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Evaluation of ceiling-supported back harnesses in preventing injury in sheep shearing

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Abstract— **Lower back injuries are a significant global problem. They are particularly common in occupations that require prolonged or repetitive spinal flexion. Sheep shearing is one such occupation and the prevalence of back injuries is severe. Ceiling-supported back harnesses are a commonly used safety device in this occupation but its effectiveness in sheep shearing tasks has yet to be quantified. It is likely that accumulated and time-dependent changes in kinematics and neuromuscular control are relevant in the development of many lower back injuries. This is supported by the literature in sheep shearing, where 68% more injuries occur towards the end of the working day compared to the start. This means that data collected over a full working day is beneficial for measuring the effectiveness of safety interventions. The previous research in safety interventions in shearing have not collected data for more than 15 minutes, and do not adequately address longer term effects. This study compares the effects of wearing a ceiling-supported back harness on shearer kinematics and muscle activity, from the collected data over a full working day and incorporating time-of-day effects. The outcome shows that the use of ceiling-supported back harness results in improvements in kinematic features, but also an increase in muscle activity and fatigue.**

I. INTRODUCTION

Sheep shearing is one industry that involves repetitive tasks and stooped postures. An expert worker will shear more than 200 sheep, and spend over six hours each day in a stooped working posture [1] (see Figure 1). Injury rates in sheep shearing are severe, with lower back injuries the biggest problem [2]. Data in shearing indicates that injury risk increases throughout the day, with 68% more injuries occurring in the last two hours of work, compared to the first two hours. Safety interventions in shearing have also been studied. Among many attempted interventions, the shearing back harness is most commonly used. As seen in Figure 2, they are designed to partially support the shearer's torso by using springs attached to a mounting point above the shearer.

The effect of back harnesses on forces in the lower back was investigated in [3] where twelve workers sheared three sheep with and without the back harness in a shearing shed. The back harness was attached to a load-cell to collect force data, and this was combined with the force estimations at the lumbo-sacral (L5-S1) and thoaco-lumbar (T12-L1) joints calculated from the subject size, weight, and kinematics, without consideration of external forces from the sheep. The back harness was found to reduce compressive forces at the T12-L1 and L5-S1 joint by $8-17\%$ and $19-27\%$. Differences were also found in anterior shear forces, where the back harness was found to decrease this by $33-49\%$, and $27-34\%$ in the T12-L1 and L5-S1 joints.

In [4], the data from [3] is re-analysed and the effects of a shearing back harness and shearer skill level on spinal kinematics were also investigated. The back harness was found to reduce time spent in axially twisted postures, while increasing time spent in laterally bent postures, with no significant change in spinal flexion/extension. No significant effects were found across varying skill levels.

In the studies above, as well as other recent research relating to sheep shearing back injuries [2]–[6], the experimental data was collected from workers shearing no more than 5 sheep (per case). In all previous studies of safety interventions in shearing, only kinematics and estimated joint dynamics have been measured, without consideration to muscle forces or activity. The experiments were arranged with limited time, limited number of sheep, outside of real working conditions, so existing results cannot fully capture the effectiveness of the back harness. Experiments for real working conditions, long working hours with sensors that can capture both kinematics and muscle activities are needed.

This study investigates the effects of the back harness on shearer kinematics and muscle activity through motion capture and surface electromyography (sEMG), using data collected over a full shearing day. The results indicate that the harness improves kinematic features, while increasing muscle activity and fatigue.

II. METHODS

A. Participants

Nine male sheep shearers aged 21-61 years, with varying skill levels, were recruited for the study. Each shearer was observed for 6-8 hours, and sheared 50-236 sheep. All shearers provided informed written consent and the experiment was approved by The University of Melbourne Human Ethics advisory group (Ethics ID 1853436). One shearer was recorded over three consecutive days and these data are included as two extra subjects.

B. Experimental Setup

Both kinematic and muscle activity data were collected. The kinematic data were collected with the Xsens Awinda portable motion capture system. The system is an inertial measurment unit (IMU) based motion capture system, which

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Fig. 1: Shearer in stooped posture with sensors attached

Fig. 2: Shearer with ceiling-supported back harness

measures joint kinematics, sampled at 60 Hz. The experimental setup can be seen in Figure 1.

