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RESEARCH ARTICLE (PEER-REVIEWED)

The impact of tool selection on back and wrist injury risk in tying steel reinforcement bars: a single case experiment

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Abstract

The paper explores the risk of work-related musculoskeletal injury in tying steel reinforcement bars. Three tools are compared to determine the extent to which ergonomically designed tools can reduce the risk of injury to the back and wrist in steel-tying. A whole body system of wearable sensors was used to measure biomechanical risk in tying. Three tools were assessed to determine their impact on the risk of work-related musculoskeletal injury when used at different heights. These were: a conventional pincer- cutter tool; a power-driven tying tool, and a long handled stapler tool.

No tool was found to work best in all situations. The long handled stapler tool significantly reduced trunk inclination when used from ground to shoulder height but produced higher trunk extension (backward bending) when used above shoulder height. The power tying tool did not reduce the need to bend when working at lower work heights. The power tying tool

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produced significantly lower peak wrist flexion values compared to the conventional pincer-cutter tool at all work heights except overhead. The power tying tool involved significantly lower levels of wrist rotation than the conventional pincer-cutter tool at all work heights above knee level.

Many assessments of ergonomic risk factors in construction rely on observational methods. The use of small, lightweight wearable sensors permits the objective measurement of biomechanical risk factors for work-related musculoskeletal injury, as well as providing objective performance data that can be used in the design and selection of task-specific tools. Our analysis of work by height also provides insight into the way in which the risk factors and reduction opportunities afforded by different tools vary depending on the height at which work is performed.

Keywords

Steel reinforcement tying, musculoskeletal injury, construction, wrist, back, wearable sensors, hand tools.

Introduction

WORK-RELATED MUSCULOSKELETAL DISORDERS (MSDS)

Work-related musculoskeletal disorders (MSDs) generally occur when a worker's physical workload exceeds the physical capacity of the human body. MSDs can arise as a result of a single event or be due to repeated exposures. Risk factors associated with work-related MSDs include repetition, force required, awkward posture, vibration, and contact stress (Wang, Dai and Ning, 2015). Contact stress is a term defined by the US Occupational Safety and Health Administration as "pressing the body or part of the body (such as the hand) against hard or sharp edges (OSHA, 2008, p.6). Musculoskeletal disorders (MSDs) are the most common work-related conditions in Australia and 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* targets a reduction in the incidence rate of claims for work-related MSDs (resulting in one or more weeks off work) of at least 30 per cent to be achieved by 2022. The *Strategy* also identifies construction as a priority industry for this reduction (Safe Work Australia, 2012).

Construction is a high-risk industry for work-related MSDs (Hartmann and Fleischer, 2005; Latza, et al., 2000). Further, construction workers suffering MSDs are less likely to return to work and more likely to retire with a disability than workers in other occupations (Welch, et al., 2009; Arndt, et al., 2005). MSDs are also costly to employing organisations, resulting in sickness absence, turnover costs, impacts on morale, lost productivity and diminished quality of work (Inyang, et al., 2012).

The prevalence of work-related MSDs in construction has been attributed to the dynamic, often non-routine, nature of work (Buchholz, et al., 1996; Welch, 2009; Hannertz, et al., 2005). The changing environmental conditions inherent in construction work also impact the frequency and content of work tasks performed by construction workers, making it difficult to reliably measure exposure to MSD risk (Paquet, et al., 2005). Despite these challenges, understanding MSD risk factors associated with specific construction tasks is important in order to encourage the development of effective primary prevention measures (Latza, et al., 2000). Further, the implementation of ergonomic interventions to match tasks, tools, and the work environment to the needs of workers is increasing in importance in light of the ageing construction workforce (Choi, 2009).

AIM

In this paper we examine risk factors for work-related MSDs in the work of tying steel reinforcement bars. In particular, we aim to identify opportunities for risk reduction through the use of ergonomically designed tools. Research objectives are to:

(a) use objective measurement methods to analyse body movements to identify specific risk factors associated with work-related MSDs in the task of tying steel reinforcement bars,
(b) compare the effect of three steel tying tools on a worker's body movements so as to investigate whether tool design can reduce the risk of work-related MSDs, and
(c) to compare the performance of three tools when used at different work heights (defined in relation to a worker's body).

RISK FACTORS FOR MSDS IN TYING STEEL REINFORCEMENT BARS

Tying steel reinforcement bars involves positioning steel rods (sometimes referred to as rebar) and fixing them together using wire ties in preparation for concreting work. This task involves heavy manual materials handling, work in awkward postures and the expenditure of high levels of energy compared to other construction tasks (Faber, et al., 2012; van der Molen, 2012; Wong, et al., 2014). Steel tying has been identified as a high-risk activity for musculoskeletal injury, particularly to the back and upper extremities (Vi, 2003).

