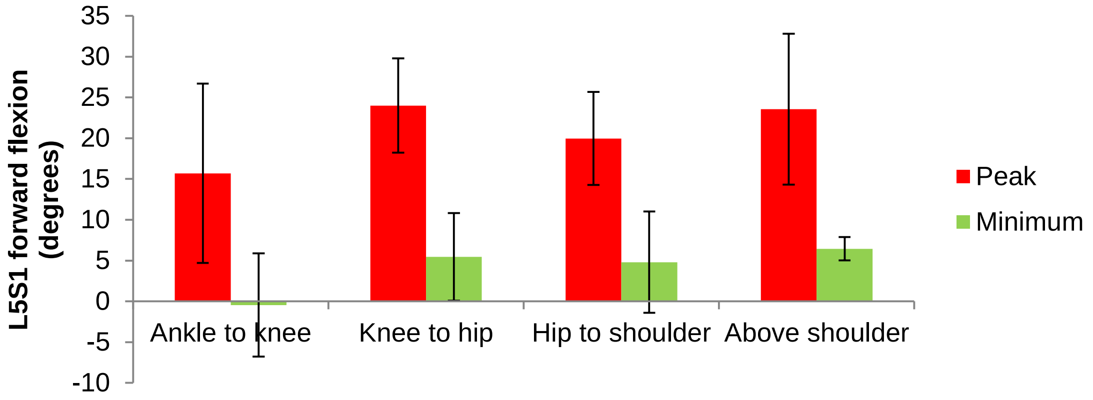


Figure 7.13: Mean, peak and minimum L5/S1 forward flexion values indicate the range of L5/S1 movement when operating the jackhammer chisel at four different heights.

7.4.3 Lumbar lateral flexion (L5/S1)

The overall ranges of lateral flexion of the lumbar spine at the L5/S1 level for each height level are similar (Figure 7.14). However, for the lowest (ankle-to-knee) and highest (above-shoulder) work heights, some small angular movement to the participant's left side occurred which was absent within the other two heights. The lateral flexion values to the participants' right side were also similar for the highest and lowest positions, and the knee to shoulder positions, although this movement was greater in these positions. These differences were attributed to the asymmetrical postures used to hold the jackhammer at these heights.

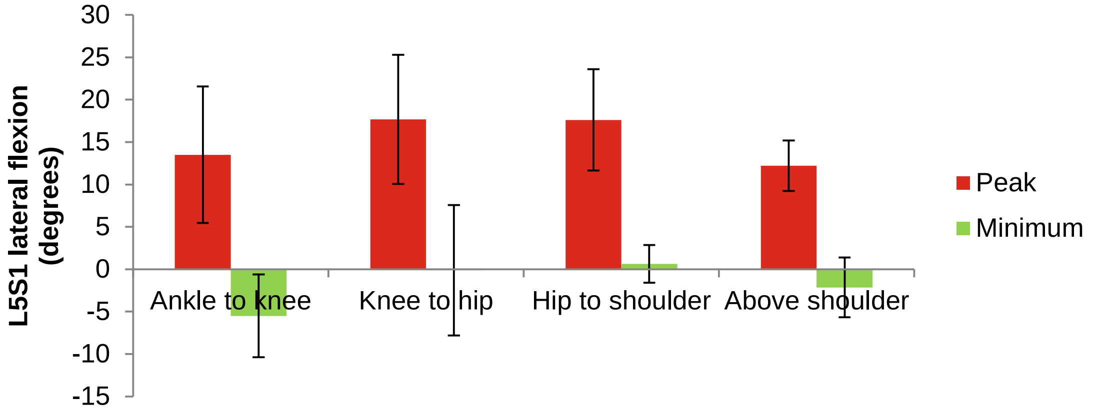


Figure 7.14: Mean peak and minimum L5/S1 lateral flexion values when operating the jackhammer chisel at four different heights.

7.4.4 EMG – muscle activity

7.4.4.1 Lifting the jackhammer to place the chisel at mid chest height

This task involved participant 4 lifting the jackhammer from a vertical position, with the chisel end resting on the ground, so the chisel end was resting against the side of the concrete column at the participant's mid chest level (approximately 1450mm above the ground). This involved first bending and reaching down with his left hand to a metal component at the base of the body of the jackhammer to obtain a grasp, and then lifting the jackhammer from this end to place it at the mid chest height level.

These EMG data (Table 7.1 and Figure 7.15) indicate that to perform this action, the participant exerted very high levels of force within his back (middle and lower back), right shoulder and right wrist. These values ranged from 134% of MVC for the left lumbar and mid thoracic right EMG, to 138% of MVC for the right shoulder, 210% for the right forearm, and 334% for the mid thoracic left EMG.

These patterns and levels of muscle use demonstrate high to very high levels of force exertion to lift the 45 kilogram jackhammer, so the chisel is at a mid chest height. (Note that this is an unconventional height for operating a jackhammer.)

Table 7.1: Peak EMG (Mean ± SD) values expressed as percentage of MVC.

%MVC	Shoulder Right	Mid Thoracic Left	Mid Thoracic Right	Lumbar Left	F/arm Right BRADLIS	F/arm Right Flexors	Bicep Right
Mean (%)	138.6	333.6	134.6	134.0	77.3	210.0	51.9
SD (%)	67.2	413.6	12.9	11.5	7.9	34.5	7.6

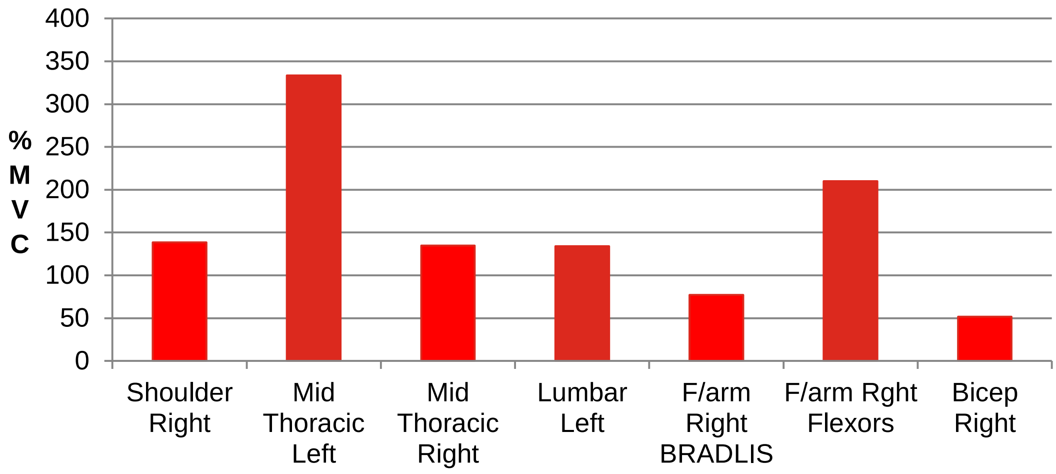


Figure 7.15: Bar plots of Mean ± SD EMG values, expressed as a percentage of the MVC.

Operating the jackhammer with the chisel at mid chest height

Once the jackhammer was lifted to this height, the participant immediately commenced operation. This involved the jackhammer oscillating to move the chisel 'out and in', relative to the body of the tool. The operator has to stabilise the jackhammer so the force exerted by the chisel is absorbed within the concrete column, causing the material to break up and dislodge. To operate the jackhammer in this way, the participant supports the handle end of the tool with his lower waist and right hand, and stabilises and moves it with his left hand at the chisel end of the body.

These results indicate a high level of activation for the right upper limb to control the weight of the tool and stabilise it so it is effective in disrupting the concrete structure (Table 7.2, Figure 7.16 and Figure 7.17). A high level of mid back stabilisation is evident, particularly on the right, the same side as the upper limb supporting the tool.

These values were selected to demonstrate muscle activity for this task. The values indicate high to very high levels for muscle activation and force exertion.

As shown in Figure 7.17, the pattern of muscle activity for the right forearm wrist flexors indicates the rhythmical nature of muscle use relative to the tool's vibration. This highlights the regular, very high peaks that consistently exceed the MVC for these muscles.

Table 7.2: Peak EMG (Mean ± SD) values, expressed as percentage of MVC.

% MVC	Shoulder Right	Mid Thoracic Left	Mid Thoracic Right	F/arm Right BRADLIS	F/arm Right Flexors	Bicep Right
Mean (%)	276.9	78.5	120.6	100.5	124.8	31.9
SD (%)	68.8	33.6	41.9	23.7	22.3	11.0

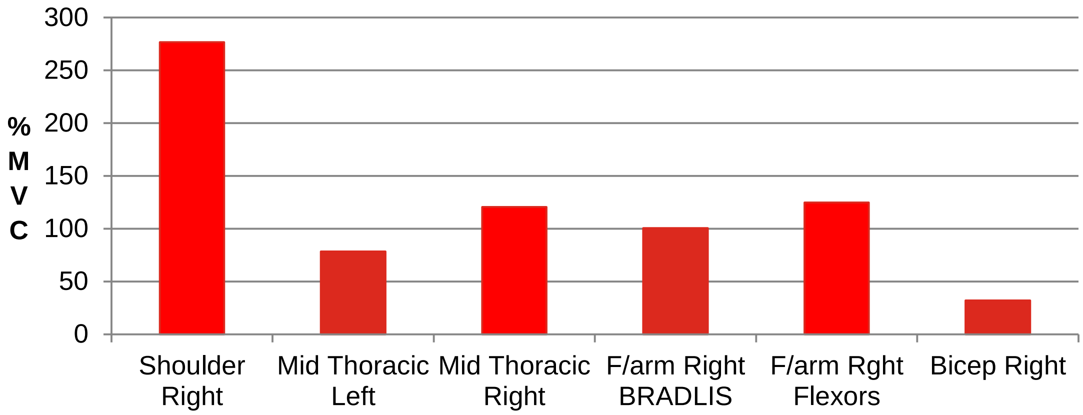


Figure 7.16: Bar plots of Mean ± SD EMG values, expressed as a percentage of the MVC.

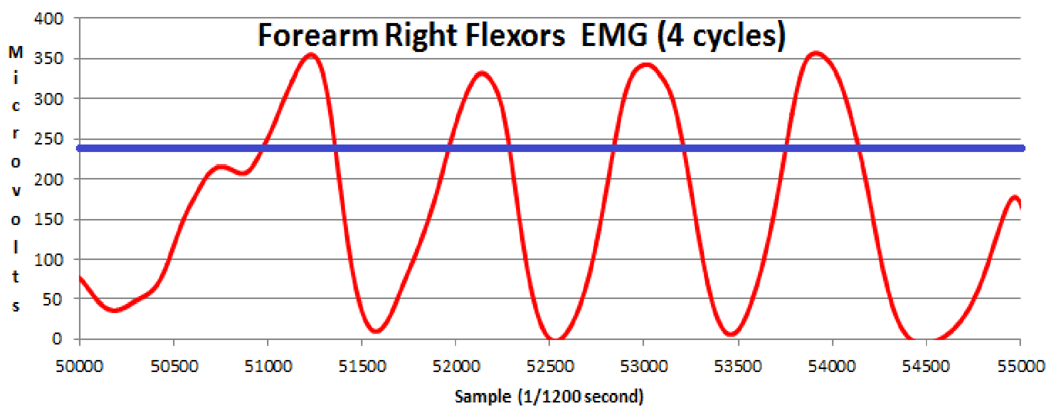


Figure 7.17: Time line plot of examples of right forearm/wrist flexor EMG, demonstrating frequency of muscle contractions peaking at very high levels, above the MVC value (represented by the blue horizontal line) for this group of muscles.

7.5 Discussion

7.5.1 Implications of the results

Using a jackhammer above ground level to break up concrete is unlikely to be consistent with the tool's inherent design and intended use. Operating jackhammer tools at these levels is hazardous because of the heavy weight, the size and length of the tool, the (generally) awkward postures and movements, exertion of high forces to handle and operate it, and the continuous exposure to hand/arm vibration that is a normal part of the tool's operation.

Considering the trunk inclination and lumbar flexion (L5/S1) data, it is apparent the postures adopted for jackhammering vary across different work heights. The greatest trunk inclination and lumbar flexion movement occurred for work conducted between knee and shoulder heights. This was attributed to the need to bend and reach downward to the chisel to grasp the tool, and then lift it and commence operation within this broad height range (and combination of the three height categories of knee-to-hip, hip-to-shoulder and above-shoulder).

When operating at the lowest and highest positions, back movement is less but other joints of the body are impacted. For example, the right upper limb exerts very high levels of muscle activity and force as a necessary part of the tool's operation at these higher levels.

A key finding of this assessment is the identified opportunity for, and potential benefit associated with, developing alternative methods for removing the end caps of piles. A priority is attached to eliminating, or substantially minimising, the need to use jackhammers to expose the steel frames within these columns.

An alternative method was described earlier. It was reported that when preparatory work to install lagging around the upper sections of the internal steel frame is conducted as intended, the duration of jackhammering work to expose them is significantly reduced, thereby reducing exposure to hazards. When lagging is correctly installed, jackhammers are still used across the height ranges described in this assessment, but the durations of work would be much less.

Conversely, if this system of work is not closely followed, or the quality of the lagging installation work is not checked before the concrete is poured, then jackhammering work to expose internal steelwork was reported by participant 10 to take 4-5 times longer (that is, from 1-5 hours to achieve the same outcome). When considering these time estimates, it should be noted that both jackhammering participants work every day as a crew specifically performing jackhammering work, and were reported to have been involved in all pile cap removals at site 3.

It appears a risk control measure has been identified and tested to reduce jackhammering use for this work. However, the effectiveness of this method requires a consistently high level of application and quality of preparation of these columns by the construction crews performing this work. These crews are typically not the same as the crews performing this follow up work to expose steel rods for the next phase of construction.

7.5.2 Task redesign considerations

It was noted that specially designed tools are used to drill a core through the lower section of a column for removal. The approach to anchoring this core drilling tool to the side of the column may be based on the need to maintain a consistent linear application of the drill to achieve the required outcome. However, this approach eliminates the requirement for the operator to manually hold the drilling device.

Given the inherent nature of jackhammering work that requires moderate to very high force exertion of the tools to move and hold them for the full duration of the task, the consideration of adaptive devices to improve grip and posture are not likely to be sufficient to prevent or reduce the risks inherent in the elevated use of jackhammers to break concrete columns.

However, alternative methods of breaking concrete in similar circumstances have been trialled and evaluated internationally (Gibb et al., 2007). Examples of such methods include hydraulic,

chemical and crack propagation methods:
(https://www.fps.org.uk/content/uploads/2017/05/Breaking-Down-of-Piles-FPS-May08.pdf)

These methods have the potential to eliminate or substantially reduce the need to use jackhammers for this type of activity.

7.5.3 Conclusions

Jackhammering tools appear to have been designed for conventional use in which they are applied vertically and downwards to concrete or rock, at ground or floor surfaces, to break them up. The use of jackhammers at site 3 is likely to involve an extended, and probably unintended, use of these tools whereby they are regularly lifted, handled and used above ground level. Exposure to the vibrating tool is also likely to increase physical demands and the risk of musculoskeletal disorders.

Reducing the level of jackhammering work to expose the steel rods within the columns via the installation of lagging requires careful installation and quality control for it to be effective.

The new methods, however, still rely on the user of a jackhammer to expose these rods. This manual method of tool application against the concrete surface is in stark contrast to the mechanical core drilling machine mounted to the side of the column, so the operator only needs to push down on the handle to drill out the core.

For activities involved in removing the concrete surface to expose the steel rods, an equivalent level of sophistication and design consideration is warranted to substantially reduce or eliminate the physical demands of jackhammering these surfaces.