Muscle activity data were also collected using sEMG sensors. Six Delsys Avanti wireless sEMG sensors were used (10 mm inter-electrode distance), sampled at 2148 Hz. Sensors were placed bilaterally on the following muscles: Erector Spinae at the level of the first and third lumbar vertebrae (L1 & L3 ES), Multifidus at the level of the fifth lumbar vertebrae (L5 MF). The EMG sensors were placed bilaterally as per the SENIAM guidelines [7] for the L1 ES, and MF muscles. As the sensor placement took place in the working environment, the sensors were placed with subjects standing naturally. Additionally, sensors were placed bilaterally on the ES muscle 3 cm laterally to the L3 spinous process (L3 ES), as in [8], [9]. To hold all sensors in place for the full work day, each sensor was further secured with kinesiology tape. The sEMG sensors were calibrated with a maximum voluntary contraction (MVC) [8]. A standing isometric back extension exercise was performed with the torso flexed at 45°, manually braced by a researcher.

C. Protocol

As the study involved instrumenting shearers performing their regular work, the shearing rest-work periods were followed. The standard shearing day starts at 7:30am, and shearing takes place in four two-hour sessions (shearing runs), with a one hour lunch break between run 2 and 3, and two 30-minute breaks between runs 1-2, and runs 3-4. Shearers were asked to be at their shearing stand 45 minutes early before run 1 to allow for sensor placement and calibration. Prior to the other runs, shearers were required at their stand 15 minutes early to allow for re-calibration of the motion capture system. The IMUs were charged during the lunch break, and were re-placed and re-calibrated prior to run 3. One shearer was instrumented each day for the working period. Some disruptions occur during regular shearing (e.g. running out of sheep), and these disruptions meant that for three subjects the final shearing run did not occur. A minimum of six hours of data was collected for each subject.

D. Analysis

1) Signal Pre-processing: The sEMG signals were filtered with a 2^{nd} order Butterworth filter with pass-band between $20-450$ Hz. The sEMG envelope was calculated by rectifying the filtered sEMG signal and low-pass filtering with a cutoff frequency of 6 Hz [10]. This envelope signal was normalised to the maximum value from the MVCs collected for that shearer. Joint kinematics were extracted from the Xsens software at a sample rate of 60 Hz.

2) Data Segmentation: In sheep shearing there are two main activities; the catch and drag (C), where a shearer walks into the holding pen and gains control of a sheep before dragging it to the shearing stand; and the shearing activity (S), where the shearer controls the sheep while removing the wool. The combination of two adjacent segments represents the full shearing task which is repeated over the day.

The data was segmented into the S, and C phases of the task using a human activity recognition algorithm for sheep shearing using a Hidden Markov Model developed in [11] with each shearer completing a different number of task iterations. The task was modelled using the two activity states (S, and C), and the classifier achieved an F_1 score of 96.47%, which was considered appropriate for this analysis.

3) Features: Based on literature review, kinematic and sEMG features were selected to give an indication of injury risk. Muscle fatigue increases injury risk and alters kinematics [12] as well as causing dysfunction in neuromuscular control [13]. It is suggested in [14] that motor control problems are likely to be the most significant factor in predicting who will develop and maintain back disorders.

To assess muscle fatigue, mean frequency (μF) is calculated from the segmented data from the shearing phase of each sheep. By using an appropriate Fourier Transform, we can obtain its frequency components with the frequency range $[f_0, f_1]$ corresponding to the pass-band of the pre-processing filter. We denote the power density spectrum of this signal is $P_{sEMG}(f)$, and the mean frequency is calculated as in (1):

$$f_M = \int_{f_0}^{f_1} \frac{f \cdot P_{sEMG}(f)}{P_{sEMG}(f)} df. \tag{1}$$

Mean frequencies from the L1 ES, L3 ES, and L5 MF are used in this analysis and denoted as features A, B, and C respectively. The amplitude of sEMG envelopes (normalised to the MVC) are also included to assist with analysis of muscle activity through a joint analysis of EMG amplitude and spectrum (JASA) [15]. The mean sEMG amplitude (μA) over the shearing phase of each sheep is calculated for the L1 ES, L3 ES, and L5 MF muscles, and these are denoted as features D, E, and F respectively.