Back injuries in workers engaged in tying steel reinforcement bars (hereafter referred to as steel fixers) are attributed to frequently working in stooped postures, manually lifting heavy materials, often from toe to hip level, and working on poor walking surfaces (Niskanen, 1985). More recent observational research confirms that steel fixers are more likely to lift loads exceeding 50 lbs (22.7kg) than other construction trades (Tak, et al., 2011). Buchholz, et al. (2003) observed ergonomic hazards experienced by 17 steel fixers performing five job tasks in a US 'cut and cover' tunnel construction project. They report the steel fixers spent 40% of their work time in non-neutral trunk postures. This has been confirmed in laboratory-based simulations studies. For example, Umer, et al. (2017) used wearable sensors to directly measure biomechanical risk factors associated with a simulated steel fixing task, finding lumbar flexion angles substantially exceed recommended limits (Umer, et al., 2017). However, field-based studies also show that ergonomic exposures vary significantly depending upon the specific work context. Buchholz, et al. (2003) found significant differences between risk exposures when erecting steel reinforcement at ground-level, wall height and for a ventilation duct. Thus, steel tying is a heterogeneous activity in which trunk posture varies according to the height at which work is performed.

Research also reveals steel tying presents a high risk of work-related MSDs affecting the hand, wrist or fingers, with up to 48 per cent of a cohort of steel fixers reporting MSDs symptoms in these parts of the body (Forde, Punnett and Wegman, 2005). In terms of doctor-diagnosed MSDs, steel fixers were most likely to be diagnosed with tendonitis, carpal tunnel syndrome and ruptured disks in the back (Forde, Punnett and Wegman, 2005).

STEEL TYING TOOLS

The prevalence of MSDs among steel fixers highlights the need for effective ergonomic interventions. One area in which the risks of MSDs could potentially be reduced is through the design and use of improved hand-held tools to tie the steel reinforcement bars (Mital and Kilbom, 1992).

The conventional method of tying steel reinforcement bars involves the operator pulling out the end of a reel of metal wire from a belt located on their left hip, bending the wire around the rod sections before twisting the wire together and cutting off the end, using a hand-held pincer-cutter tool. This tying/cutting cycle takes approximately two seconds and is a repetitive action. It has been estimated that steel fixers may make 400–600 ties using this method per workday (Dababneh and Waters, 2000). Li (2002) observes that the action of wire twisting involves repetition of awkward hand/wrist postures, including flexion/extension, ulnar deviation of the wrist, as well as supination and pronation of the arm. This observation is consistent with the types of musculoskeletal injury reported in the literature to be common among steel fixers, including injuries to the hand, forearm and wrist (Vi, 2003).

Two alternative commercially available steel tying tools were assessed in the current study, i.e., a power-driven tying tool and a long-handled stapler tool. These are described below.

The power-driven tying tool (hereafter referred to as the power tying tool) looks and operates much like a hand-held power drill. The handle and power button are like those on a drill, while the upper body of the tool houses a small reel of tying wire that 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. The upper head section has a curled and downward facing end and the smaller lower section sits directly below. The jaws of the tool are placed around two intersecting sections of steel rod (rebar). When the trigger 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 the head creates a twisting action to generate the fixing tension required to hold the metal rods 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.

The long-handled stapler tool was manually operated. The stapler tool 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 intersecting steel bars to be fixed. When the head is in place, the operator pushes down on the tool. When the tool cartridge stops, the two ends of the staple are crossed over and joined together.

EVIDENCE TO SUPPORT THE USE OF ALTERNATIVE TYING TOOLS

Dadabneh and Waters (2000) report that well designed power tying tools can enable workers to tie steel rods while keeping their wrist straight. They also observe that the use of a long-handled rebar stapling tool can reduce the need for a worker to bend or twist, particularly when tying steel rods at ground level. However, these conclusions were based upon information provided in manufacturers' materials and video data, rather than objective measurement of a worker's movement.

Albers and Hudock (2007) also compared the ergonomic aspects of tying steel rods using a conventional pincer-cutter tool and a power tying tool, with and without an extension handle. They used a combination of direct measurement (to determine wrist motion) and observation (to assess trunk position). Albers and Hudock (2007) confirmed that manual tying of steel rods at ground level involves sustained deep bending of the trunk combined with rapid and repetitive hand and wrist movements. Further, their direct measurement revealed that hand-wrist movements measured during conventional tying (i.e., with pincer-cutters) exceeded levels associated with high cumulative trauma disorder risk in the flexion/extension and ulnar/radial planes. Using a power tying tool significantly reduced hand-wrist and forearm movements and provided one hand free with which a worker could support the weight of their trunk while tying steel rods at ground level. The power tying tool did not significantly reduce the amount of time workers spent in positions of extreme trunk flexion (defined as being equal to or greater than 90 degrees). However, when the power tying tool was fitted with a specially designed extension handle, the workers were observed to use neutral trunk position (less than 15 degrees flexion) for 83 per cent of the time and moderate forward flexion (16-30 degrees) for 15 per cent of the time (Albers and Hudock, 2007).