Alternative technologies and methods of breaking concrete piles are being developed internationally. These techniques may be usefully investigated for their viability and potential adoption in Australia.

Part 8: Shovelling

8.1 Description of work task

8.1.1 Overview of shovelling work

Mechanical devices – such as suction machinery, and excavation vehicles of different sizes – were reported by stakeholders and participants within this project to be the most common methods of digging holes and trenches. Using shovels was reported to be limited to infrequent and smaller scale tasks of scraping, clearing surfaces of debris, and levelling small areas.

These reports are consistent with shovelling work observed during this project which was found to be ad hoc and not a routinely scheduled task. Three test sessions were conducted. The first session involved pilot work to test the measurement system and refine methodology. The second session captured the motion of a participant working onsite and demonstrating shovelling techniques. The third session assessed a shovel handle modification while two participants completed shovelling tasks. This was performed in a long-jump sandpit at RMIT University.

8.1.2 Shovelling equipment

Shovels observed at the construction sites during this project were mostly square edge shovels. Some tapered edge shovels were also seen. All shovels seen had long handles. No shorter handle spades were observed at any of the sites visited.

The only shovelling observed to be part of one of the tasks being assessed during this project was prior to jackhammering. For this task the operators used a square edge, long handle shovel to clear debris on the ground and in front of a large concrete column. The debris had become a trip hazard and obstructed their access to the column.

8.1.3 Work methods (pilot)

Shovelling was one of the first tasks assessed with the measurement system. This was performed at an equipment depot. The participant shovelled sand within a large sandpit (Figure 8.1). This was done as pilot work to assess system capability and refine methodology. From this, the following shovelling tasks were identified as being representative.

Figure 8.1: Measurement equipment worn by participant (underneath PPE clothing) during first assessment of a shovelling task.

The first shovelling task was digging with the handle at an approximate 45 degree position relative to the ground, and shovel contents transferred to one side at ground level. The second task involved the same digging action, but transferring the contents to a height of approximately 700mm, to imitate actions used to load a wheelbarrow. The third shovelling task involved scraping the top surface, with the handle at an oblique and almost horizontal handle angle (relative to the ground) and transferring the contents to one side at ground level.

For each of these three shovelling tasks, two distinct methods were observed. The first method involved digging with the shovel in a more vertical position. His left hand moved up the handle so it was closer to his right hand at the end of the handle. This was observed to be done so his left hand could help to manipulate the handle for digging. His left hand would then move back to the middle of the handle (approximately) and the handle moved to a more oblique position to lift the contents and transfer them.

The second method involved the shovel handle at an oblique angle. In this position the participant grasped the shovel by placing his dominant hand at the end of the handle and his non-dominant hand approximately halfway along the handle, providing a fulcrum to lift the shovel and its contents, and to deposit the contents at the required height. For repeated actions with the handle in this position, the participant kept his hands in these positions.

8.2 Pilot work for project design

8.2.1 Site 1 and 2 assessments

Testing at site 1 involved participant 1 demonstrating examples of shovelling tasks (Figure 8.2). These involved scraping and moving material over the top of an excavated surface, digging and transferring gravel, and scraping the top of a pit lid.

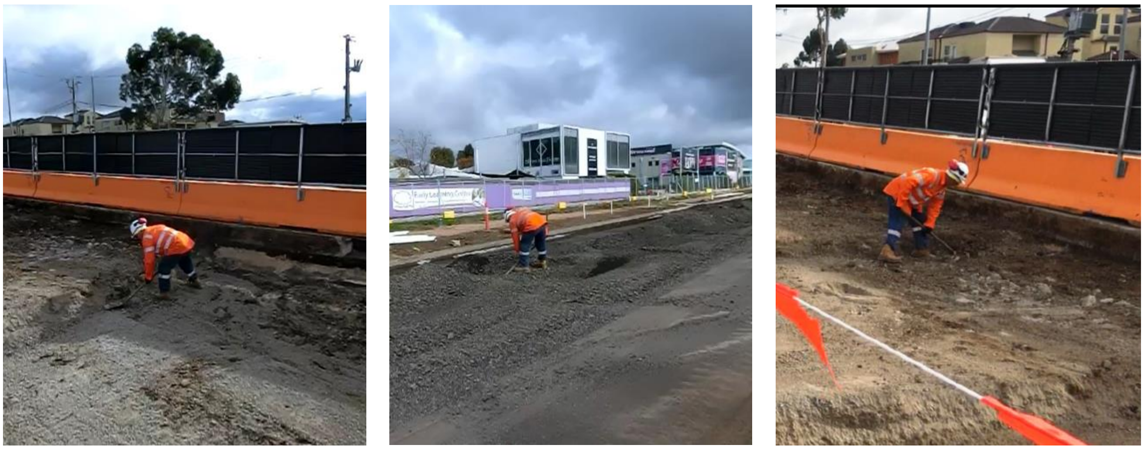


Figure 8.2: Images demonstrating site 1 shovelling tasks.

Observations from equipment testing and site 1 assessments were that participants consistently used noticeable trunk inclination for shovelling tasks. It was determined to investigate alternative shovel design options that may reduce trunk inclination across a representative range of shovelling tasks.

8.2.2 Development of a supplementary shovel handle

A web based review of commercially available shovel handles, designed and marketed on the basis of reducing back movements for users, found no readily available options for long handle shovels. Several alternative handle designs were found for spades that seemed oriented towards domestic gardeners and individuals clearing snow from areas around their homes. Neither design appeared relevant or suitable for evaluation within this project because long handle shovels, not short handle spades, had been reported and observed as the construction industry’s tool of choice.

RMIT’s research team then sought to develop a prototype supplementary shovel handle that could be tested to evaluate its impact on trunk inclination, lumbar flexion (L5/S1) and the movements of upper limb joints.

The supplementary handle developed for testing comprised short lengths of black, 30mm diameter, tubular irrigation piping (Figure 8.3). The lengths of piping were found to have inherent structural integrity, and the 30mm diameter is suitable for a handle of this type for an adult population. The handle was 120mm long. The upper section was 350mm long, and the lower section used to secure the supplementary handle to the shovel handle near the head was 50mm long (Figure 8.3). The long upper section was designed to provide structural integrity to the overall structure. It was not intended that a user to grasp it while using the shovel during testing.

Figure 8.3: Images of range of views of supplementary handle design on long handle shovel.

This supplementary handle was constructed to be fixed to the main shovel handle and remain in its set position during testing tasks. The design was based around providing a single-handed handle for the user's non-dominant hand, situated approximately at the mid-point of the shovel handle. This is the location where participants, in previously conducted assessments, had regularly placed their non-dominant hand when lifting the shovel to transfer the load.

The supplementary handle was developed to provide two angular offsets to the long handle, primarily to limit non-dominant wrist deviation and shoulder rotation. The first angular offset developed was a 'forward' angle of 20 degrees towards the head of the shovel. This handle angle would be similar to the handle angle of a range of industrial hand tools where the 20 degree angle places the handle more 'naturally' within the palm of the users' hand so it can maximise surface area to hold it and limit localised pressure points within the hand. The shape of the handle also influences the effectiveness of these design features. As part of its expected use, shovel users often need to apply force to the tool in combination with awkward wrist deviation. This handle or handgrip angle places the wrist of the operator's lower hand in a more neutral posture when using this tool. These features of handle or handgrip design are commonly accepted norms within ergonomics.

A second angular offset developed was 20 degrees to the right side of the handle; that is, 20 degree rotation about the longitudinal axis of the shovel handle when looking down or along the handle. The supplementary handle was not placed at a right angle in this position. The 20 degree offset to one side was designed to suit the left hand of a right hand dominant user. The purpose of this angular offset was to favour slight wrist pronation for users. This is another accepted norm within ergonomics. This slight angle, and the 20 degree forward offset angle, favours tools that require repeated and/or sustained use of force as a normal requirement for using the tool.

Each supplementary handle component was fixed to the long shovel handle using hose clamps. The offset handle was fixed to the midway point between the mid point of the head of the shovel, the estimated centre of mass of the shovel head when loaded, and the upper end of the handle. At the shovel head end, tape was also used to reinforce the strength of this connection.

This estimate of the position of the supplementary handle was based on initial shovel testing both with and without the handle. Circular hose clamps, used to secure each end of the supplementary handle to the shovel handle, were chosen because they provided the option of adjusting the position of the handle along the length of the shovel handle to match the body size or preference of the participant testing the shovel. However, the length was not adjusted in the interest of completing the assessment as an initial test of this concept and design, and to maintain structural integrity of the test handle during assessments.

The supplementary handle was tested and assessed before the assessment was conducted to ensure it was sufficiently robust and that no hazards were present that may affect a participant.

8.3 Research methods

8.3.1 Participants

Two participants were involved in the initial assessments of shovels at sites 1 and 2. These participants (participant 1: age – 54yrs; height – 178cm; mass – 78kg; participant 2: age – 57yrs; height – 175cm; mass – 86kg) were reported to be able to competently perform shovelling tasks.

Two RMIT assessment team members who acted as participants to test the supplementary handle were novice shovel users (participant 11: age – 24yrs; height – 182cm; mass – 88kg; participant 12: age – 60yrs; height – 173cm; mass – 73 kg).

8.3.2 Description of work tasks

Findings of supplementary handle testing assessment at the athletics track are described below. The findings provide a comparison of methods used for three shovelling tasks when using the existing long handle, and a supplementary handle (Figure 8.4and Figure 8.5). A single shovel was used in testing three shovelling tasks. First, the participants placed their non-dominant hand at their preferred position on the long handle and completed the tasks. The participants then placed the same hand on the supplementary handle, in their preferred position, and completed the tasks.

The first task was to dig sand with the handle at an approximate angle of 45 degrees relative to the ground, and then to transfer the contents to one side at ground level (Figure 8.4). The second task involved the same digging action, but transferring the contents to a 700mm high level, to imitate loading a wheelbarrow (Figure 8.5). The third shovelling task involved scraping the top surface with the handle at an oblique, almost horizontal, angle and transferring the contents to one side at ground level.

Left panel **Right panel**

Figure 8.4: Participant 12 using usual handle (left panel) and supplementary handle (right panel) for shovelling.

For each of these tasks, the two participants commenced by using the long handle of the shovel only; that is, grasping the shovel handle with their dominant and non-dominant hands (Figure 8.4, left panel). First, they performed all three shovelling tasks using the same handgrip along the shovel handle. Second, the participants performed the same shovelling tasks with the dominant hand still grasping the end of the shovel handle; however, in this second part of the testing phase their non-dominant hand grasped the supplementary handle in their preferred position (Figure 8.4, right panel).

Each participant performed several practice actions to confirm their preferred hand placement for both shovelling techniques. They then proceeded to perform each task. The only prompting provided was a count of the number of shovelling actions performed. Each participant performed each version of the three tasks 13 times to ensure the preferred minimum data capture of 12 repetitions was achieved.

Figure 8.5: Participant 11 shovelling sand over a barrier to imitate loading a wheelbarrow.

For the assessment of other tasks within this project, a series of six work height categories was used. For this task, the action of digging and gathering sand on the head of the shovel was assessed to be the most relevant work height level. Within the six categories, this task was carried out at the lowest height: (1) floor or ground level.

8.4 Data analysis

8.4.1 Trunk inclination

Trunk inclination data (trunk forward flexion and extension in the sagittal plane) were extracted by using the positions of the T12 and S1 vertebrae (Figure 8.6 and Figure 8.7). This level was chosen as the data best matched a visual representation of the participant's trunk movements in this plane. A higher level, such as T8 within the back, was not used as angles from this level were greater than the apparent angle of the trunk, most likely reflecting greater mobility of the mid thoracic spine.

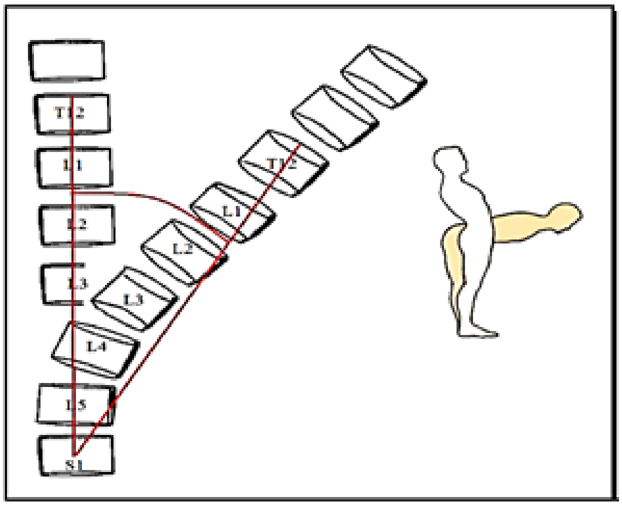


Figure 8.6: Schematic representations of forward trunk inclination angle.

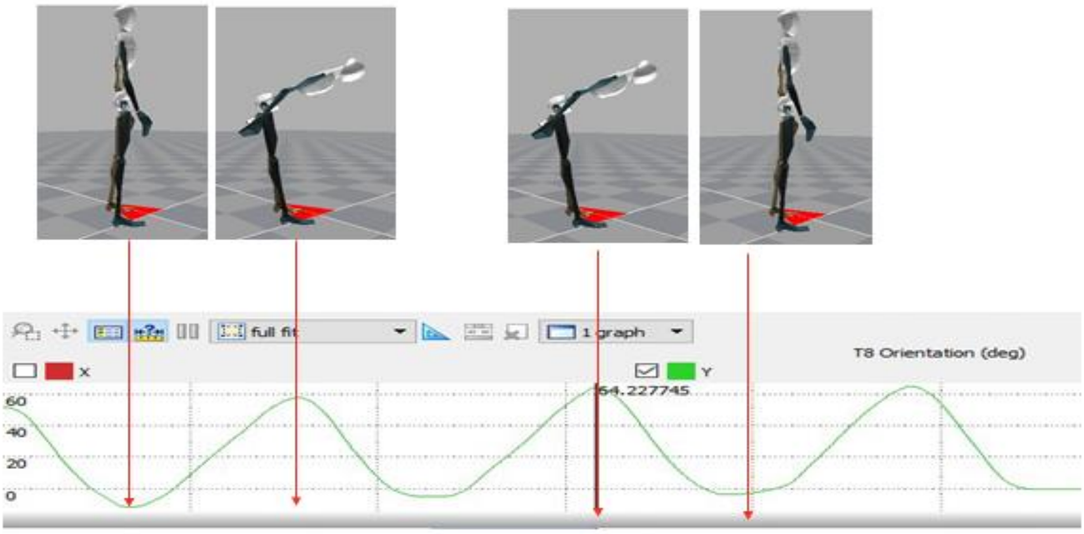


Figure 8.7: Avatar representation of trunk inclination as generated by the Xsens system.

8.4.2 Lumbar flexion

Lumbar flexion data (Figure 8.8) were calculated within the Xsens system at three levels of the lumbar spine (low back), T12/L1, L3/L4 and L5/S1. The range of overall lumber flexion is determined by the relative position of the Xsens shoulder and pelvic sensors. This value is divided by the number of spine represented within these movements and then allocated to the different levels of the lumbar spine according to previously established proportions.

