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Understanding and Prevention of Shearers' Injuries

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Contents

1. Introduction

Historically, wool harvesting in Australia has been economically vital and still remains an important rural industry. Australia is the leading producer of wool, supplying 25 per cent of all wool globally and 90 per cent of all fine apparel wool [1]. There are approximately 74 million sheep shorn in Australia each year by a workforce of 4000 shearers, producing 340 million kilograms of wool and earning more than $3.5 billion in export income [2].

Sheep shearing is the key part of the wool supply chain, representing woolgrowers' largest annual cost. Wool harvesting comprises more 60 per cent of woolgrowers' total costs and absorbs 30 per cent of growers' wool sales [3]. Wool harvesting is labour intensive and work teams are itinerant, shearing for only seven working days on average per sheep station per year [4].

Sheep shearing can be separated into two parts. The first is the catch-and-drag phase, where a shearer enters the catching pen and gains control of a sheep before dragging the sheep out of the pen to the shearing stand. The second is the shearing phase. The shearer removes the fleece of the sheep using a mechanical handpiece and then pushes the shorn sheep down a chute to return it to the yards.

The catch-and-drag phase represents a significant manual handling challenge. A skilled shearer can shear more than 200 sheep per day. With each sheep weighing approximately 70 kilograms, the typical cumulative manual handling for an expert shearer is more than 14 tonnes per day [5].

In the shearing phase, the shearer must manoeuvre the sheep into various positions necessary to remove wool from each part of the sheep. This requires the shearer to deftly apply high forces with their off-hand and both legs, often with their limbs fully extended. The shearer can then remove the wool from each part of the sheep by skilfully guiding the mechanical handpiece through the wool, peeling off the fleece. The cycle is completed when the shearer coaxes the often-reluctant sheep into the return chute, where it slides back down to the yards. The shearer must remove the fleece while fully bent over at the waist in an awkward and strained body position [6]. Despite this, an expert shearer can accomplish this in less than two minutes.

The task is physically demanding and skill-intensive, making it is hard to attract workers into shearing. Shearing is classified as extremely difficult physical labour, with energy costs at the level of elite sport [7]. The average daily energy usage of sheep shearing was calculated in [8] to be greater than 21 megajoules (MJ), which is more than 80 per cent of the average daily energy expenditure for competitors in the Tour de France [9]. It is no surprise that this limits the potential workforce and that the industry experiences challenges in attracting younger workers [10].

Once workers enter shearing they have short careers. It is estimated in [11] that on average shearers remain in the industry for as little as five years and a shearer remaining in the industry for 10 years or longer would have a 50–90 per cent chance of permanent injury [12]. Along with promoting workforce longevity, the Shearing Contractors Association of Australia suggests that improving safety outcomes among shearers is the key factor in attracting people to the occupation to overcome skills shortages [13].

Shearers suffer from extreme rates of injury characterised by an incidence rate six times the industrial average in Australia. Compared with the average Australian occupational injury, the average sheep shearing injury takes twice as long to rehabilitate and has a 70–140 per cent greater cost due to the additional lost productivity [5]. There is also some anecdotal evidence of injury under-reporting in shearing [14]. These injuries affect the wool industry's ability to attract and retain a skilled workforce and increase costs for woolgrowers.

Data for the types of injuries suffered in shearing are presented in [15] and indicate that most common injuries are at the hand and fingers (22 per cent), followed by the back (19.6 per cent), the wrist (14 per cent) and arm (13.4 per cent). Despite the majority of injuries occurring on the upper limbs, back injuries contribute approximately 50 per cent of the costs due to the extended time period usually required for rehabilitation [6]. The data also indicate that the most common time of injury for shearers is between the hours of 4pm and 6pm, late in the shearing day, indicating a high correlation to the level of fatigue.

Many ergonomic risk factors remain in modern sheep shearing, which in its 120-year history have eluded widespread task modifications. This is not from any lack of trying. It is prudent for any new endeavour to appreciate the lessons from the rich library of Australia's world-leading technological and scientific efforts to address these problems and why potential solutions have not been widely adopted.