Vi (2003) evaluated the impact of using a long-handled power tying tool among nine apprentice steel fixers, measuring the apprentices' wrist and arm angles using electrogoniometers, and low back muscle activation using electromyography. Vi (2003) reports that the use of the power tool significantly reduced wrist acceleration in all planes of movement measured (flexion/extension, radial/ulnar and pronation/supination) compared to manual steel tying techniques. The long-handled power tool also decreased peak loading in the lower back, as well as the cumulative loading on the back when compared to conventional steel tying methods. However, this study did not include direct measurement of trunk inclination.

Alternative tools for tying steel reinforcement are not yet in widespread use in the Australian construction industry. Thus, the current research involved a rigorous assessment of the impact of a three commercially available steel tying tools on the risk of work-related MSDs to steel fixers.

Research methods

STUDY DESIGN

A single case controlled experimental design was utilised. Such designs are ideally suited to evaluating the effects of interventions in work settings because they do not require large samples, nor do they rely on the random assignment of participants into treatment and control groups (which is not usually possible in a work setting) (Kazdin, 2011). Unlike an uncontrolled case study, in which outcomes are observed and recorded as they occur, single case experiments involve the use of replicable, reliable and valid measurements that are repeated continuously throughout the experiment. Conditions and the timing of interventions are carefully controlled and measurements of variables of interest are compared between phases of the experiment (e.g. baseline conditions and one or more phases of an intervention). Repeated testing provides multiple assessment points, which help to rule out alternative explanations of an observed effect in pre-and post-test experimental designs in which a single measurement point is utilised (Kazdin, 2011).

Our study commenced with the baseline assessment of the steel fixing work task using a conventional pincer-cutter tool. The participant performed a minimum of 12 consecutive rebar tying repetitions at each of six work heights using the pincer-cutter tool. These work heights represent the height of the tool relative to the participant. They do not represent the participant's hand height. The work 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. 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. Once the measurements had been taken using the conventional pincer-cutter tool for the six work heights, the participant performed the same task using the power tying tool, and then the long handled stapler tool. In total this produced 18 distinct work conditions (3 tools x 6 work heights). Continuous measurements (taken at high frequency) were compared between each tool and work height within a single case (the participant) to determine whether the alternative steel tying tools produced any significant benefits in reducing risky postures and movements in the trunk and wrist.

DATA COLLECTION

Data was collected at a participating construction site engaged in the delivery of a major transport infrastructure program of work in Melbourne, Australia. The research team completed required training and induction sessions before visiting the construction site. The research was approved by the Human Research Ethics Committee of the researchers' institution. Data collection was conducted while the participant was tying steel inside a box-girder steel frame section being constructed in an area designated for the manufacture of pre-cast concrete components at the construction site. This allowed the measurement of body movement when tying steel at different work heights. Data was collected in a single assessment session. However, the day and time of the assessment was not controlled by the research team but was determined by the principal contractor at the construction site.

Prior to recruiting participants, a plain language statement in English was read to workers and any questions were answered before they agreed to participate. Participation was voluntary and participants were advised that they could withdraw at any point during the research process.

Table 1 Placement and fixing of sensors

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

Figure 1 Positioning of the sensors

Initially two male steel fixers indicated that they were willing to participate in the study. Preliminary testing revealed that one participant quickly adapted to the power tying tool and the long handled stapler tool, demonstrating a low error rate in comparison to the second participant. Due to time constraints and limitations regarding site access, the single case experiment was conducted with the first participant only. At the time of the data collection the right-handed male participant was 27 years of age, 173 cm tall and had a body mass of 73 kg.

Data was collected using a portable, whole body system of lightweight wearable sensors (The Xsens three-dimensional motion capture system (MVN BIOMECH, Xsens Pty Ltd, Netherlands). Increasingly, researchers advocate the use of objective direct measurement of whole-body movement to understand MSD risk factors (Yan, et al., 2017; Brandt, et al., 2015). Lightweight wearable sensors are capable of providing large quantities of highly accurate data on a range of MSD risk exposure variables (Inyang, et al., 2012). To date, whole body measurement systems have been used in a laboratory context (Umer, et al. (2017), however, it is less common for such systems to be used in construction work settings.