Flexion, twist and lateral bend angles have been used to assess risk in occupations, including shearing, previously [4], [16]. In this study the angles of lumbar flexion, twist, and bending are used. For lumbar flexion, the median flexion angle from the shearing phase is used, and is feature G. For the twist and lateral bend angles, the RMS value is calculated as in Equation (2), as the neutral position for these angles is

0. These are denoted as features H and I respectively.

$$RMS = \sqrt{\frac{1}{N_{p,s}} \sum_{k=1}^{N_{p,s}} x(k)^2}, \tag{2}$$

where $x(k)$ is a signal of interest, for $k = 1, \ldots, N_{p,s}$ samples.

4) Statistical Analysis: The statistical analysis was performed using a Linear Mixed Model (LMM) [17]. Due to the hierarchical nature of the data, an LMM is chosen to incorporate various random processes including variances between subjects, as well as account for the unbalanced nature of the data-collection [18].

Subject (shearer) was included as a random effect (RE), as well as the shearing run nested within it. The harness condition, shearing run, and their interaction were included as fixed effects (FE). The model for each feature can be approximated by a relationship shown in Equation (3). For the i^{th} subject, the j^{th} run, and the k^{th} measurement, the feature Y^s_{ijk} can be expressed as

$$\begin{aligned} Y^s_{ijk} &= \beta_0 + \alpha \cdot h_i + \delta \cdot r + \gamma \cdot h_i \cdot r + a_i + b_{ij} + e_{ijk} \\ h_i &= \begin{cases} 0, & \text{if no harness used} \\ 1, & \text{if harness used} \end{cases}, \end{aligned} \tag{3}$$

where $s \in \{A, B, C, D, E, F, G, H, I\}$ and r is the run number ($r \in \{1, 2, 3, 4\}$). This relationship combines two cases: one is with harness and the other is without. Here β_0 is the model intercept and δ is the run fixed effect. These two parameters are not dependent on the harness. Two parameters (α, γ) are related to the effect of the harness. α is the harness fixed effect and γ is the harness/run interaction fixed effect. The REs $(a_i, b_{i,j}, e_{i,j,k})$ are Gaussian distribution, characterized by zero mean and their corresponding variances. The random variable $a_i \sim \mathcal{N}(0, \sigma_i^2)$ is the subject dependent and the random variable $b_{ij} \sim \mathcal{N}(0, \sigma_j^2)$ is the run-dependent with the variance, which is assumed to be same across subjects. The residual $e_{ijk} \sim \mathcal{N}(0, \sigma_k^2)$ is assumed to have the same variance across subjects and runs. By fitting the data to this model in (3), we can compute these parameters $(\beta_0, \alpha, \delta, \gamma, \sigma_i^2, \sigma_j^2, \sigma_k^2)$. We take averages of these parameters over runs and measurements, we can obtain averaged values as shown in Table 1.

III. RESULTS

The results of the statistical analysis is presented in Table I. The intercept values for six features in Table I are all highly significant, β_0 with $P < 0.001$ in this LMM (3).

From (3), two linear relationships are obtained: one is with harness and the other is without harness, as shown in Figure 3. The averaged value of selected features over subjects at each run is obtained at either the orange dots (without harness) and the blue dots (with harness). The data is fitted by the linear relationships from (3), and the vertical bars reflect the standard deviation of the actual measurements.