In this unique industry, the productivity requirements and incentive structure severely limit the adoption of any safety improvements that reduce the speed (sheep shorn per day) of the task. Furthermore, the itinerant nature of sheep shearing – where shearers travel to many different properties in the space of a season and use the woolgrowers' infrastructure – needs to be considered in any solution on the division of investment responsibilities [14] (roughly speaking, the woolgrower provides the shearing quarters, shearing shed and shearing plant, while the shearers provide and maintain their own equipment).

2. Literature review

The consideration of factors that potentially affect the adoption of new technology led to a conclusion that the current process of manual shearing is a balanced compromise that is optimal for the industry. The focus of the investigation was therefore on the one factor that has been compromised in favour of many other factors: the wellbeing of the shearers as expressed in the high injury risk.

Epidemiological studies of workplace injury data identify high-intensity work, holding static postures, bending and twisting, lifting and repetition – all characteristics of the shearing task – as risk factors associated with lower back disorders [16]. More specifically, lower back disorders are especially prevalent among occupations that require prolonged or repetitive spinal flexion (stooping) [17] [18]. These types of studies investigate risk factors at the population level and can connect risk factors to rates of injury, but they do not account for individual variations among the population [19]. For example, many workers may be exposed to the exact same stresses but only some will sustain an injury.

To further reduce injuries and explain the individual variations in injury risk, the causal mechanisms for lower back injuries have been studied [16] [19]–[23]. It is presented in [19] and [20] that the majority of back injuries do not occur from a single large exposure, but from repeated and prolonged sub-acute exposures to stresses. It is further explained in [19] and [20] that the continued exposure reduces individuals' tolerances to these forces over time, and that different individuals will have varying injury tolerances and these tolerance levels could feasibly change at different rates.

It is very likely that these time-dependent changes in kinematics and neuromuscular control are important in the aetiology of many back injuries. There is strong evidence to suggest that kinematics and neuromuscular control are altered in people who are experiencing, or have previously experienced, back pain [24]–[26]. It is accepted that muscle fatigue increases injury risk and results in altered kinematics [27], and also leads to changes in neuromuscular control [28]. There is also evidence to suggest that prolonged and repetitive spinal flexion, typical in stooped work, also changes neuromuscular control [22] and movement [29] and can lead to lower back injury and pain [21], [30]. It is suggested in [31] that motor control issues could be the most significant determinant of who will develop back disorders in the future.

Therefore, the development of kinematic and neuromuscular control-based indicators of lower back injury is important to prevent injury and guide safety improvements. Indicators enable the evaluation of proposed interventions, equipment and task redesigns. Continuous monitoring with wearable sensors could help to provide relevant information for clinicians to assist with diagnoses of back problems and guide treatment when injuries do occur. With further study, continuous monitoring could provide real-time feedback to workers around injury risk or even provide early warnings of injury.

While it has been repeatedly established that changes in kinematics and neuromuscular control could reflect an increased risk of injury [32], laboratory-based investigations are unable to confirm a causal link without injury data. Therefore, there is a desperate need for longitudinal studies to confirm or rebut a link between kinematics and neuromuscular control to injury in real-world occupational tasks, incorporating population-level injury data. This requires long-term collection of large amounts of biometric data in real working conditions.

Improvements in sensor technology allow for the collection of biometric data outside the laboratory setting, but challenges remain for long-term data collection and analysis. It is not practical to collect data that requires expertise in placement and calibration of sensors for many subjects over very long periods of time. A simple wearable device that can be used by non-experts could alleviate this problem and allow for longitudinal studies. However, it is not clear what sensors are required and what should be measured in each case.

Many of the potential indicators established in the lab are challenging or not feasible to measure in the workplace [33]. It is also suggested in [34] that because the patterns of movement and neuromuscular control are different for different tasks, deficiencies will also be task specific. It follows from this that the development of indicators will also have a task-specific component.

Last, but not least, indicators of injury risk need to be determined without access to the data that could link the various measures to injury, which presents a significant challenge. To elaborate on this statement, sensor readings do not directly capture the moment an injury occurs, which would provide the opportunity to connect the injury to the biomechanical and physical measurements leading up to the moment. Instead, injuries may only be felt or realised by the shearer (if at all) during the time of rest, in the evening or the following days after the actual injury occurred.