Seventeen light-weight inertial sensors (length: 36 mm; width: 24.5 mm; height: 10 mm; mass: 10g) were attached to the participant. The positioning of the sensors is described in Table 1 and shown in Figure 1. The Xsens motion capture system sampled at 240 Hz and recorded the participant's body posture and movement patterns continuously while performing the steel tying task using the three tools at each work height.

The following data collection protocol was followed.

Step 1. The participant's age, height, mass and body dimensions were recorded.

Step 2. The attachment of the sensors onto the participant occurred in two stages to inimise the need for the participant to completely undress down to their underwear. Firstly, the Xsens sensors were fitted to the participant's trunk and upper body. These sensors were then fitted to their lower limbs. In total, seventeen Xsens sensors were attached. Nine of the sensors were attached to known body landmarks by using non-allergenic double-sided tape. Eight of the sensors were attached by using Velcro straps that went around a limb segment. The sensors were then connected by cables to a light-weight transmitter and battery pack worn on the participant's waist.

Step 3. The participant put on the remainder of their personal protective equipment (PPE) required for the work task. This included a hard hat, protective glasses, gloves, orange coloured high visibility vest and steel-capped boots.

Step 4. The participant's height, mass and body dimension data were then entered into the Xsens software. The participant then stood in an anatomical position for about 1 minute whilst their posture was recorded by the Xsens system. This is required for the Xsens system to generate a full body model of the participant.

Step 5. The Xsens and two high speed CASIO cameras (EXLIM, CASIO) were then synchronised by having the participant laterally raise (shoulder level) and lower the right arm (to the side of the trunk) three times. These actions were simultaneously recorded by the systems.

Step 6. Upon completion of the participant and instrument setup, and after a 10 to 20 minute familiarisation period (walking about so as to become comfortable with the sensors placed on the body), the participant was asked to perform the designated work task. This involved completing steel fixing for about 30 to 60 minutes.

Step 7. Upon completion of the work task, the sensors were removed.

Step 8. In total, the capture session lasted for approximately two to three hours (from preparation to removal of the sensors).

DATA ANALYSIS

Before analysis, data was reviewed to check for magnetic interference or possible sensor movement. Markers were inserted into each data file along the timeline of the captured work task to define the start and end of each task cycle for each of the different work heights.

The participant performed a minimum of 12 repetitions of the tying task in a continuous sequence at each work height. Periods of non-task related activity were also marked for exclusion from the analysis. These periods related to the operator preparing to move between work height levels

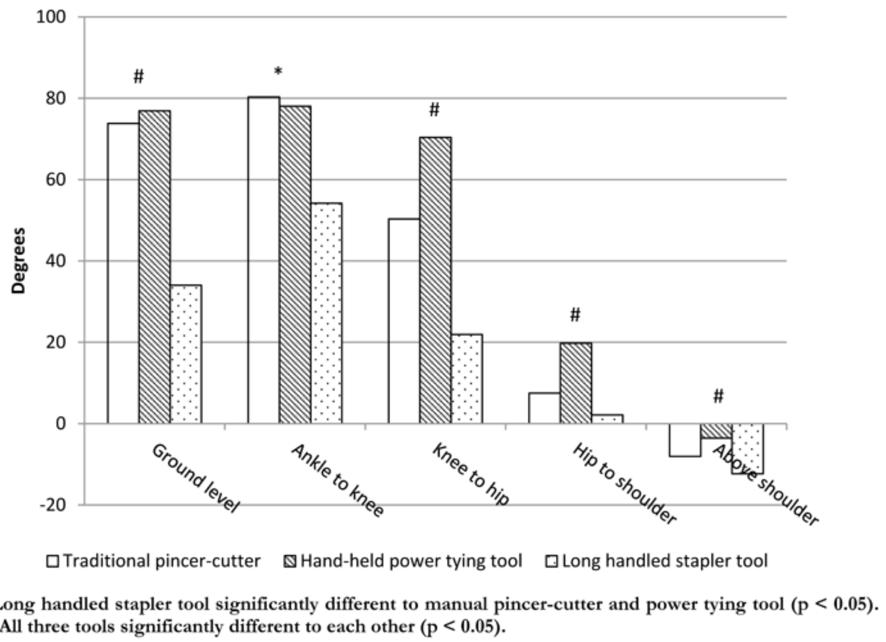

Figure 2 Mean trunk inclination by tool and work height

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Table 2 Comparison of mean trunk inclination measurements by tool for each work height

Variable	Work height	Traditional pincer-cutter	Hand-held power tying tool	Long handled stapler tool	F-ratio	*p*
Mean trunk inclination	Ground level	73.8	76.9	34.0	1386.07	< 0.001
	Ankle to knee	80.3	78.0	54.2	155.96	< 0.001
	Knee to hip	50.3	70.4	21.9	345.89	< 0.001
	Hip to shoulder	7.5	19.8	2.1	37.41	< 0.001
	Above shoulder	-8.1	-3.6	-12.3	31.84	< 0.001

NB: Positive values indicate forward flexion. Negative values indicate backward flexion

Each marked file was exported and loaded into a MATLAB data processing software program developed by the research team. Data processed in MATLAB was then exported into Microsoft Excel for further analysis. Statistical analyses of the data were performed using the IBM SPSS statistical software package (Version 23, SPSS Inc., Chicago, Illinois).