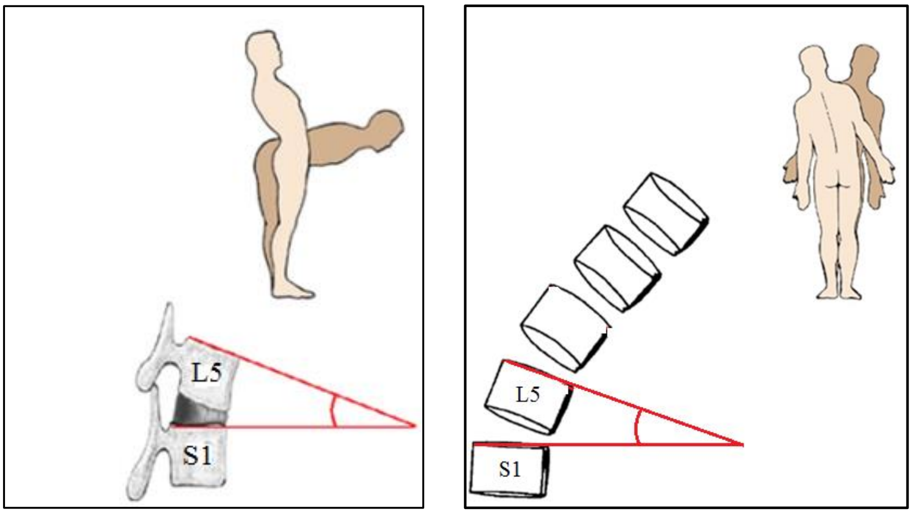


Figure 8.8: L5/S1 forward and lateral flexion.

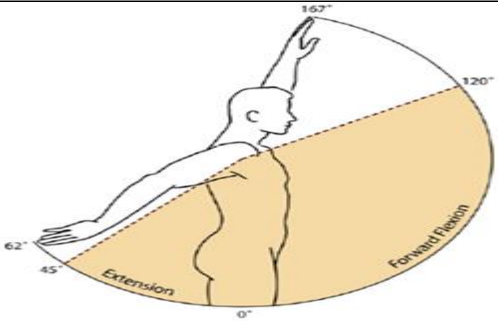
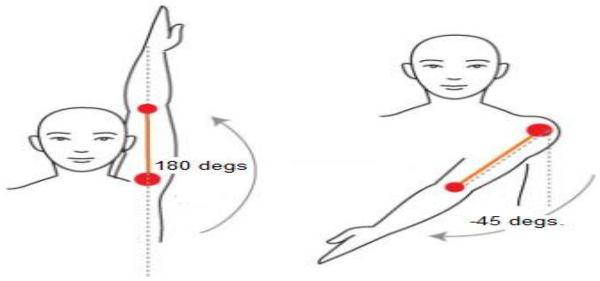
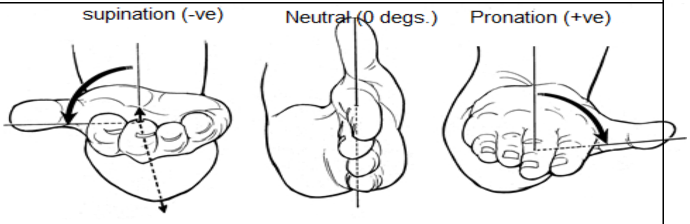
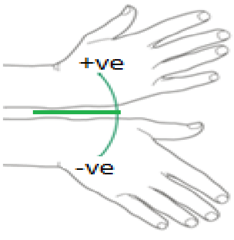
These data at all three lumbar levels were reviewed and data at the L5/S1 level only was selected for reporting. This was because the range of movement at this level, relative to the two levels above, was much greater and more likely to represent any changes between different tools and work methods. Also, this level is the base of the spine where high levels of leverage and disc compression can occur and is a commonly referred to location within workplaces.

Lumbar flexion data at the L5/S1 level was analysed and reported for forward and lateral (side to side) flexion. Lumbar forward flexion has positive values while extension uses negative values. For lateral flexion, movement to the person's right side is positive while movements to their left side is shown with negative values.

8.4.3 Shoulder and wrist (left, non-dominant side)

Each participant was right hand dominant. However, the action to use the shovel requires the left hand to hold the handle approximately halfway along to act as a pivot point for moving and lifting the shovel and its load. The right hand grasps the end of the shovel to activate and control these movements. The design feature being tested was the supplementary handle at the midpoint of the long handle, so Xsens posture and movement data was analysed to identify if this resulted in any changes to left shoulder or wrist movements.

The range of shoulder movement did not result in upper arm elevation exceeding 90 degrees, so the simple joint angles across the three planes of motion (sagittal, frontal and transverse) were used. Respectively, these rotations represent shoulder abduction/adduction, flexion/extension and internal/external rotation (Figure 8.9).

Data (degrees)	Illustration
Shoulder joint motion Vertical flexion (+ve) Vertical extension (-ve)	
<u>Shoulder joint motion</u> Left panel: Abduction (+ve) Right panel: Adduction (-ve)	
<u>Wrist joint motion</u> Wrist supination (-ve) Wrist pronation (+ve)	
<u>Wrist Joint motion</u> Radial deviation (+ve) Ulnar deviation (-ve)	

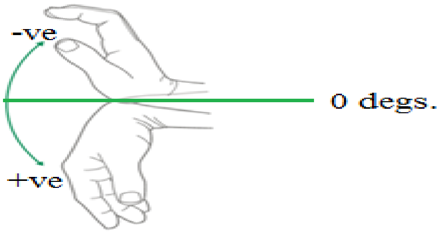
<u>Wrist Joint motion</u> Wrist flexion (+ve) Wrist extension (-ve)	

Figure 8.9: Schematic representation of shoulder joint motion in the sagittal and frontal planes (i.e. abduction/adduction, flexion/extension), and wrist motion in the sagittal, frontal and transverse planes (i.e. flexion/extension, radial/ulnar deviation, internal/external rotation). Joint angular convention is shown in the left panels.

Left wrist data was also reviewed. Data for the three planes of motion, flexion/extension, ulnar/radial deviation and pronation/supination (rotation), are described to demonstrate the differences in right wrist/hand postures and movements that resulted with the use of each tool.

Given the disparity in results between participants, this left upper limb assessment was conducted only for the first RMIT participant. This was done to match these data with the trunk inclination data to indicate differences between the two handle designs.

8.5 Results

This section reports only mean trunk inclination (trunk inclination sustained during the work task) and percentage of total task time with trunk inclination above 40 degrees. This is because of the small sample size of two participants and their different results. Note that standard deviation values are not reported for these data.

8.5.1 Trunk inclination

8.5.1.1 Mean trunk inclination

These mean values mostly demonstrate the inherent differences in the shovelling posture for the two participants, with regard to back movements. For all tasks and handle options, participant 11 maintains lower mean trunk forward flexion than participant 12 (Figure 8.10).

Noticeably, the mean trunk inclination values for participant 11 (Figure 8.11) ranged from 23.7 to 27.1 degrees for all tasks and handle types, except for task 3, scraping and tossing the load to one side, which was 14.0 degrees. The higher values were greater than the preferred threshold value of 20 degrees for manual tasks.

The mean trunk inclination values for participant 12 were all much higher than the preferred 20 degree threshold, ranging from 37.3-48.8 degrees. This result, even from a single participant, would be sufficient to indicate a possible manual handling hazard that requires further evaluation of shovelling tasks and means of reducing the range of trunk movement.

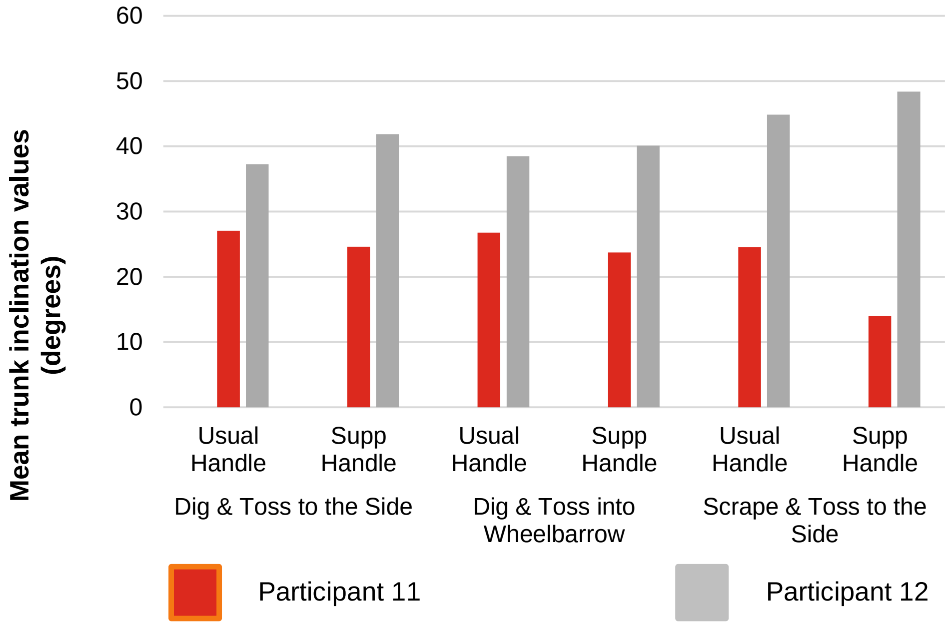
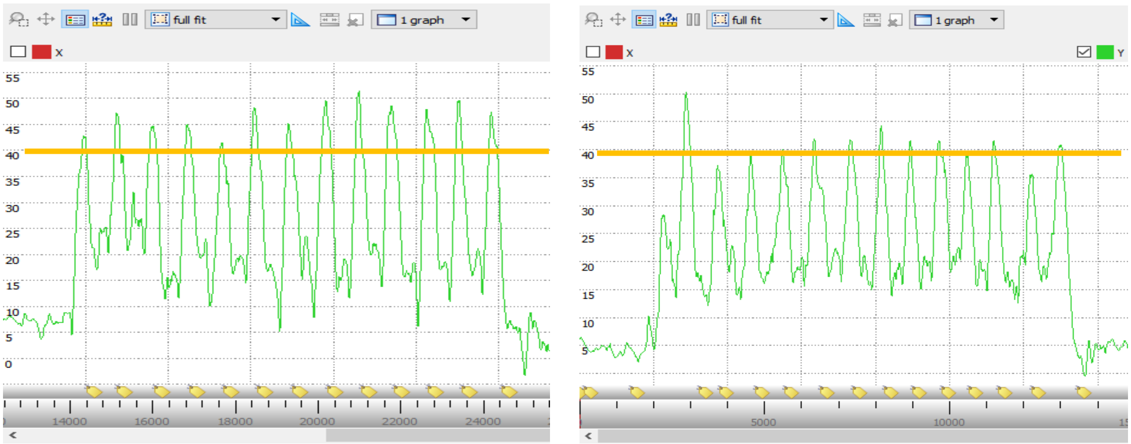
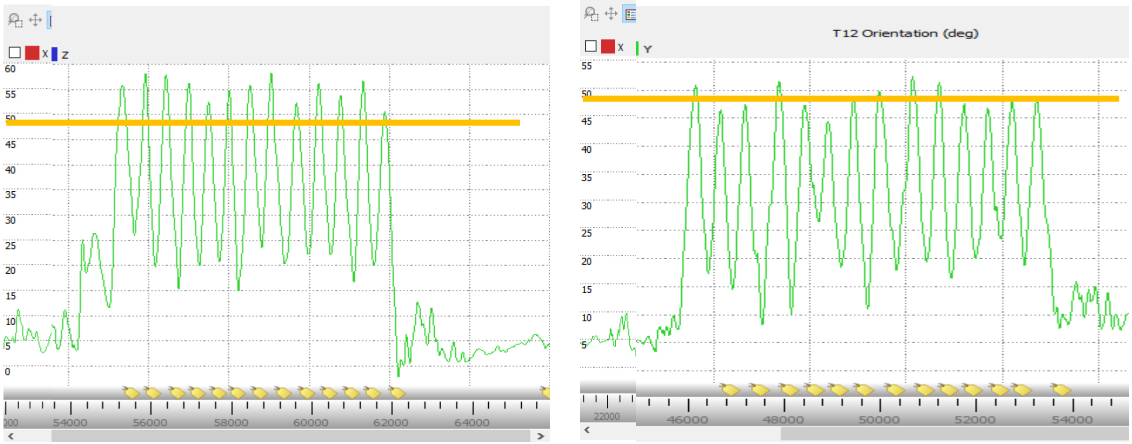


Figure 8.10: Mean trunk inclination values for usual and supplementary handle methods for tasks 1, 2 and 3.



Task 1: Dig and toss to the side.

Task 2: Dig and toss into a (mocked) wheelbarrow. Horizontal line indicates 40 degree threshold



Task 3: Scrape and toss to the side. Horizontal line indicates 40 degree threshold

Figure 8.11: Screen images of trunk inclination (T12/L1) angles for participant 11's usual (left panels) and supplementary handle (right panels) methods.

8.5.1.2 *Peak and minimum trunk inclination*

A similar pattern of difference, as reported in the previous section between the two participants, was found for peak and minimum trunk inclination data. The only similarity between the participants was when both used the usual handle for scraping and tossing the load to the side.

For all tasks, participant 11's peak trunk forward flexion (Figure 8.12) is greater when using the usual handle than when using the supplementary handle. For participant 12, this only occurred for task 1, and for the other two tasks the mean peak movement was greater when using the supplementary handle.

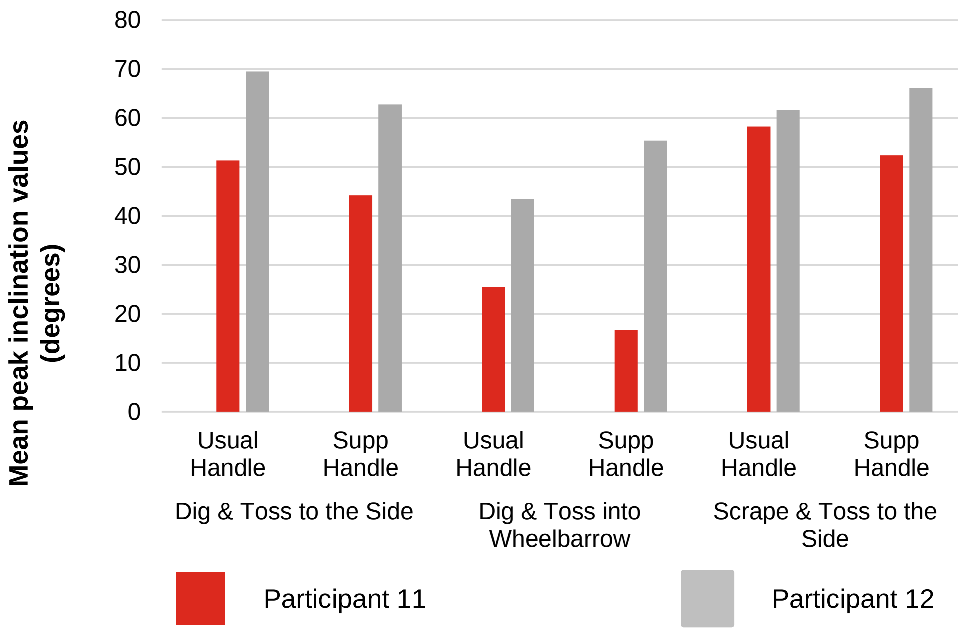


Figure 8.12: Mean peak trunk inclination values for usual and supplementary handle methods for tasks 1, 2 and 3.

The average minimum trunk inclination (Figure 8.13) for participant 11 were low, where they describe him as effectively adopting a neutral upright posture during each task, almost regardless of the type of handle being used. This indicates a broader method adopted by participant 11 that results in him consistently moving back to an upright posture while shovelling. Conversely, these values for participant 12 were assessed to be relatively higher, indicating that unlike participant 11 he did not move to an upright posture between shovelling movements.