In this project, it is important to establish, for the first time, a set of measurements of the biometric-based data that is realistic to the understanding of the injuries associated with the shearing task. This means a non-laboratory-based measurement, carried out under the realistic condition of the task: in the actual shearing shed and for the realistic duration of work (where measurements are long enough to capture fatigue and prolonged exposure characteristics to the shearing task).

Then a set of metrics needs to be established to understand which of the biometric variables are most effective in predicting risk of injuries. Identifying these variables will allow us to focus our measurement efforts on the most sensitive information variables, lowering the complexity of the sensor systems needed.

This identification will also allow us to propose two types of assistance to minimise shearer injuries: (1) a passive approach, where the measurements are used to inform (warn) shearers of their current risk of injury without active physical intervention; and (2) an active approach, where an assistive technology can be designed to physically support the shearers where most needed to minimise the risk of injuries. The well-informed and justified construction of the passive and active solutions is the scope of the next stage of the project.

3. Project objectives

The overall aim of the project is to establish a solution or solutions to shearers' injury problems. Specifically, in this 12-month project, the investigators sought to establish the first stage of the study by achieving the following objectives:

1. To establish a data collection platform that is realistic to the conditions. This means that the measurements are to be done in the shearing venues (i.e. portable). Furthermore, measurements will be collected in a realistic shearing session (measurements across a full workday to reflect a realistic workload and across multiple workdays). This is expected to capture the effect of prolonged exposure and fatigue, which have been identified as important in these studies.
2. To identify the primary contributors to the injury risk. This is done through finding the correlation of potential features in the data with the risk of injury. The most important variables that correlate to the high risk of injury are ranked. This forms the priority variables to be measured in the shearing process through wearable sensors.
3. Using the outcomes from Objective 2, develop a conceptual design for an active solution for fatigue management and injury prevention. Having identified the variables most effective as predictors to injury risk, the efficient sensor arrangement with the lowest complexity (the least number of sensors) that provides the most relevant information is selected as a practical sensor design. The findings will inform us what physical interventions are most useful to provide through assistive technologies (for example, robotic devices in supporting the shearer's task) to minimise the risk of injury.
4. To develop a prototype of a monitoring tool that can be used by shearers. A basic wearable system will be prototyped to measure the several variables identified in Objective 2.

4. Methodology

The following methodology was used in this study.

- Data collection: electromyography (muscle activation signals) measurements combined with a motion capture system were purchased and integrated into a portable system. This system could be used at the shearing sheds and had the capability to record for a full workday in terms of battery and data storage capacities. Four field measurements were carried out in three different states. Ten male sheep shearers aged between 21 and 61 years were recruited for the study. All shearers provided informed written consent and the experiment was approved by the University of Melbourne Human Ethics Advisory Group (Ethics ID 1853436). The field group represented a wide-ranging selection of shearers with varying levels of skill, from two weeks' experience to more than 40 years. One shearer was recorded over three consecutive days to give some insight into inter-day variations. The resulting motion data was visualised as shown in Figure 1.

Figure 1. The portable data collection system that captured the motion and muscle activities of the shearer.

Figure 2. The rest/work period for sheep shearing: four two-hour shearing sessions (runs) with two 30-minute breaks and a one-hour break for lunch. The catch-and-drag and the shear cycle, showing one 'sheep', is shown in the pull-out.

- Data processing: the large amount of data was processed. An algorithm to automatically segment the data into individual 'sheep' was constructed and reported in [35]. One sheep is defined as one cycle of the shearing process, which comprises the catch-and-drag segment and the shearing segment (of the same sheep). algorithm
- Features: many potential features (376) were constructed to be tested against the data for correlation to risk of injury. An assumption was made that the risk of injury increases with the progress of the shearing task over the duration of the day, with potential fluctuation due to various rest periods. A list of features was established that most correlated to the perceived increase in injury risk (with the highest suitability scores), where this correlation was also found to be consistent among the sampled population.
- Assessment of differences: in order to maximise the amount of information from each selected feature, features in this list were also assessed on their orthogonality, or difference from the rest of the features. Relevant features with high levels of orthogonality were selected as the top features.