Descriptive statistical analyses including means and standard deviation were calculated for the relevant movement variables. One-way repeated measures ANOVAs were used. These tests assessed trunk and wrist motion across the three tools for each work height condition. ANOVAs are employed instead of multiple t-tests when there are three or more conditions under which a dependent variable is measures, e.g. tool being used or working height (Vincent, 2005). Significant differences ($p < 0.05$) were further examined in post-hoc testing using pairwise comparisons with Bonferroni adjustment.

Results

TRUNK INCLINATION

Trunk inclination data (trunk forward flexion and extension in the sagittal plane) was determined with reference to the positions of the T12 and S1 vertebrae. Figure 2 shows the mean trunk inclination values for each of the three tools by work height. Mean trunk inclination was highest when work was performed below hip level and frequently exceeded levels considered safe. For example, the ISO consensus standard ISO 11226:2000 describes acceptable trunk postures and maximum acceptable holding times for potentially harmful postures. In this standard, postures with trunk flexion greater than 60 degrees are not recommended. WorkSafe Victoria's *Manual Handling Code of Practice* identifies working with a trunk inclination greater than 20 degrees combined with undertaking a task for more than 2 hours over a whole shift, or continually for more than 30 minutes at a time, as a risk factor for work-related MSDs (WorkSafe Victoria, 2000).

Figure 3 Use of the conventional pincer-cutter (A), power tying tool (B) and long handled stapler tool (C) at ground level

The three tools produced significantly different values for mean trunk inclination at all work heights ($p < 0.05$). Work at ankle to knee height had the highest values for all three tools. Work above the shoulder had the lowest mean trunk inclination values for all three tools (Table 2).

Analysis of post hoc test data revealed mean trunk inclination scores differed significantly between the pincer-cutter tool and the long handled stapler tool for work undertaken at all work heights ($p < 0.05$). Differences in trunk inclination when using the three tools at ground level are shown in Figure 3.

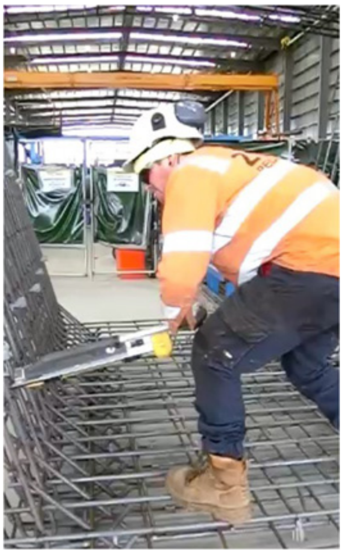


Figure 4 Use of the long handled stapler tool at ankle to knee level

When used between ground and shoulder heights, use of the long handled stapler tool produced lower mean trunk inclination scores. However, when used above shoulder height, the long handled stapler tool involved higher extension (backward bending) of the trunk. Mean trunk inclination scores were also significantly different between the power tying tool and the long handled stapler tool ($p < 0.05$). At all work heights the power tying tool produced higher mean trunk inclination scores than the stapler tool. At all work heights, except ankle to knee, the power tying tool also produced significantly higher mean trunk inclination than the manual pincer-cutter tool ($p < 0.05$).

When using the long handled stapler tool between ankle and knee level the participant needed to apply the tool at a 90-degree angle to the steel bars. This action involved the adoption of an awkward posture with an average maximum trunk inclination of 68.7 degrees (see Figure 4).

Wrist movement

The tools also produced different wrist movement results (Table 3).

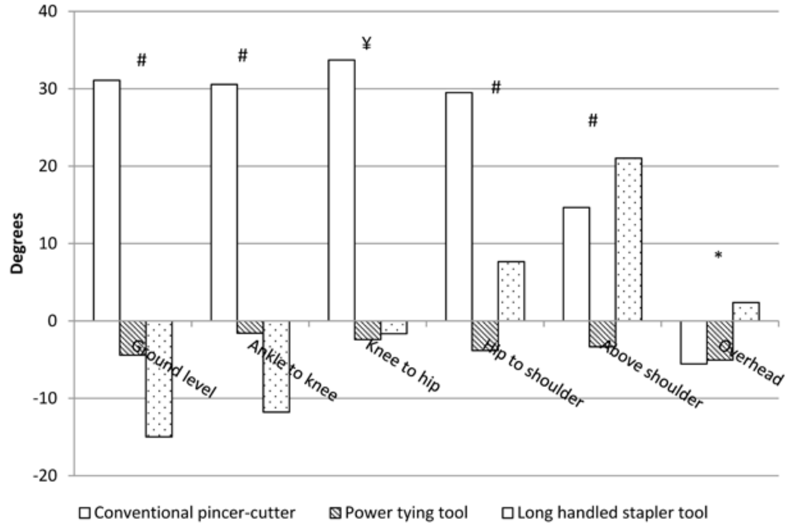
Table 3 Peak right wrist movement values by work height for each tool