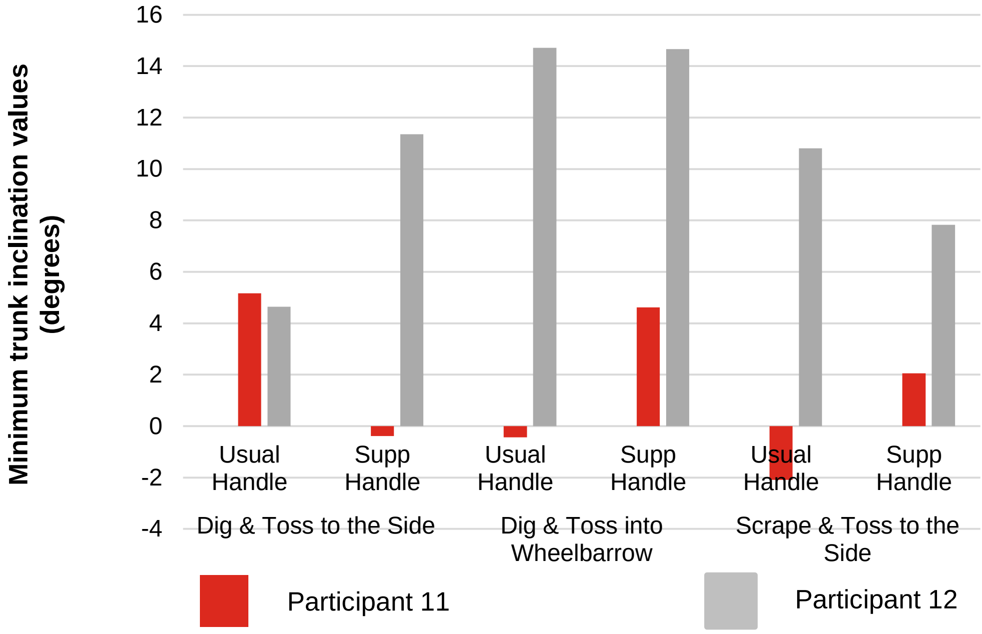


Figure 8.13: Minimum trunk inclination values for usual and supplementary handle methods for tasks 1, 2 and 3.

8.5.1.3 Per cent time duration above 40 degree trunk inclination

Another way of reflecting on the impact of work postures and movements, in particular a participant's back posture and movements, is to consider what proportion of their total work cycle time was spent within each of the postural categories or above postural thresholds. WorkSafe Victoria's *Manual Handling Code of Practice* (WorkSafe Victoria, 2000, page 17) indicates trunk postures and movements greater than 20 degrees inclination present a higher risk to workers than lower postures and movements.

However, considering trunk inclination data above or below this value as being hazardous or safe is simplistic. It provides little sensitivity regarding postures and movements greater than 20 degrees. This approach is inconsistent with biomechanical models showing that net anterior shearing force (horizontal force) acting on the intervertebral discs within the spine significantly increases with trunk inclination and lumbar flexion. This is due to reduced capacity of the back extensor musculature (for example, longissimus thoracis and iliocostalis lumborum) to generate posterior shearing forces within the vertebral column (Figure 8.14).

The posterior shearing force, generated by back extensors, counters the anterior shearing force generated by trunk inclination and lumbar flexion. The combination of trunk inclination and lumbar flexion, as seen in Figure 8.14 below, can lead to disc rupture where the anterior portion of the disc is squeezed. Accordingly, using 20 degrees of trunk inclination as a single threshold value could result in underestimating physical work demands and injury risks.

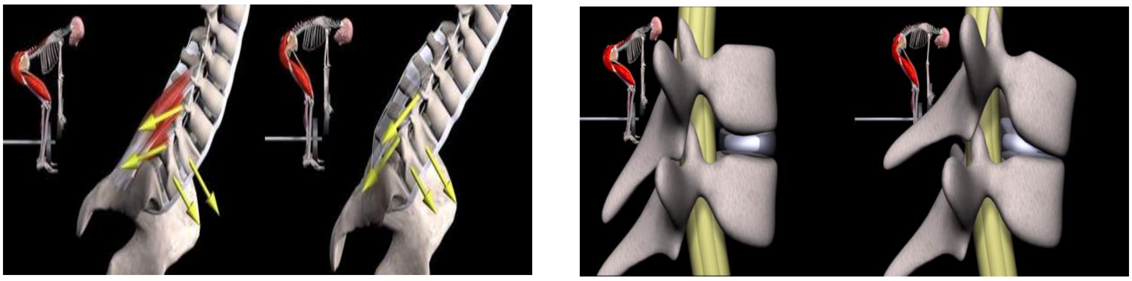


Figure 8.14: Schematic representation of anterior and posterior shearing forces within the vertebral column.

Source: Muscle and Motion Ltd (2017)

Considering trunk inclination in categories greater than 20 degrees can provide a more descriptive understanding of the nature of the task. This type of analysis is now possible with movement sensing technologies (for example, Xsens system). It provides an objective way of investigating work exposures to awkward or hazardous postures, and movements for occupational tasks.

A threshold value of 40 degrees is used for all construction tasks assessed within this project to provide common means of comparing this factor between each task. An investigation of the proportion of total work cycle time spent in the higher range of trunk inclination (that is, above 40 degrees) provides critical insight into the inherent requirement of the task. The figures below show the per cent of time both participants spent with a trunk inclination posture of more than 40 degrees.

For both participants, a proportion of their task time for all three tasks and both handles resulted in time spent with greater than 40 degrees of trunk inclination. However, the range of time spent above this level of trunk inclination varied widely between participants (see Figure 8.15).

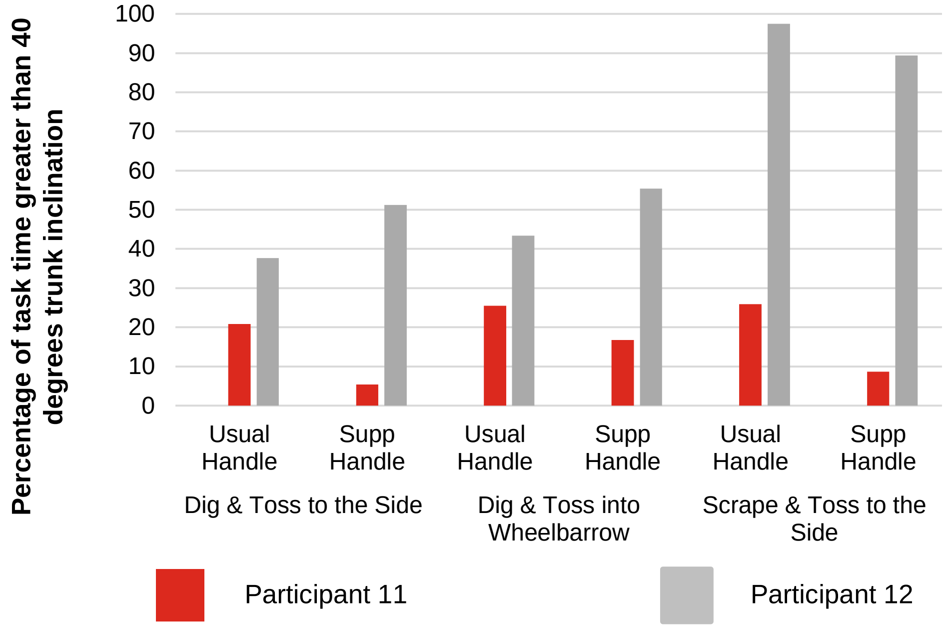


Figure 8.15: Percentage of total task time spent by participants with trunk inclination greater than 40^0 for shovelling tasks 1, 2 and 3.

8.5.2 Lumbar forward flexion (L5/S1)

Lumbar (L5/S1) forward and lateral (side to side) lumbar flexion values were analysed for participant 11 only. This was done on the basis that this participant demonstrated a movement response between the different handles for his trunk and upper limb, so this analysis was conducted to demonstrate possible impact between the two designs.

8.5.2.1 Peak forward lumbar flexion

Peak L5/S1 joint forward lumbar flexion (Figure 8.16) was significantly greater ($p < 0.05$) when using the usual handle compared to the supplementary handle in the dig-and-toss-into-wheelbarrow and scrape-and-toss-to-side conditions.

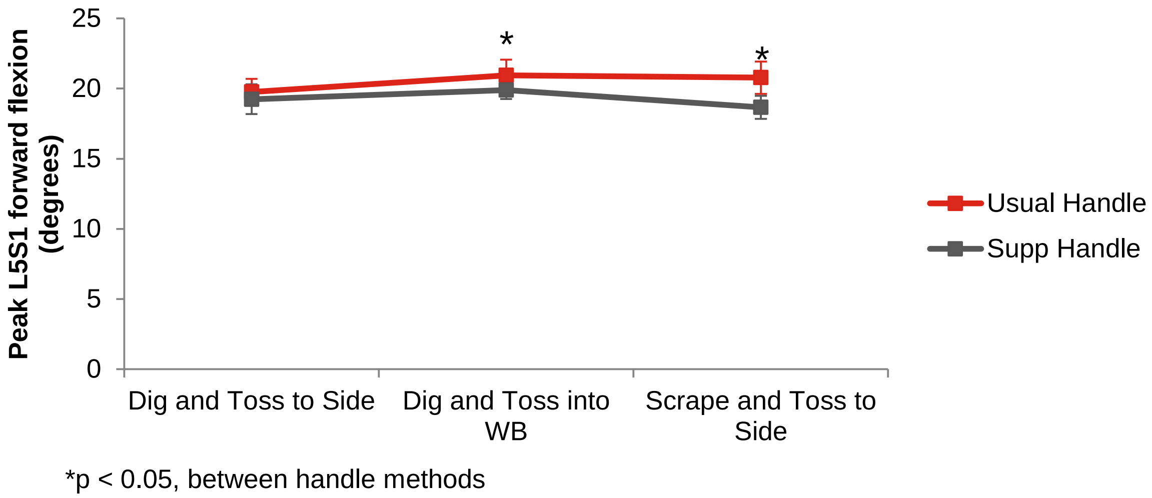


Figure 8.16: Peak lumbar forward flexion (L5/S1).

8.5.2.2 Minimum forward lumbar flexion

Minimum forward L5/S1 joint lumbar flexion (Figure 8.17) was significantly greater ($p < 0.05$) when using the usual handle compared to the supplementary handle in the scrape-and-toss-to-side condition only.

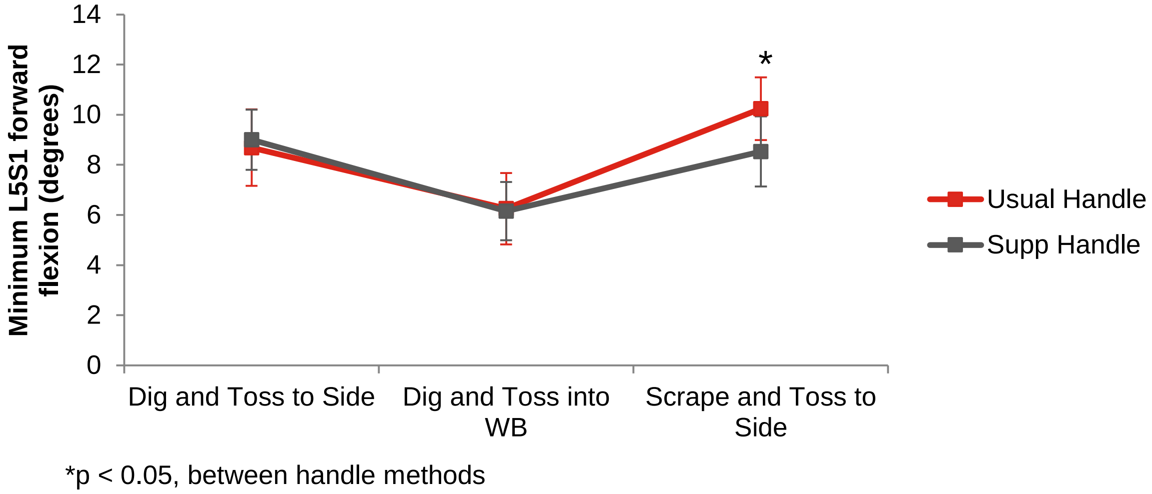
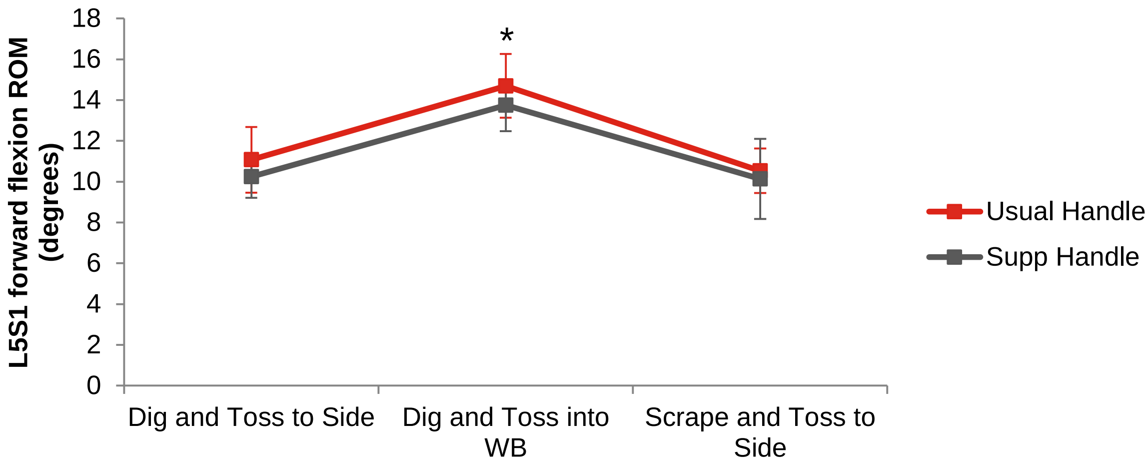


Figure 8.17: Minimum lumbar forward flexion (L5/S1).

8.5.2.3 Lumbar forward flexion range of movement

Forward lumbar flexion range of movement in the L5/S1 joint (Figure 8.18) was greater ($p < 0.05$) when using the usual handle in the dig-and-toss-into-wheelbarrow condition.



*p < 0.05, between handle methods

Figure 8.18: Range of lumbar forward flexion (L5/S1).

8.5.2.4 Summary of forward lumbar flexion results

No significant differences were found between the two handle designs for the dig and toss to the side task. For the dig and toss into the wheelbarrow task, the minimum forward flexion was almost the same when using both handles. However, the range of peak forward flexion was significantly less for the supplementary handle and this also resulted in it having a significantly larger range of forward flexion movement. For the scrape and toss to the side task the supplementary handle had significantly lower maximum and minimum ranges of forward flexion than the usual handle, indicating low L5/S1 flexion when using this handle. The overall range of forward flexion for this task, from the minimum to maximum mean values, were almost the same for both handles (approximately 10 degrees).

8.5.3 Lumbar lateral flexion (L5/S1)

8.5.3.1 Peak lumbar lateral flexion

Peak lateral lumbar flexion of the L5/S1 joint (Figure 8.19) was not significantly different between the usual handle and the supplementary handle *(positive values denote lateral flexion to the right; negative values denote lateral flexion to the left)*.