5. Results

A significant amount of data was captured during this 12-month study. Each session consisted of the posture and muscle activity data of one shearer working through full working days over five successive days. The recorded data quickly confirmed the trend that we sought, assumed to correlate with the increase of injury throughout the progress of the work day.

A sample set of data for one shearer is shown in Figure 3, where a variable (normalised electromyography signal magnitude) is plotted over the course of the day. Each dot represents the average value of the variable over one sheep shorn. It shows the exponentially decreasing trend, recovering after each rest period (morning coffee, lunch, afternoon coffee). Recovery was shown to diminish each time due to the build-up of fatigue. Such a trend is aligned with the observation that most injuries occur towards the end of the day.

It provides us with an excellent tool to find the connection between the variables and the risk of injuries, which is made difficult by the observation that there was no means of identifying the exact occurrence of injury during the shearing exercise. The challenge is in correlating any specific set of measurement that immediately precedes the onset of an injury.

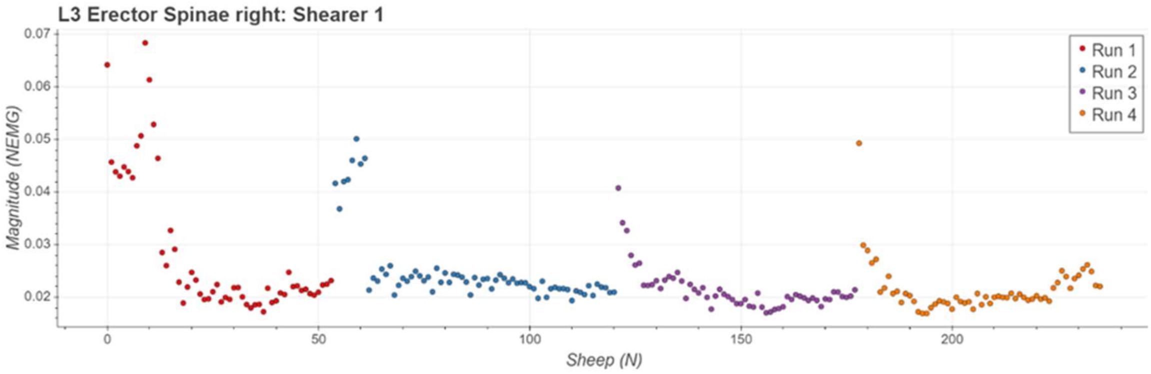

Figure 3. The magnitude of the normalised electromyography (EMG) signal of the lower back muscle of a shearer.*

* The figure shows the variable over the course of the day, over the 250 sheep shorn by the shearer that day. Each dot represents the average of the variable over the course of one sheep. The trend confirms the sensitivity of this variable to muscle fatigue, with a high value at the start of the day and an exponential drop over the number of sheep shorn. Recovery is shown after every rest period (after the 53rd sheep – morning tea, after the 122nd sheep – lunch break, etc.) but the amount of recovery also reduces with the progress of the day (with accumulated fatigue).

Processing the recorded data as described in the methodology allowed us to identify the variables most correlated to the trend of increasing risk of injury. Table 1 shows the top 10 features with the highest suitability scores. After accounting for feature orthogonality with the proposed feature selection algorithm, the top 10 selected features are shown in Table 2.

Table 1

Top 10 Features by suitability scores

Feature	Suitability ($\Delta = 0.15$)
L3 ES right envelope 10th percentile	0.5075
L3 ES right envelope 25th percentile	0.4342
L3 ES right EMG Shannon entropy	0.3571
L5 MF left evelope 10th percentile	0.3498
L1 ES right 10th percentile	0.2065
L3 ES right envelope 50th percentile	0.3119
L5 MF right envelope 10th percentile	0.3046
L5 MF left envelope 25th percentile	0.2864
L5 MF left EMG Shannon entropy	0.2767
L5 MF right EMG Shannon entropy	0.2559

Table 2

Top 10 Suitable Features accounting for the orthogonality of information

Feature	Suitability	Orth. part
L3 ES right envelope 10th percentile	0.5075	0.5075
L5 MF left shannon entropy	0.2767	0.2180
L5 MF right envelope 10th percentile	0.3046	0.1581
L1 ES right EMG auto-correlation	0.1890	0.1420
L3 ES right EMG mean frequency	0.2065	0.1310
Pelvis-T8 sagittal angular velocity	0.1597	0.1235
L3 ES right EMG_{CD} auto-correlation	0.1428	0.1106
L1 ES right envelope 10th percentile	0.3219	0.1001
RA left envelope auto-correlation	0.1245	0.0978
L5 MF left EMG_{CD} shannon entropy	0.1941	0.0857

6. Discussion

The features in Table 1 had the highest suitability scores, while Table 2 lists the top 10 features after accounting for the fact that some of the features are highly correlated to each other and therefore do not carry independent information.