Variable	Work height	Traditional pincer-cutter	Hand-held power tying tool	Long handled stapler tool	F-ratio	*p*
Peak wrist flexion/ extension*	Ground level	31.1	-4.4	-15.0	324.92	< 0.001
	Ankle to knee	30.6	-1.6	-11.8	750.87	< 0.001
	Knee to hip	33.7	-2.4	-1.7	734.70	< 0.001
	Hip to shoulder	29.5	-3.8	7.7	359.25	< 0.001
	Above shoulder	14.7	-3.3	21.0	184.69	< 0.001
	Overhead	-5.6	-5.1	2.7	11.60	< 0.001
Peak wrist rotation**	Ground level	0.2	-6.8	-12.5	42.86	< 0.001
	Ankle to knee	6.2	5.1	-33.5	345.61	< 0.001
	Knee to hip	8.9	1.7	-22.7	265.03	< 0.001
	Hip to shoulder	21.2	0.1	-11.4	153.10	< 0.001
	Above shoulder	30.9	-2.5	-16.1	239.77	< 0.001
	Overhead	36.7	3.3	-5.2	503.79	< 0.001

*Positive values indicate wrist flexion. Negative values indicate wrist extension.

** Positive values indicate wrist pronation. Negative values indicate wrist supination.

Figure 5 shows peak wrist flexion/extension values by tool and work height. Use of the conventional pincer-cutter tool involved potentially harmful levels of wrist flexion when working at heights up to shoulder level. The peak wrist flexion values across these work heights ranged from 29.5 to 33.7 degrees. WorkSafe Victoria's *Manual Handling Code of Practice* recommends that where the fingers are bent or applying higher forces (for example, gripping), flexion in excess of 15 degrees presents an elevated risk of injury when undertaking a task for more than 2 hours over a whole shift, or continually for more than 30 minutes at a time (WorkSafe Victoria, 2000). In comparison, the use of the power tying tool involved close to neutral wrist extension/flexion irrespective of the height of work (See Figure 5).



NB: Positive values indicate wrist flexion. Negative values indicate wrist extension. * Long handled stapler tool significantly different to the pincer/cutter and power tool. # All three tools significantly different to each other. ¥ Pincer-cutter tool significantly different to the long handled stapler and power tying tools.

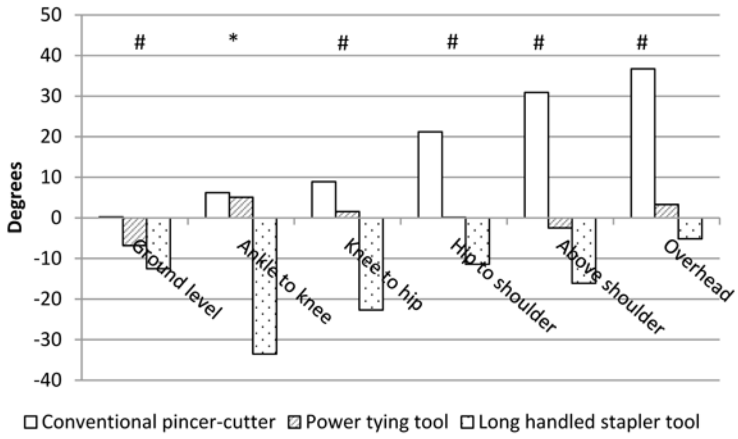
Figure 5 Peak right wrist flexion/extension by tool and work height

Analysis of post hoc test data revealed that peak flexion/extension scores for the right wrist differed significantly between the pincer-cutter tool and both of the alternative tools at all work heights except when working directly overhead ($p < 0.05$). When working directly overhead there was no significant difference between the wrist extension values for the pincer-cutter and the power tying tool. Peak wrist flexion/extension also differed significantly ($p < 0.05$) between the long handled stapler tool and the other tools at all work heights, except when working between the knee and the hip when there was no significant difference between the stapler tool and the power tying tool.