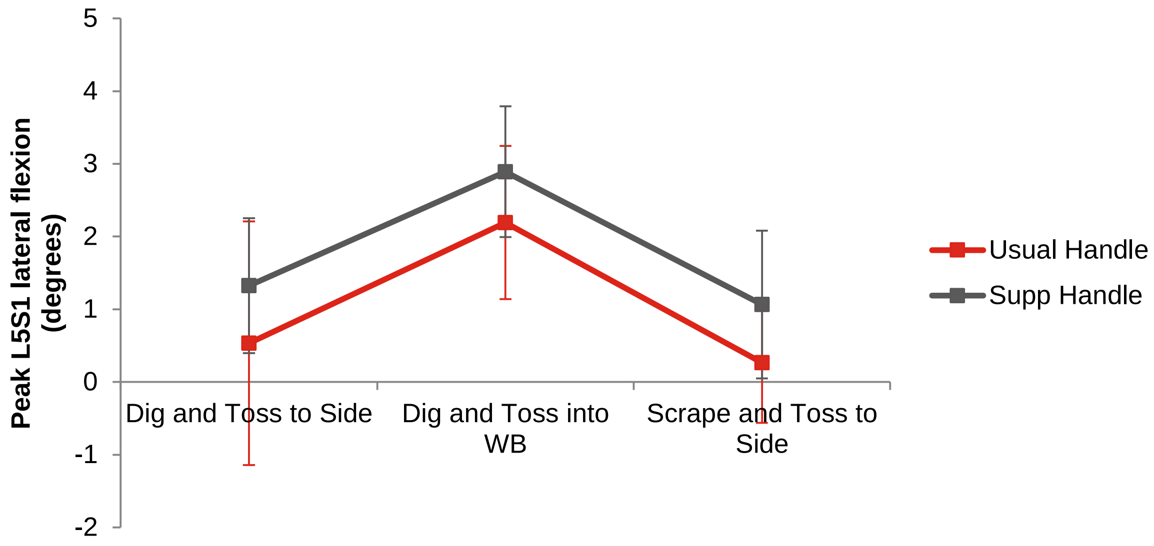


Figure 8.19: Peak lumbar lateral flexion (L5/S1).

8.3.5.2 Minimum lumbar lateral flexion

Minimum lateral lumbar flexion of the L5/S1 joint (Figure 8.20) was significantly less ($p < 0.05$) when using the supplementary handle compared to the usual handle in all task conditions. In other words, minimum lateral flexion was significantly closer to neutral when using the supplementary handle compared to the usual handle.

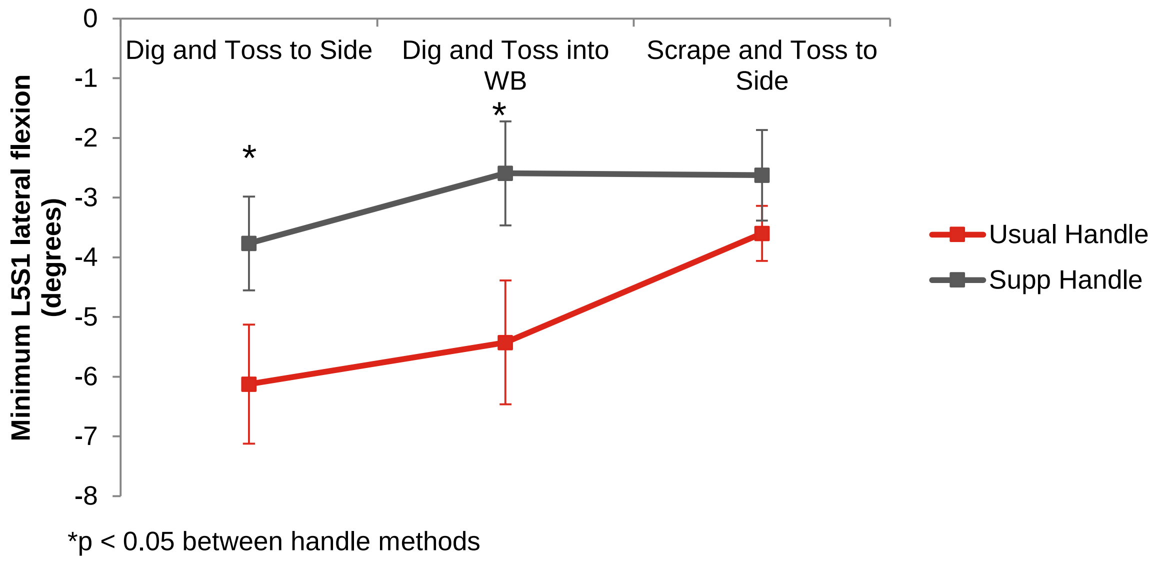


Figure 8.20: Minimal lumbar lateral flexion (L5/S1).

8.3.5.3 Lateral lumbar flexion range of movement

Lateral lumbar flexion range of movement of the L5/S1 joint (Figure 8.21) was significantly greater ($p< 0.05$) when using the usual handle compared to the supplementary handle in the dig-and-toss-to-side and dig-and-toss-into-wheelbarrow conditions. However, there was no significant difference for the scrape and toss to the side task where the range of movement values were almost the same for both handles at approximately 4 degrees.

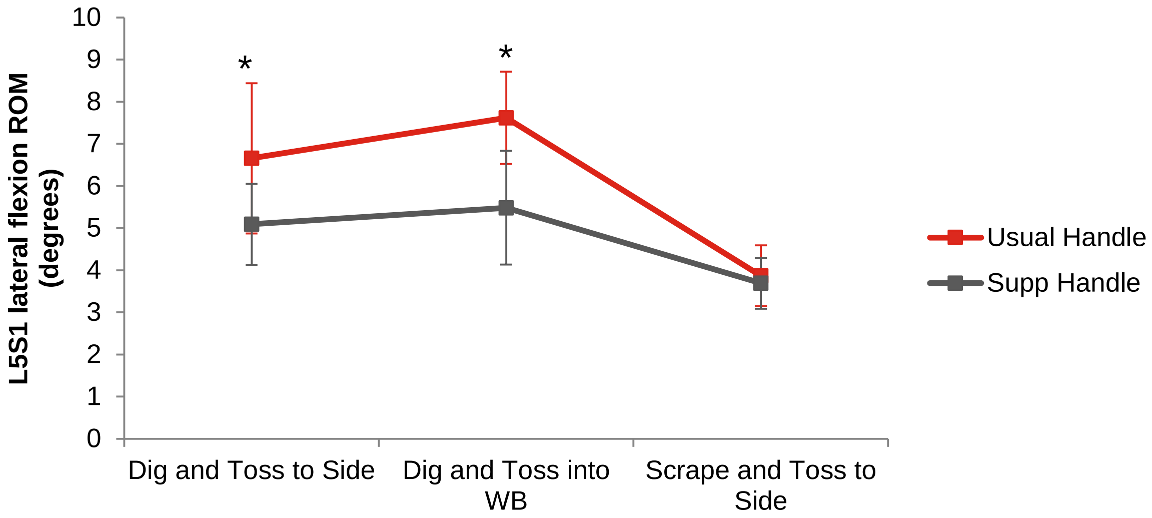


Figure 8.21: Range of lumbar lateral flexion (L5/S1).

8.3.5.4 Summary of lateral lumbar flexion results

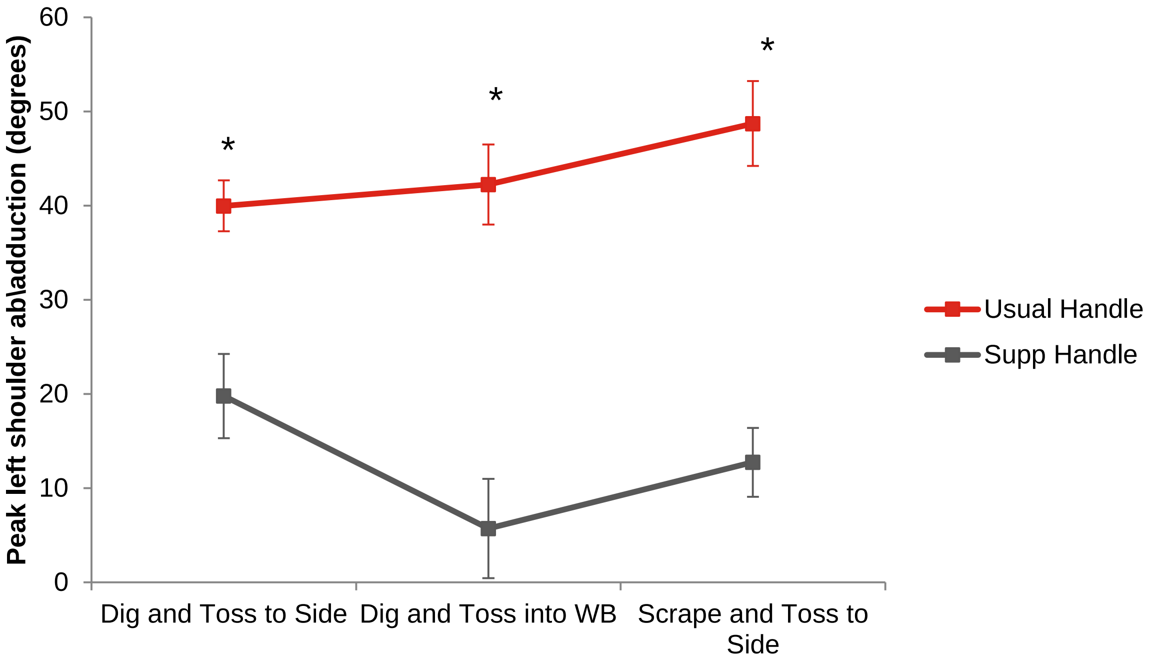
No significant differences were found between the handle designs for peak L5/S1 lateral lumbar flexion for each task. However, for minimum lateral flexion, the supplementary handle exhibited significantly lower values for all three digging tasks. Because these values were all negative values, this demonstrates that the range of lateral movement to the participant's left was less for each digging task when using the supplementary handle, which is grasped by the participant's left hand. The overall range of right to left lateral flexion movement at L5/S1 was significantly lower for both digging tasks, but not for the scrape and toss to the side task.

8.5.4 Shoulder movement (left)

Note that shoulder and wrist data is analysed and reported for participant 11 only.

8.5.4.1 Abduction – mean peak and minimum movements

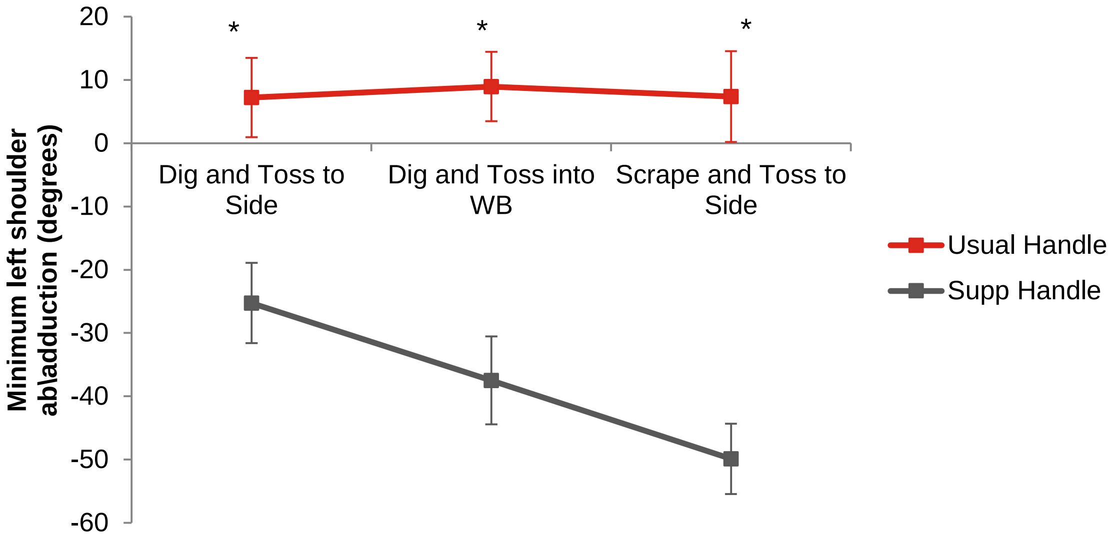
Peak left shoulder abduction (Figure 8.22) was greater in all shovelling conditions when using the usual handle, compared to the supplementary handle.



*p < 0.05, between handle methods

Figure 8.22: Peak shoulder motion (Mean ± SD) showing shoulder abduction with both handles and all three shovelling tasks.

Minimum left shoulder abduction (Figure 8.23) was greater when using the usual handle in all conditions, compared to the supplementary handle. Note that minimum left shoulder abduction when using the supplementary handle shows negative values, meaning the shoulder was in adduction.

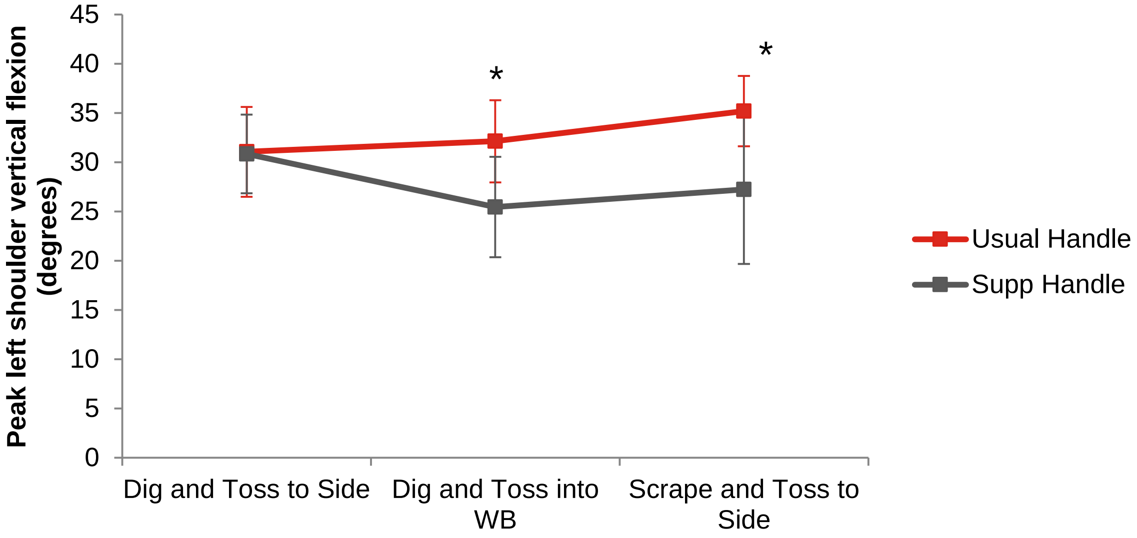


*p < 0.05 between handle methods

Figure 8.23: Minimum shoulder motion (Mean ± SD) with both handles and all three shovelling tasks. The usual handle shows shoulder abduction whereas the supplementary handle shows shoulder adduction.

8.5.4.2 Flexion – mean peak and minimum movements

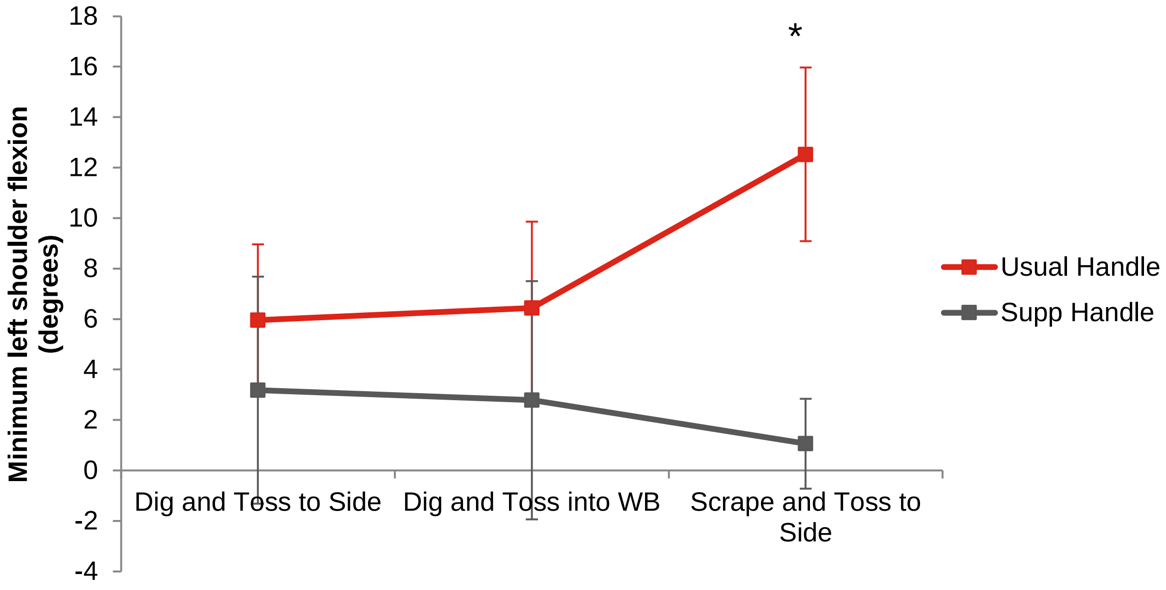
Peak left shoulder flexion (Figure 8.24) was greater when using the usual handle, compared to the supplementary handle in the dig-and-toss-into-wheelbarrow and scrape-and-toss-to-side conditions.