The top feature was observed to be L3 Erector Spinae (ES) right envelope 10th percentile. ‘L3 Erector Spinae right’ is the location of the EMG sensor, while envelope 10th percentile refers to the methods with which the data was processed to form a feature. In this case, ‘envelope’ refers to the envelope of the EMG signal processed for magnitude and ‘10th percentile’ refers to the value denoting the 10 per cent of the lowest magnitude values. Each sensor at its specific location (e.g. EMG sensor at the L3 Erector Spinae on the right-hand side) can provide more than one set of independent information; for example, it can provide the magnitude or the frequency of the muscle activation signals. The post-processing technique provides the variety of information that can be extracted from the sensor data.

The features on Table 2 are therefore the most effective measures to obtain to be able to quantify the increased injury risk. Note that some of these features can come from the same sensor; for example, L3 ES and L5 MF both appear three times on the list. Using these sensors would be the minimum number of sensors that we need to put together to obtain as much information as we can to quantify risk of injury. This significantly informs the design of a portable (wearable) monitoring system if we were to build one to monitor risk of injury.

It should also be noted that the relative angular displacement and velocity between the pelvis and the T8 vertebrae (or anywhere in the ribcage) are needed to be able to segment the collected data automatically into each ‘sheep’ . These would also provide us with the information of the posture of the shearer. Note that the relative angular velocity between the pelvis and T8 vertebrae shows in the top 10 list of features for identifying risk of injury. This posture information combined with the EMG sensor information identified in Table 2 are the minimum required to yield much of the necessary information to quantify the risk of injury.

The primary results of the 12-month study comprehensively addressed objectives 1 and 2. These are the primary goals where it is necessary to thoroughly understand the mechanism of the injury risk and to have systematic and data-justified methods to evaluate the efficacy of our intervention.

Wearable sensor

The project validated the feasibility of integrating basic EMG sensors and IMU (Inertial Measurements Unit) sensors in a wearable sensor with a display on a mobile phone. This is deemed practical for the task of shearing. The design includes a back-stabilising belt to localise the sensors and maintain contact pressure. It allows for multiple sensor locations to target different muscles and accommodates shearers of different sizes. The device includes electronics to synchronise the EMG and IMU sensors and acquire data and transmit wirelessly to a mobile device at the speeds required. The device and mobile user interface can be seen in Figure 4.

WearableEquipment

IMU NORMALIZATION: ON

EMG NORMALIZATION: ON

START SAMPLING: OFF

Figure 4. Wearable sensor prototype (left) with data collection mobile user interface (right).

It should be noted that a thorough product design and useability exercise will still need to be carried out. It should include a survey and a feedback-gathering process from the shearers and other stakeholders. The willingness of the shearer to invest in and wear such a device is important in the design (and the eventual adoption) of the product.

To improve the technical robustness of the wearable device, an off-the-shelf EMG sensing and IMU system was purchased for testing. These commercial systems are mature technologies that contain cutting-edge and proprietary algorithms to address typical issues with the IMU sensors, such as synchronisation over wireless and the measurement drift. These are the strengths of commercial products. For example, the Xsens Dot IMUs (purchased) enable wireless synchronisation, Bluetooth connectivity, resistance to magnetic interference, and ingress protection to water and dust suitable for a shearing shed.

Therefore, the main outcome of the project is the contribution that our team can best make, which is to identify what needs to be measured to produce an effective outcome and to put together the sensor prototype. As the outcomes show in Table 1, two IMU sensors to the torso and upper leg plus two EMG sensors placed on L3 and L5 (with the appropriate post processing to obtain independent information) would maximise the information needed to evaluate the increase in the risk of injury in a shearing task.