Figure 6 shows average peak rotation (pronation or supination) values for the right wrist by power tool and work height. Use of the power tying tool involved statistically significantly less wrist rotation than the other tools ($p< 0.05$). The pincer-cutter tool exhibited the greatest pronation whereas the long handled stapler tool exhibited the greatest supination of the right wrist. When using the long handled stapler tool, the participant's wrist remained in a supinated posture. The conventional pincer-cutter tool demonstrated the largest range of right wrist rotation. 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 work heights with the level of supination increasing with each increase in level.

Analysis of post hoc test data revealed the power tying tool involved significantly lower levels of wrist rotation than the conventional pincer cutter tool at all work heights above knee level ($p < 0.05$). When being used at ground level, the power tying tool involved significantly greater right wrist rotation than the pincer cutter tool ($p < 0.05$). The difference in right wrist rotation between the pincer-cutter tool and the power tying tool was not significant when work was performed between the ankle and the knee. The power tying tool involved significantly lower levels of right wrist rotation than the long handled stapler tool at all work heights ($p < 0.05$).

The long handled stapler tool involved significantly less right wrist rotation than the conventional pincer-cutter tool when used at work heights below the hip ($p < 0.05$). However, when working above hip level, the right wrist rotation when using the pincer-cutter tool was significantly greater than when using the long handled stapler tool ($p < 0.05$).



NB: Positive values indicate wrist pronation. Negative values indicate wrist supination. *Long handled stapler tool significantly different to pincer/cutter and powered tying tools. #All three tools significantly different to each other.

Figure 6 Peak right wrist rotation by tool and work height

Discussion

RISK FACTORS AND TOOL IMPACTS

The research builds on previous analyses of risk factors in two respects. First, we used a full body system of wearable sensors to capture objective direct measurements of the body movement of the workers in a workplace setting. Second, we conducted a controlled analysis of steel tying work being performed at different work heights using three different tools.

Previous research has identified the lower back and hand/wrist as areas most likely to be affected by work-related MSDs in tying steel reinforcement bars (Choi, 2010). Our results indicate that steel tying is a heterogeneous activity with risk factors changing depending on the height at which work is performed (see, also, Buchholz, et al., 2003). When tying work is performed below hip level, workers are required bend forward to reach down, involving potentially harmful repetitive or sustained trunk inclination over long periods of time.

The results show that the use of a long handled stapler tool significantly reduces the amount of trunk inclination when working below the hip level. However, it is noteworthy that the mean trunk inclination values for the long handled stapler tool still exceeded 20 degrees, for work at ground level, from ankle to knee height and from knee to hip height. As such, they would still be classified as a risk factor for work-related MSDs if maintained for more than 2 hours over a whole shift, or continually for more than 30 minutes at a time (WorkSafe Victoria, 2000). Also, when used from ankle to knee height, the positioning of the long handled stapler tool required greater trunk inclination than when used at ground level as the tool needed to be applied at approximately 90 degrees to the reinforcement bars to be fixed.

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It should also be noted that tying steel above shoulder height required the participant to bend backwards, particularly when using the long handled stapler tool. The difference between the backward bending involved in the three tools was also significant when working above shoulder height.

Compared to the conventional pincer cutter tool, the power tying tool required significantly greater trunk inclination when used at all work heights except between the ankle and the knee. Thus, the power tying tool appears to increase work-related MSD risk to the back.

In contrast, the power tying tool was associated with significantly reduced movement of the right wrist. The power tying tool involved low levels of wrist flexion/extension and rotation. In comparison, the conventional pincer-cutter tool involved significantly greater levels of wrist movement than the power tying tool at all work heights, except when work was being performed directly overhead.

The conventional pincer-cutter tool also involved steadily increasing wrist pronation as the work height increased from ground level to work overhead.

IMPLICATIONS FOR TOOL SELECTION AND DESIGN

Researchers and ergonomists have recommended the development of trade-specific tools to reduce the risk of work-related MSDs in the construction industry (Rinder, et al., 2008; Li, 2002). However, our analysis suggests that there may not be a 'one size fits all' solution to tool selection. The two alternative tools considered in our analysis improved different risk factors for work-related MSDs, but only under certain conditions. The long handled stapler tool significantly reduced trunk inclination, while the power tying tool reduced potentially harmful wrist movements. The long handled stapler tool also performed differently, in terms of its impact on trunk inclination and wrist movement, depending on the height of work that was being performed.