*p < 0.05 between handle methods

Figure 8.24: Peak shoulder motion (Mean ± SD) showing vertical flexion with both handles and all three shovelling tasks.

Minimum left shoulder vertical flexion was greater when using the usual handle compared to the supplementary handle in the scrape-and-toss-to-side condition (Figure 8.25).



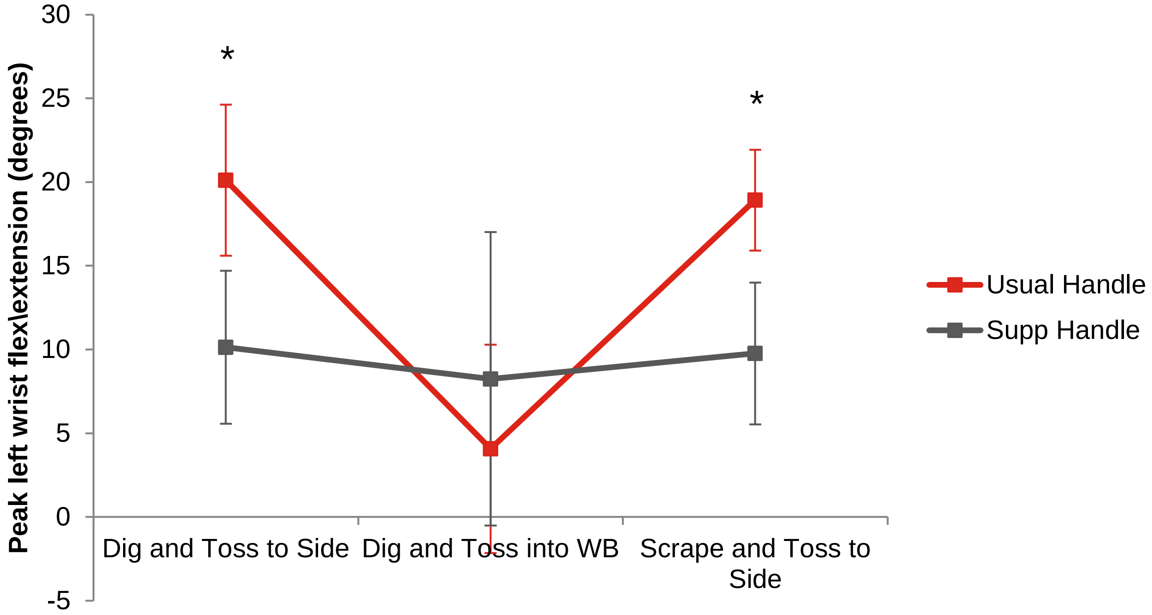
*p < 0.05 between handle methods

Figure 8.25: Minimum shoulder motion (Mean ± SD) showing vertical flexion (positive magnitudes) with both handles and all three shovelling tasks.

8.5.5 Wrist movement (left)

8.5.5.1 Flexion and extension – mean minimum and peak movements

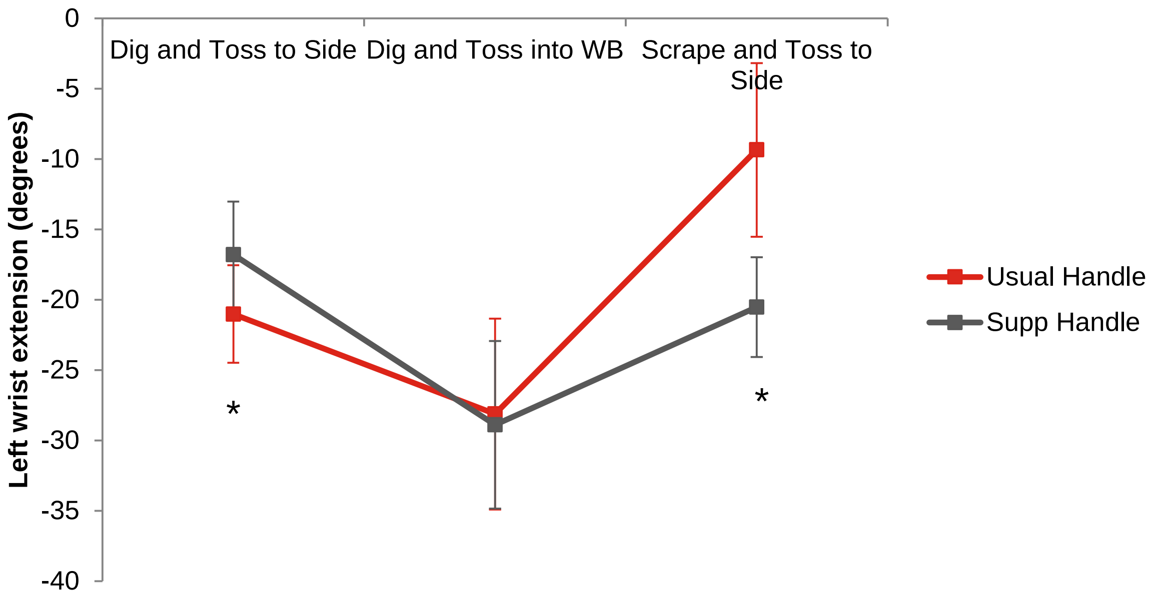
Peak left wrist flexion (Figure 8.26) was greater when using the usual handle, compared to the supplementary handle in the dig-and-toss-to-side and scrape-and-toss-to-side condition.



*p < 0.05 between handle methods

Figure 8.26: Peak wrist motion (Mean ± SD) showing wrist flexion with both handles and all three shovelling tasks.

Note that all minimum left wrist flexion values are negative, denoting wrist extension. Minimum left wrist flexion was greater when using the supplementary handle (that is, wrist flexion values closer to zero), compared to the usual handle, in the dig-and-toss-to-side condition. The opposite was true for the scrape-and-toss-to-side condition (Figure 8.27).

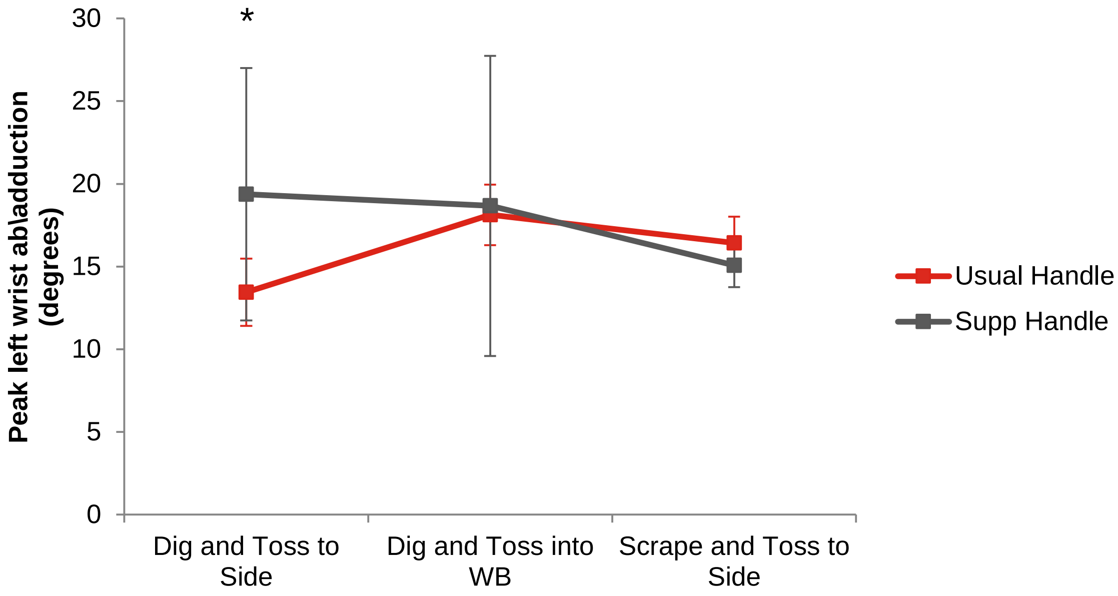


*p < 0.05 between handle methods

Figure 8.27: Minimum wrist motion (Mean ± SD) showing wrist extension with both handles and all three shovelling tasks.

8.5.5.2 Ulnar and radial deviation – mean minimum and peak movements

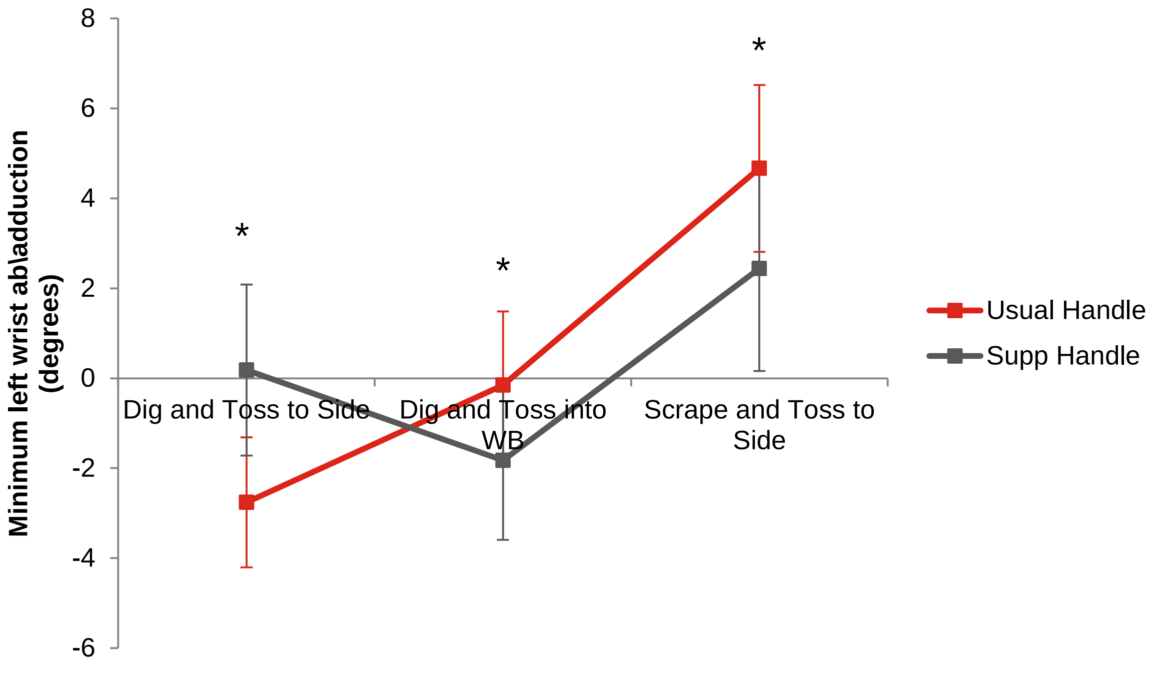
Peak left wrist abduction (radial deviation) was greater when using the supplementary handle, compared to the usual handle, for the dig-and-toss-to-side condition (Figure 8.28).



*p < 0.05 between handle methods

Figure 8.28: Maximum wrist deviation (Mean ± SD) showing radial deviation with both handles and all three shovelling tasks.

Minimum wrist adduction (ulnar deviation) (Figure 8.29) was greater when using the supplementary handle, compared to the usual handle, for the dig-and-toss-to-side condition. The opposite was found for the dig-and-toss-into-wheelbarrow condition. Minimum left wrist abduction (radial deviation) was greater when using the usual handle, compared to the supplementary handle, for the scrape-and-toss-to-side condition.

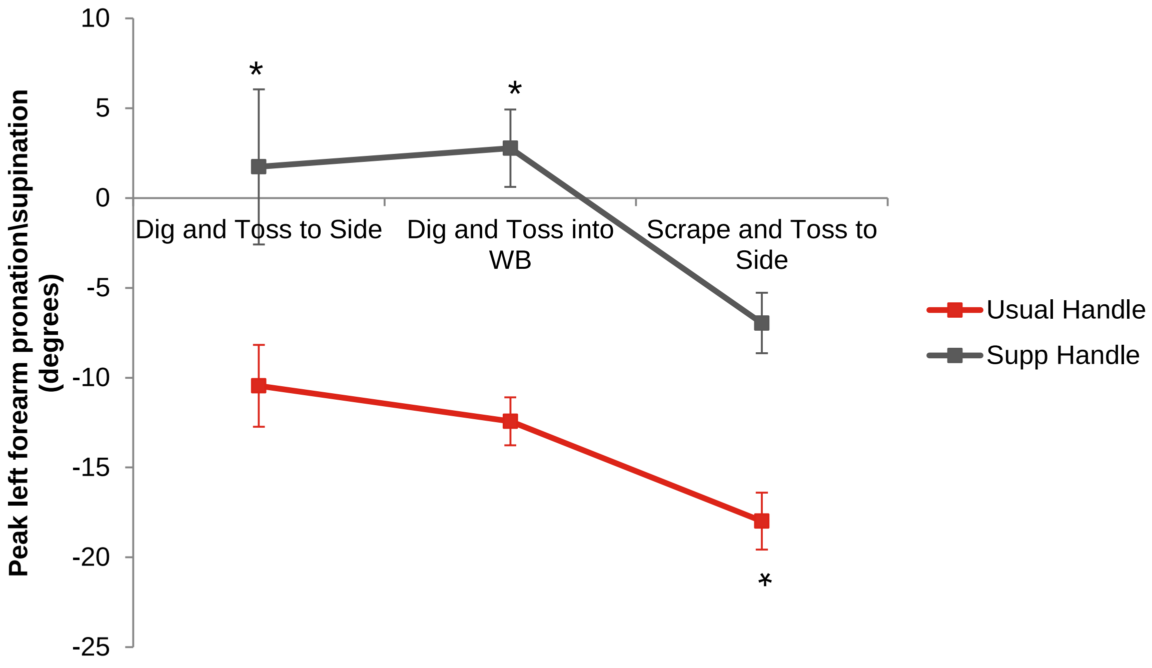


*p < 0.05 between handle methods

Figure 8.29: Minimum wrist deviation (Mean ± SD) with both handles and all three shovelling tasks.