Physical assistive strategy

While the wearable sensors assist by measuring the risk of injury, they can only warn shearers if their risk of injury is increasing. The shearer will be able to better avoid injury by taking a rest or an appropriate stretching exercise at the expense of productivity. An active intervention strategy means that it is possible to lower the accumulation of the injury risk (compared with no assistance) while allowing the shearer to continue to work, thus minimising the impact on productivity.

The active approach needs to be carefully considered. The history of innovation in this space has taught us that there are a lot of factors to consider not only to produce an elegant technological solution, but also one that suits the practical and socioeconomic conditions of the sector.

To our knowledge the only approach to physical assistance that has gained any popularity is the shearer back-harness, which applies a small supportive force to the torso with a set of springs attached to a mount above the shearer while still allowing free movement (Figure 5).

Figure 5. Shearer support back-harness (left). Concept of a modification to provide additional active support using a simple cable robot driven from above by electric motors (right).

The team expects to still carry out a formal requirement derivation and brainstorming process to collect possible solutions that respect all the identified constraints and factors to optimise. A potential idea could be to use an existing solution that we know is well accepted by the shearing community, such as the shearing harness.

The electromechanical version of the harness, with the concept shown in Figure 5, is straightforward and could be retrofitted to existing devices. The challenging part of such a device is a control strategy that would allow for the continued free movement of shearers while providing additional support to reduce bad postures and/or relieve stresses in the lower back.

Connectivity with wearable IMUs and/or EMG sensors would inform the device on the best strategy to adopt. These ideas are to be developed and it is part of the team's suggestion for AWI to pursue.

While the results of the work indicate the overarching goal of such a device driven by biometric feedback from the shearer, the development of lower-level strategies to achieve these goals with such a device remains a significant challenge because of individual movement patterns of different shearers.

7. Impact on the wool industry

This work aims to contribute to the better understanding of the causes of lower back injuries in shearers. Several important features have been identified that, if monitored continuously, could allow for the prediction or early warning of lower back injuries. The established indicators can also be used to evaluate the effectiveness of future intervention strategies. This will allow for quantitative evaluation of future work in wearable sensors, or wearable robotics, that could reduce injuries in the occupation.

An anecdotal example can be seen in this study with respect to the understanding of the cause of injuries. There is a perception among shearers that injuries are often attributed to the catch-and-drag process. However, while that is true, the primary cause actually lies in the shearing process. The forces typically encountered during catch-and-drag are generally well within the capability of a typical human's (shearer's) body to withstand safely, when the body is in its peak condition.

However, the frequently stooping posture during shearing creates muscle fatigue and a noticeable stretch to the passive muscle length [36]. A stretched passive muscle length means that when the shearer is standing upright, the muscles holding up his spine are no longer as taut as their nominal length. Such understanding demonstrates the value of the study and the establishing of modern measurement technology that can be deployed in a realistic shearing environment.

The efficacy of the study was created through the understanding of what sensors to deploy and what exact information to extract from the measured data that would best inform the study. Creating a portable and cutdown version of the sensing equipment that could be worn by the general shearer population improved the availability of the data and the quality of the study. It will be necessary to engage in a product design process to turn the prototype into a practical wearable device.

The understanding of what to assist and the ability to quantify the effect of the physical assistance/process improvement on the risk of injury provides us with a concrete way to develop and evaluate the effectiveness of assistive devices.

8. Conclusion and recommendation

In this stage of the study, a quantitative measure was established to access the increase in the risk of injury, based on specific measurements taken from the posture and the muscle activations of the shearer. The specific locations of the sensors were specified to yield the maximum amount of information using the minimum number of sensors.

Such a measure will be useful in quantifying any improvements or interventions introduced into the sheep shearing process, such as ergonomic shed redesign, changes in warm-up and stretching exercises, changes in rest/work cycle, or a more active solution through physical assistance such as robotic devices. The next steps will be to:

- use the measures established to investigate and realise an effective intervention strategy to reduce injuries
- realise a practical wearable sensing device to provide the ability to monitor the risk of injury on shearers as they carry out their task
- design an active (physical) assistive device that would assist in lowering the risk of injury while maintaining (or, dare we hope, improving) the productivity of shearers.

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