The results suggest that the benefits of using a long handled tool are limited to tying steel at ground level, and that the potential to use a power tying mechanism in a long handled tool could reduce the risks of back and wrist injury in some circumstances. Although they are commercially available, the types of tool that we assessed are not widely used in the Australian construction industry. Glimskär and Lundberg (2013) observe that, even when developed and offered to market, the take-up and use of ergonomically designed construction tools is low. Researchers observe that the construction industry is not conducive to adopting new ideas or ways of working (Kramer, et al., 2009). Van der Molen, et al. (2005) attribute this to the way that work is organised, in particular the reliance on temporary employment and multi-level contracting. Kramer, et al. (2010) similarly argue that the adoption of new ways of working that reduce work-related MSD risk in construction will not be straightforward and will be influenced by many factors. The adoption of innovation can fail at many different levels, including at the industry level, the organisation level, the project level and at the level of the innovation itself (Kramer, et al., 2010).

Researchers have noted that the primary reason that decision-makers adopt new tools or work methods is unlikely to lie in their potential to reduce the risk of injury (Van der Molen, Sluiter and Frings-Dresen, 2005). As such, the potential for ergonomically designed tools to positively impact production efficiency and work quality should also be examined (Boatman, et al., 2015; Weinstein, et al., 2007). Future research should focus more attention on understanding how, why and by whom ergonomic measures are implemented in practice in the construction context.

Our results also suggest that, although ergonomic tools can make a positive difference in reducing the risk of work-related MSDs in steel fixing, further improvements in design and performance should be pursued.

INTEGRATION INTO CONSTRUCTION DESIGN AND PLANNING

Boatman, et al. (2015) suggest that the principles of ergonomics should be integrated into all phases of construction (e.g. bidding, engineering, pre-planning, purchasing, materials handling, job site management, training of supervisors and workers). Consideration of work height, methods of steel fixing and suitability of tools should be considered in the design and planning of work.

In some instances, the need to work at ground level or overhead may be eliminated through careful work process design. Opportunities to improve workplace ergonomics and reduce biomechanical risk factors may be identified through the use of three-dimensional virtual visualisation of the construction work environment (Golabchi, et al., 2015). Li, et al. (2017) have developed and tested three-dimensional skeletal modelling tools that imitate body movement in construction process visualisation activities. Such approaches, if further developed and validated, could enable evidence-informed ergonomic assessments and risk reduction decisions to be made at the construction design and planning stages.

Conclusions

Field-based biomechanical measurement of risk factors for work-related MSDs in tying steel reinforcement bars revealed that work at different heights involves different levels of risk to the wrist and back. The use of tools specifically designed for the work task can significantly reduce risk factors, including trunk inclination, wrist flexion/extension and rotation. However, the tools perform differently at different work heights. No tool was perfect for all situations. A long handled stapler tool significantly reduced trunk inclination when working below hip height, while a power tying tool reduced potentially harmful wrist movement but increased trunk inclination compared to a conventional pincer-cutter tool.

The results provide new evidence relating to the impact of these tools when used at different heights relative to conventional methods of tying steel. The data also identifies opportunities for tool improvement and further design. For example, the attachment of a long handle on a power tying tool could reduce potentially harmful trunk as well as wrist movement.

The availability of light weight whole body systems of wearable sensors enables the measurement of biomechanical risk factors in the construction context. This has the potential to provide access to large sets of objective and reliable data upon which to base the assessment and evaluation of ergonomically designed tools. It also overcomes problems associated with replicating construction site conditions in a laboratory setting, which is inherently challenging.

LIMITATIONS AND FUTURE RESEARCH

Our study was limited in a number of respects. Firstly, due to site access constraints, we were only able to collect data from a single participant. While single case experimental designs compare data within cases (or participants) rather than between them and do not require large sample sizes, the study would have been strengthened by repetition with other participants. It is possible that results when tying steel at ground level or directly overhead are potentially affected by an individual worker's height. However, the other working heights are relative to worker's body, i.e. between the ankle and the knee, between the knee and the hip etc. These are not likely to be affected by height. Notwithstanding this, further data collection and analysis among workers of different body sizes and builds is recommended. If the findings were replicated, this would add to the body of evidence relating to the performance of the tools at different work heights. The timing of our data collection was also based on convenience sampling and reliant upon opportunities to observe steel tying in the context of the construction of a box girder bridge deck section. This allowed us to control the experimental conditions in relation to work height. However, it does not reflect the wide variety of different worksite conditions or steel tying scenarios. Thus, no claims to generalizability are made and we recommend that further research be conducted to determine if our findings are replicated in other settings. Similar considerations have been recognized by other researchers, for example, Karsh et al. (2001) who suggest that, although randomised controlled trials are considered the 'gold standard' for experimental research, most field intervention studies are unable to use such designs in a 'real world' workplace setting. Single case experiment designs are an acceptable and internally valid alternative to randomised controlled trials (Kazdin, 2011).

Neither did our research investigate the impact of the ergonomic tools on production speed or quality. In considering the likely barriers to, or factors facilitating the uptake of ergonomic tools, we recommend that future research examines these factors.

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