8.5.5.3 Rotation – mean minimum and peak movements

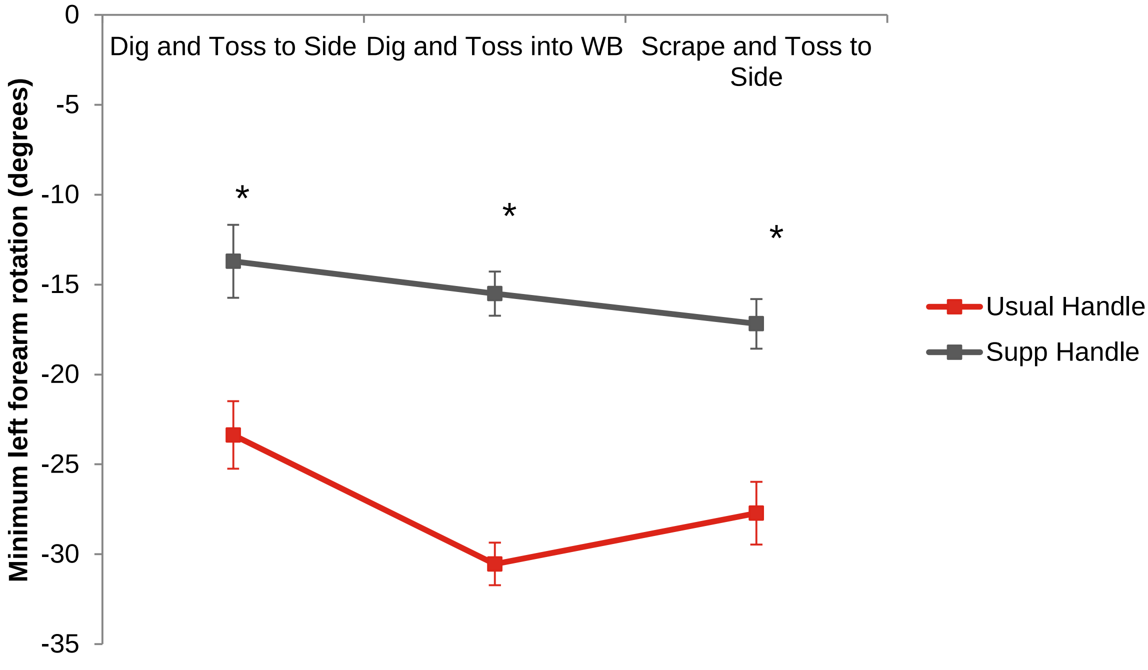
Peak left forearm rotation was closer to zero (more neutral) in all conditions when using the supplementary handle, compared to the usual handle (Figure 8.30).



*p < 0.05 between handle methods

Figure 8.30: Peak wrist rotation (Mean ± SD) with both handles and all three shovelling tasks. A positive value denotes pronation, whereas a negative value denotes supination.

Minimum left forearm rotation was closer to zero (more neutral) in all conditions when using the supplementary handle, compared to the usual handle, whereas it was in a supinated position when using the usual handle (Figure 8.1).



*p < 0.05 between handle methods

Figure 8.31: Minimum wrist rotation (Mean ± SD) showing supination with both handles and all three shovelling tasks.

8.5.6 Summary of left upper limb movements

Left upper limb movements were analysed for only one participant. The results show an overall improvement in the range of shoulder and wrist movements when using the supplementary handle.

These results show this design may be beneficial for users across several different types of shovelling tasks. Further investigation and development may be worthwhile.

8.6 Discussion

8.6.1 Implications of the results

Results of this assessment are interesting in that they are very different for both participants.

For participant 11, there was a reduction in overall trunk inclination and shoulder and wrist movement when using the supplementary handle on the shovel. This was so for all three tasks and conditions, except for the minimum trunk inclination values when digging and tossing the load into an imitation wheelbarrow, and scraping the shovel over the surface and tossing the load to one side.

Some of these differences are notable, such as the reduction in the proportion of total task time spent above 40 degrees of trunk inclination. For digging and tossing to the side, there was a reduction from 20.8% to 5.4%. For digging and tossing into a wheelbarrow, there was a reduction from 25.5% to 16.8%. For scraping and tossing to the side, there was a reduction from 25.9% to 8.7%. This level of impact on participant 11's trunk inclination was not represented with the other assessed results on mean trunk inclination and mean values for peak and minimum trunk inclinations.

These results can only be reported as being representative of participant 11's performance. However, they provide an insight into the possible outcomes of this design across a broader population of shovel users. They also highlight different conclusions that can be drawn from this type of human movement measurement assessment. The quantified mean values of other trunk inclination measures were unremarkable. However, when expressed as a reduction in the proportion of task time spent with trunk inclination of more than 40 degrees, the reductions are of interest. For tasks 1, 2 and 3, the reductions were, respectively, 74.1%, 34.3% and 76.4%.

Participant 12 had a very different experience when using both grasping methods. Unlike participant 11's results, participant 12's mean trunk inclination was slightly greater for each task when using the supplementary handle (4.6 degrees, 1.6 degrees, and 3.5 degrees, for tasks 1, 2 and 3 respectively). In addition, participant 12's mean peak trunk inclination values reduced for tasks 1 and 2, but were greater for task 3. The percentage of total task time spent above 40 degrees increased by 13.6% and 12.0% for tasks 1 and 2, but reduced by 8.1% for task 3.

These results for participant 12 were varied and represent a very different outcome to that for participant 11. To investigate these differences, the video footage obtained of both participants was reviewed. It was noted that when participant 11 used the usual grasping method, he placed his hand approximately halfway along the long handle. This is the same point at which the supplementary handle was secured. Participant1 2, however, placed his hand on the long handle approximately 80mm closer to the end of the handle. He was also observed to occasionally, slightly slide his hand along the handle at different times during a task. Grasping the supplementary handle created a fixed grasping point for participant 12 that was further along the long handle than his other grasping position. This may have contributed to his greater levels of mean trunk inclination, and the greater percentage of task time spent above 40 degrees of trunk inclination for tasks 1 and 2.

In summary, these results for these two participants are too diverse to represent a clear outcome between these two grasping methods of a shovel. However, they arouse interest in this type of handle design which appears to warrant further investigation. In particular, the outcome for participant 1 is of particular interest. His percentage of time above 40 degrees of trunk inclination was reduced for all three tasks, and substantially reduced (74.1% and 76.4%) for two of these tasks. It would be worthwhile to determine if this is an outlier measure, or more representative of a broader population of users.

8.6.2 Task redesign considerations

The results indicate a supplementary handle design intended to reduce trunk inclination and shoulder and wrist movements should be considered. Further design considerations for this handle design should be driven by the data obtained in testing. However, providing adjustability of its position along the main shovel handle is strongly indicated. Testing would determine if participant selection on its location results in improved trunk inclination, or whether a formula for its position could be developed based on user body dimensions and likely use of the shovel.

8.6.3 Conclusions

The use of supplementary handles has previously been considered for shovels and spades. There are some models of commercially available irregular shaped handles or handles that can be attached to an existing shovel or spade. However, the application of these handles is more common in shorter handled spades than in longer handled shovels. The uptake of supplementary handles in Victoria's rail construction industry was neither observed nor reported.

Construction sites use small to large scale mechanical devices to excavate ground surfaces, and to dig holes and trenches. Use of shovels in the rail sector of the construction industry appears to be low and ad hoc. Use of shovels appears to be limited to incidental tasks, such as clearing a ground surface of small volumes of debris which collects as a by-product or jackhammering, or clearing around and on top of structures within the ground, such as pit lids.

This assessment used Xsens human movement measuring technology to explore whether there is any impact on trunk inclination, or other joints of the body, when using a supplementary handle on a shovel. Trunk inclination results from this assessment were too disparate to provide a clear direction of the likely impact of the supplementary handle used in this assessment.

The results for the two participants assessed are too diverse to represent a clear outcome between these two grasping methods of a shovel. However, they arouse interest and this type of design warrants investigation. In particular, the outcome for participant 11 is of particular interest. His percentage of time above 40 degrees of trunk inclination was reduced for all three tasks, and substantially reduced (74.1% and 76.4%) for two of these tasks. It would be worthwhile to determine if this is an outlier measure, or more representative of a broader population of users.

Part 9: Discussion and key findings

9.1 Key findings

The research results reveal that, in some cases, ergonomic risk factors in the construction tasks we analysed may be reduced by relatively simple, low cost measures.

For example, our findings in relation to steel fixing are consistent with findings in international research that found particular risk factors could be reduced significantly by using modified steel fixing tools. In particular, previous research has assessed long handled stapler tools, similar to that assessed in our research, as capable of reducing the need for a worker to bend when tying steel rods at ground level. We found similarly that dangerous degrees and frequency of trunk inclination or forward flexion were significantly reduced when the long handled stapler tool was used.

However, our analysis by categorised work heights, which is relatively novel, enables more nuanced conclusions to be drawn. In particular, the benefits of reduced trunk forward flexion when steel fixing work is undertaken at ankle-to-knee height were less than when work was performed at knee-to-hip level. This was due to the need for a worker to place and hold the long handled stapler tool at a right angle to the rebars being fixed together. Although trunk inclination returned to an upright posture when the tools were used above-shoulder height, shoulder postures and movements became excessive for all three tools. Once work height was overhead, these shoulder postures further increased for the pincer/cutter and power tying tools, but substantially reduced for the long handle tool where minimal shoulder movements were used.

Previous research calls for an analysis of activities within work tasks to understand the way the aspect of a task impacts the risk of work-related MSD. The importance of such an understanding is evidenced by the finding of Buchholz et al. (2003) that the characteristics of the work area, in particular work height, will have an impact on ergonomic risk factors. During construction of a ‘cut and cover’ tunnel, Buchholz et al. (2003) found risk factors varied significantly depending upon whether steel fixers were engaged in erecting reinforcement at ground level, wall height, or for a ventilation duct.

We extended this analysis of work height by classifying work according to the level at which it takes place. The work height classifications were: (1) floor or ground level; (2) ankle-to-knee; (3) knee-to-hip; (4) hip-to-shoulder; (5) above-shoulder; and, (6) directly overhead.

This classification by work according to height enables specific risk factors to be identified for work performed at each of these levels. It may also inform development of standardised solutions or design features for tools that address risk factors for work at different heights.

Our analysis of potential benefits associated with using different steel fixing tools also suggests the ergonomic risk factors inherent in work undertaken at different heights may be best addressed through developing and using tools designed specifically for activities performed at a particular height, or in a specified range of heights.

9.2 Measuring versus estimating

This research highlights benefits associated with using technology-enabled measurement tools to objectively measure human movement. The resulting data can be used to:

- understand risk factors for work-related MSD
- evaluate the potential impacts of ergonomic interventions, and
- provide evidence to guide the development of future ergonomic interventions to reduce MSD risk in the construction industry.

Historically, MSD risk factors have been evaluated using self-report or observational methods (Buchholz et al., 1996). Some of these methods have been carefully designed to capture a wide range of relevant factors. For example, the Posture, Activity, Tools, and Handling (PATH) method has been previously used to analyse ergonomic hazards experienced by steel fixers (Buchholz et al., 2003).

However, increasingly, international researchers have begun to use wearable movement sensing technology to capture movement data more precisely than is possible using observational methods.

These technologies have been used to compare the ergonomic impacts of different construction methods, tools and techniques. For example, (Albers & Hudock, 2007) compared three methods of steel tying, using a twin axis goniometer and a torsiometer to measure wrist motion and position.

Technological developments, and the availability of lightweight and portable whole body systems of wearable sensors, now allow measurement (rather than estimation) of human movement in an objective and reliable way, without disrupting construction work too greatly (Yan et al., 2017). This creates the opportunity to more precisely and objectively quantify ergonomic risk factors, and to evaluate risk reduction opportunities and outcomes.

The portability of these systems also enables data to be collected in workplaces, better reflecting the realities and risks associated with work tasks as they are practised in the construction site context.

The use of whole body systems to measure human movement is also rapidly becoming accepted practice in international applied ergonomics research in the construction field (Umer et al., 2017a; Umer et al., 2017b). It is recommended in international intervention studies focused on reducing the risk of work-related MSD in the construction industry (Brandt et al., 2015).

9.3 Evaluating, and predicting the likely viability of, new construction tools and methods

One advantage associated with using whole body systems to measure human movement during work tasks is that it can provide a robust evidence base for designing and selecting construction tools and methods.

Adopting evidence-informed policies, programs and practices is a key Action Area in the *Australian Work Health and Safety Strategy 2012-22* (Safe Work Australia, 2012). Our research provides important new evidence relating to MSD risk factors inherent in the selected manual rail construction tasks, as well as the potential to reduce these risks through ergonomic interventions.

In particular, we have highlighted potential for significantly reducing MSD risk through designing/selecting tools and equipment, notably in steel fixing, cable pulling and shovelling.

This evidence can inform industry-wide initiatives that further develop and evaluate ergonomically effective tools and equipment for these (and potentially other) work tasks.

We evaluated two simple interventions designed to reduce frequency and extent of trunk inclination or forward flexion during shovelling and cable pulling. We found evidence that supports both these redesign solutions as means of producing significant improvements.

This evidence can therefore be used to inform further design and evaluation studies which refine the simple equipment modifications trialled in our study.

Our results also provide important new evidence on the potential to reduce ergonomic risks associated with steel fixing, an internationally recognised high risk task for work-related MSD.

Our research shows that commercially available tools can potentially reduce the risk of MSD. In particular, the hand-held power tying tool reduced hazardous wrist movements and the long-handled stapler tool reduced trunk inclination. However, neither of these tools was perfect. In terms of trunk inclination, the hand-held power driven tool performed less well than the traditional manual steel tying method. Dababneh and Waters (2000) also note that powered tools are heavier than non-powered tools, potentially increasing external moments of force about joints of the upper extremities that must be countered by increased internal muscle moments of force about joints (that is, muscular effort). They are also generally associated with vibration and high kickback forces that can increase with the tool’s age.

The long- handled stapler tool was awkward to use at some work heights and required a ballistic, manually exerted, downward push to operate. This could potentially contribute to fatigue, and potentially create excessive moments about upper extremity joints (Dababneh & Waters, 2000).

Our results suggest some opportunities for further developing and improving these types of tools. This is consistent with previous research undertaken in the US showing a custom designed extension handle fitted to a power driven steel tying tool can reduce both harmful wrist movement and trunk inclination for steel fixing at ground or floor level (Albers & Hudock, 2007).

However, the US research did not involve whole body biometric assessment. We recommend that any tool design developments are subjected to such assessment so that the impacts on MSD risk factors can be considered holistically.

The ability to systematically and rigorously evaluate the ergonomic performance of different tools for tasks such as steel fixing, also supports development of tool design performance benchmarks.

The evidence created by this type of assessment is likely to be critical to refining and improving new tools, and ultimately adopting them into use.

9.4 Research to practice

Some ergonomic risk factors we identified in the research can be addressed by relatively simple, cost effective methods, such as selecting alternative steel fixing tools or using a simple trestle device to reduce manual handling during cable pulling. However, other significant risk factors cannot be addressed so readily.

In particular, our analysis identified risk factors associated with using jackhammers to break concrete caps on structural foundation columns to expose the steel reinforcement bars. The analysis revealed high levels of trunk inclination, particularly when work is performed between knee and hip levels. It also identified that lifting the jackhammer to the required work height presents significant manual handling risk.

Other hazards noted during this task were vibration, dust and noise exposure.

In this case, opportunities to reduce ergonomic risk factors through tool redesign were considered to be relatively limited.

In contrast, alternative methods for breaking the concrete pile caps were identified in the international literature as being of potential benefit.

These methods have been examined in the European construction context. Gibb et al. (2007) have documented a number of them in an analysis of reducing health hazards through promoting better designed work.

Examples of pile breaking methods that substantially reduce the amount of time jackhammers are required to perform this task include hydraulic, chemical and crack propagation methods.

For example, ThyssenKrupp Steelcom, a sheet piling and pile driving equipment specialist, has developed a hydraulic concrete pile breaking device, known as a ‘muncher’.

The device is suspended from an excavator or crane and placed over the pile to be broken. When activated (using the hydraulic power of an excavator combined with a power pack), the device uses hydraulic cylinders to drive opposing chisels into the concrete piles, making a horizontal fracture.

Once the fracture is made, the chisels penetrate further into the concrete causing it to break. It can then be lifted off the pile. The broken concrete is contained within the unit so the risk of falling/flying objects is reduced. Benefits associated with this method include:

- converting a physically demanding manual task to a mechanical task that potentially eliminates MSD exposures
- reduced risk from flying debris, noise and vibration (as is the case with jackhammering)
- easy handling and maintenance
- opportunity to use an excavator during its down time to perform work often performed by a sub-contractor
- improved productivity and limited cutting out required, and
- a variety of square and round models to suit different pile dimensions and rebar configurations (https://www.projectlink.com.au/news/effective-concrete-pile-breaking).

Thus, our findings suggest that for some high risk tasks, the opportunity to reduce the risk of MSD may be better addressed by reviewing international research and best practice technology-based risk reduction approaches. This is consistent with applying the hierarchy of control in selecting the best available risk reduction approaches.

Similar opportunities may be identified for shotcreting which creates hazards associated with rebounding material and dust, as well as high potential for MSD (Ono, 1996). Mechanised shotcreting methods developed in the mining industry and through international research have focused on applying robotics to eliminate or reduce the use of manual shotcreting methods (Cheng et al., 2001; Więckowski, 2017).

9.5 Lessons learnt and future directions

This research has highlighted opportunities and potential impacts associated with undertaking whole body biometric assessment to inform and evaluate redesign of tools or work methods, and ultimately enable the reduction of MSD risks in manual rail construction tasks.

This research was the first study of its kind in the Australian construction industry. It reflects recent developments in international applied ergonomics research.

The ability afforded by the sensor system we deployed to measure human movement in work undertaken on construction sites provided critical new evidence about specific sources of MSD risk inherent in the selected work tasks. Collecting data in field-based work settings allowed us to assess tasks such as shotcreting that would be difficult to simulate in a laboratory. The sensor system generated realistic data reflecting site-based work practices. However, a number of lessons have been learnt and will guide amended research processes in future studies.

In particular, logistical aspects of accessing construction sites will be streamlined in future. For example, training requirements will be identified in the research planning stage to avoid data collection delays. It is possible this could allow us to identify key variants and replicate certain aspects of assessment in a laboratory setting, supplementing field-based data collection.

In addition, we recommend an initial in-field pilot assessment of a work task prior to data collection. This would enable us to identify key variants associated with a given work task and develop specific data capture methodologies. It will also support design of a customised data collection protocol and data analysis tools for this task which may combine laboratory and site-based assessment activities.

Shotcreting is an example of where this approach could have been beneficial. It was observed that the force involved in the shotcreting action is likely to be a significant risk factor. We were able to make some estimates of force in this instance. However, objectively measuring force through using force transducers, and biomechanical modelling of shotcreting, are recommended in future studies.

Finally, the timing of our data collection was based on convenience sampling, based on opportunities to collect data. This approach is limited to a small number of participants.

The exposure information we report is necessarily based on the assumption that the time periods and workers we involved in the research are broadly representative of the tasks we studied. Informal conversations with workers who participated in the research indicated the assessment was undertaken under normal work conditions.

However, given the variability of construction work, it is also possible we may not have collected data relating to less frequently used ways of working. Further research with larger groups of participants would therefore be beneficial.

Where possible, future research should replicate and extend the analysis of these tasks and incorporate evaluation of ergonomic interventions.

Part 10: References

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Appendix A: Participant information sheet and consent form

Title	Major Transport Infrastructure Program Musculoskeletal Injury Reduction Research Project
Chief Investigator/Senior Supervisor	Distinguished Professor Helen Lingard
Associate Investigator(s)/Associate Supervisor(s)	Professor Stephen Bird Associate Professor Noel Lythgo Associate Professor Olga Troynikov Dr Isaac Selva Raj Mr Alf Camilleri Mr Chris Fitzgerald Dr Martin Dubaj
Principal Research Student(s)	Mr Dong Gyoon Na

1. Introduction

You are invited to participate in a research project being conducted by RMIT University, on behalf of the Department of Economic Development, Jobs, Transport and Resources (DEDJTR) and WorkSafe Victoria.

You have been invited because you are a construction worker engaged in the rail construction activities, and are working within the Major Transport Infrastructure Program of works.

Please read this information carefully and be confident that you understand its content before deciding whether to participate.

If you have any questions about the project, please ask one of the research team.

2. What is the purpose of this research?

Construction work involves frequent exposure to awkward body postures and movements including lifting, bending, twisting or kneeling.

As a consequence, musculoskeletal disorders (MSD) or injuries (for example, strains and sprains) are common among construction workers.

This research will investigate body posture and movement patterns during the performance of manual work tasks that are routinely performed in the rail construction sector.

The purpose of this study is to provide information about the physical demands that may contribute to the development of MSD, and the ways that risks can be reduced.

3. Why have you been approached?

You have been approached because:

- you are a healthy male adult worker aged between 18 to 50 years, and
- you have no musculoskeletal, neuromuscular or medical conditions that affect your ability to perform your daily work task/s.

4. Do you have to participate in the research?

Participation in the research is voluntary. You do not need to participate in the research unless you choose to do so. If you agree to participate, you may withdraw from the study at any point.

You are also encouraged to ask questions if you require more information about any part of this research.

If you participate in the first stage of the study, you do not have to participate in the second or third stages.

5. If you participate, what would you have to do?

There are three stages to the research. You can volunteer to participate in any of these three stages. These are described below.

Stage one – measurement of work tasks

If you participate in this stage of the research, your total time commitment will be approximately two hours.

The first hour will be spent attaching miniature sensors to your skin. These sensors will:

- look like the ones in the photo below, and
- measure the way your body moves.

The sensors will be placed over six major upper limb muscles, six major trunk muscles and four lower limb muscles.

The researcher will prepare small sections of your skin by shaving an area measuring about five square centimetres using a battery powered razor. There may be a need to use a manual razor at times, but this is unlikely.

The researcher will then gently abrade the skin surface and clean it with an alcohol wipe before attaching the sensor with tape.

The second hour of your time will be spent collecting data while you are wearing the miniature sensors.

During data collection you will perform your daily work tasks at the construction site where you would normally work.

This task could be concrete cutting, jackhammering, shovelling, hole drilling, cable pulling, steel fixing or shotcreting, and other tasks which are routinely performed in a rail construction work site environment.

You will not be asked to undertake any task that you are not familiar with or do not feel confident in your ability to undertake.

During the data collection session, you will be asked to perform the task either repetitively or continuously. The measurement will last for approximately 45 minutes.

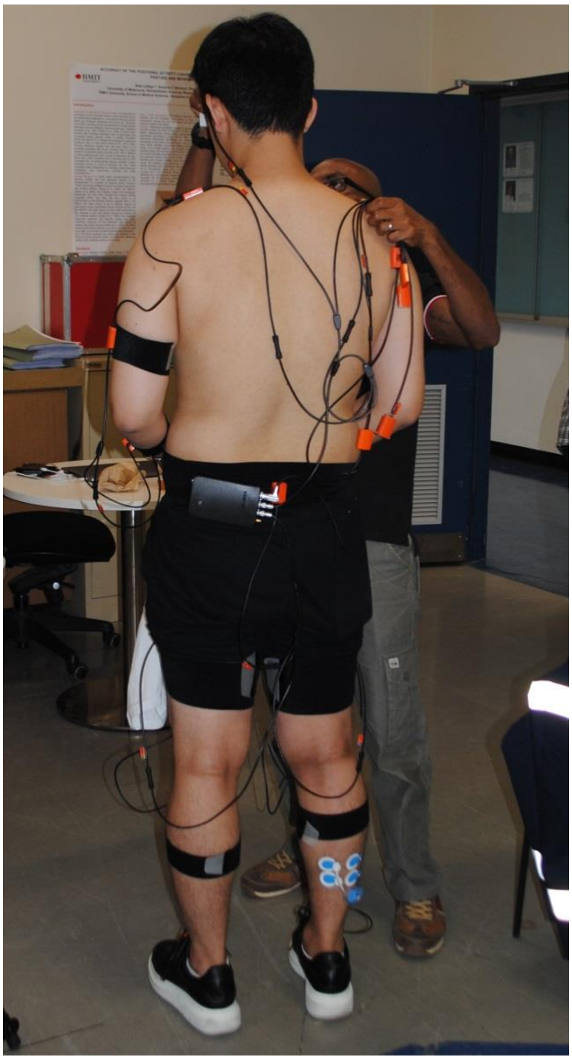
While performing your work, you will be video-taped and your motion recorded with the sensors.

Your muscle activities will also be recorded.

You will be given time to rest between tasks as appropriate to prevent fatigue.

After data collection, it will take an additional 15 minutes to remove the sensors from your body.

You will be asked to come to the data collection session wearing a loose t-shirt and pair of shorts under your normal personal protective equipment.



Stage 2 – Participatory work task re-design

After the initial measurement, you may be invited to attend a meeting (on a different day) at which the data we collected will be shown to you as a video.

Other people, may also be at this meeting, including (for example other workers who perform similar work tasks as you, supervisors and health and safety representatives or specialists).

In this meeting, we may seek your input into the identification and development of changes that could be made to the way your work tasks are performed that could reduce the risk of MSD.

This meeting will take approximately one hour.

Stage 3 – Measurement of re-designed work tasks

You may also be invited to participate in a further assessment of the work task that was measured in Stage 1 and discussed in Stage 2.

This measurement would:

- involve the same data collection methods as described in Stage 1, and
- be performed in a way that reflects your suggestions from Stage 2 (if practicable).

This measurement would take another two hours of your time and is likely to take place on a different day to the initial measurement and the work task re-design meeting.

Data collected during the second measurement would be compared with your original information to determine whether the risk of MSD has been reduced in the re-designed work task.

6. What are the likely benefits of taking part?

The research will:

- identify risk factors in the conduct of selected manual rail construction tasks,
- help to redesign some of these manual rail construction tasks where possible, and
- show how MSD risks can be reduced in manual rail construction tasks.

If you participate in Stages 1 or 3, you will be provided with a short animation showing your movements while you performed your work task. This is not a medical assessment and the researchers will not provide advice to you about the data we have collected.

7. What are the risks or disadvantages of taking part?

The tasks you will be recorded performing will be tasks commonly performed in rail construction work. Therefore, you will not be exposed to any risk of injury that is greater than that presented in your normal work activities.

The tasks will be performed at your workplace, during the course of your normal work activities. The occupational health and safety (OHS) risks at this site will be managed under the principal contractors' OHS management system, in accordance with the OHS legislation.

The research team will have construction industry white card induction training and may have a Rail Industry Workers' card (if required by the specific site location).

8. What if I withdraw from this research project?

You may withdraw from the research at any time. If you decide to withdraw from the project, please notify a member of the research team.

If you wish to withdraw from the research, this will not affect your relationship with RMIT University or your employer.

If you withdraw from the research, you may ask for any unprocessed data collected from you to be withdrawn and destroyed.

9. What happens when the research project ends?

A research report will be written that will contain aggregated findings. You will not be named or otherwise identified in this report.

A set of video-based training materials will be developed using the research data.

We seek your consent to use some of your data in these video materials. However, we will not use your data unless you have provided written informed consent to do so in the form attached to this document.

10. What will happen to the information we collect about you?

- Your results will be kept in a locked filing cabinet at RMIT University and only the investigators will have access to this information. If you wish to gain access to your data, contact a research team member and it will be provided to you.
- Data collected from you will remain confidential and will not be shared with other participants in the study. No material that could identify you will be used in any written reports of this project, including those provided to your employer and representatives of the Major Transport Infrastructure Program.
- There may be a delay of several months between data collection and the publication of the research results. At the completion of the research project a summary of the results will be available to interested participants with all data de-identified.
- Your individual results will also be available to you on request.
- We expect to publish a paper in a scientific peer-reviewed journal at some stage in the future. No details that would allow others to identify you (or your employer) will be included in this paper. We will only report aggregated data.
- Depending on the stage of the research you chose to participate in, video and photographic images of you completing the tests will be taken. These images may be used for conference presentations and journal publications if you provide written consent for us to do this in the form attached to this document.
- Not all participants will be photographed or videoed, and not all photos or video taken will be used.
- If you agree to participate in the study, you do not have to agree to be photographed or videoed. Any future publication of any images taken will not allow identification of you unless you have granted permission for this to occur on the informed consent form provided.

11. Who is organising and funding the research?

This research is being conducted by RMIT University, on behalf of the Department of Economic Development, Jobs, Transport and Resources (DEDJTR) and WorkSafe Victoria.

12. Who has reviewed the research project?

All research in Australia involving humans is reviewed by an independent group of people called a Human Research Ethics Committee (HREC). This research project has been approved by the RMIT University HREC.

This project will be carried out according to the *National Statement on Ethical Conduct in Human Research* (2007).

This statement has been developed to protect the interests of people who agree to participate in human research studies.

13. Who should you contact if you have any questions or concerns?

If you have any questions or concerns or would like more information about the research, you can contact any of the researchers listed below.

Research contact personnel

Name	Distinguished Professor Helen Lingard
Position	Chief investigator / Senior supervisor
Telephone	99253449
Email	helen.lingard@rmit.edu.au

Name	Professor Stephen Bird
Position	Chief investigator / Senior supervisor
Telephone	99257257
Email	Stephen.bird@rmit.edu.au

14. Who should you contact if you have a complaint?

Should you have any complaints about this research project, which you do not wish to discuss with the researchers listed in this document, then you may contact:

Reviewing HREC name	RMIT University
HREC Secretary	Peter Burke
Telephone	03 9925 2251
Email	human.ethics@rmit.edu.au
Mailing address	Research Ethics Co-ordinator Research Integrity Governance and Systems RMIT University GPO Box 2476 MELBOURNE VIC 3001

Title	Major Transport Infrastructure Program Musculoskeletal Injury Reduction Research Project
Chief Investigator/Senior Supervisor	Distinguished Professor Helen Lingard Centre for Construction Work Health and Safety Research, RMIT University helen.lingard@rmit.edu.au, 99253449 Professor Stephen Bird School of Health and Biomedical Sciences, RMIT University stephen.bird@rmit.edu.au, 992557257 Associate Professor Noel Lythgo School of Health and Biomedical Sciences, RMIT University noel.lythgo@rmit.edu.au, 99256518 Associate Professor Olga Troynikov Centre for Advanced Textiles and Materials Science, RMIT University olga.troynikov@rmit.edu.au, 99259108
Associate Investigator(s)/Associate Supervisor(s)	Dr Isaac Selva Raj School of Health and Biomedical Sciences, RMIT University isaacselva.raj@rmit.edu.au, 99257037 Mr Alf Camilleri Centre for Construction Work Health and Safety Research, RMIT University alf.camilleri @rmit.edu.au, 99255028 Mr Chris Fitzgerald Consultant chris.fitzgerald@rimservices.com.au Dr Martin Dubaj Consultant

Principal Research Student(s) | Mr Dong Gyoon Na
School of Health and Biomedical Sciences,
RMIT University
s3551105@student.rmit.edu.au

Acknowledgement by participant

I have read and understood the Participant Information Sheet.

I understand the purposes, procedures and risks of the research described in the project.

I have had an opportunity to ask questions and I am satisfied with the answers I have received.

I freely agree to participate in this research project as described and understand that I am free to withdraw at any time during the project without affecting my relationship with RMIT.

I do / do not (delete as applicable) agree to any images/videos of me taken during this project being used in future publications and training materials.

I understand that I will be given a signed copy of this document to keep.

Name of Participant (please print)	______________________________
Signature ____________________	Date ____________________

Declaration by Researcher†

I have given a verbal explanation of the research project, its procedures and risks and I believe that the participant has understood that explanation.

Name of Researcher† (please print)	______________________________
Signature ____________________	Date ____________________

† An appropriately qualified member of the research team must provide the explanation of, and information concerning, the research project.

Note: All parties signing the consent section must date their own signature.