TABLE I: Results

Feature		Value	P		Value
A	β_0	63.234	$< 0.001^*$	σ_i^2	163.185
	α	22.747	0.007^*	σ_j^2	20.103
	δ	1.370	0.117	σ_k^2	21.646
	γ	-1.437	0.292		
B	β_0	63.809	$< 0.001^*$	σ_i^2	179.645
	α	8.973	0.366	σ_j^2	51.607
	δ	4.186	0.003^*	σ_k^2	113.618
	γ	-2.610	0.239		
C	β_0	68.753	$< 0.001^*$	σ_i^2	488.590
	α	41.088	0.005^*	σ_j^2	51.379
	δ	2.206	0.127	σ_k^2	213.219
	γ	-4.546	0.045^*		
D	β_0	0.053	$< 0.001^*$	σ_i^2	0.001
	α	0.058	0.001^*	σ_j^2	0.000
	δ	0.000	0.871	σ_k^2	0.0003
	γ	-0.01	0.006^*		
E	β_0	0.056	$< 0.001^*$	σ_i^2	0.001
	α	0.025	0.231	σ_j^2	0.000
	δ	-0.008	0.002^*	σ_k^2	0.0005
	γ	-0.001	0.746		
F	β_0	0.046	$< 0.001^*$	σ_i^2	0.001
	α	0.034	0.077	σ_j^2	0.000
	δ	-0.002	0.228	σ_k^2	0.0006
	γ	-0.002	0.395		
G	β_0	47.676	$< 0.001^*$	σ_i^2	174.323
	α	-3.352	0.740	σ_j^2	63.080
	δ	1.325	0.388	σ_k^2	18.884
	γ	0.800	0.738		
H	β_0	6.593	$< 0.001^*$	σ_i^2	0.408
	α	-2.295	0.017^*	σ_j^2	1.294
	δ	0.047	0.829	σ_k^2	1.130
	γ	0.160	0.640		
I	β_0	5.687	$< 0.001^*$	σ_i^2	1.547
	α	-0.817	0.374	σ_j^2	0.427
	δ	-0.197	0.130	σ_k^2	1.268
	γ	0.195	0.339		

As shown in Table I and Figure 3, the harness is found to produce an increase in L1 ES mean frequency (A) (α with $P < 0.05$), while the decrease in mean frequency over time is not different to the no harness case. The L3 ES mean frequency (B) is found to increase over the course of the day (δ with $P < 0.05$), the presence of the harness makes no difference here. The L5 MF mean frequency (C) is found to be higher with a harness (α with $P < 0.05$), and the decrease in mean frequency over the day is also found to be different compared to the no harness case (γ with $P < 0.05$).

For the sEMG amplitude, it can be seen in Table I that the L1 ES mean amplitude (D) is higher with the harness (α with $P < 0.05$), and also decreases over the day which is different to the no harness case (γ with $P < 0.05$). The L3 ES mean amplitude (E) decreases over the day for both cases (δ with $P < 0.05$), but no difference is seen between the harness and no harness cases. The L5 MF mean amplitude (F) is also higher with the harness, but this is not a significant result (α with $P = 0.077$). For the kinematic features, it was found that the harness results in a decrease in lumbar twisting (H) (α with $P < 0.05$).

IV. DISCUSSION

The purpose of this study is to assess the impact of the back harness as a safety intervention strategy in shearing. Previous investigations in [3], [4] have identified changes in kinematics, and a reduction in joint forces with a harness, but none of them study shearers working for more than 15 minutes. As the likely causes of back injury in shearing are cumulative effects that occur over time [4], it is worthwhile to investigate these over a more relevant time-frame.

The two relevant variables observed in this study are the shearing run (time of day), and the use of a back harness. A limitation of this study is that it does not contain a paired set of data. As many shearers use a back harness to reduce pain during shearing, it was considered unethical to require shearers to forgo using a back harness for an entire day. Additionally, for shearers who do not use harnesses, there is likely to be some adaptation to the harness, which would take time and may distort the data. To partially mitigate this, an LMM was used to perform the statistical analysis, which incorporates the shearer as a random effect while enabling the comparison of the harness and non-harness groups. The LMM is also able to handle the unbalanced nature of the observational study, where not all shearers performed four runs, and sheared different numbers of sheep.

The statistical analysis is presented in table I. The sEMG signals are interpreted with the JASA method [15]. Table I, and Figure 3(A),(D) shows the L1 ES mean frequency increases ($P = 0.007$) with the use of a harness, which is accompanied by an increase ($P = 0.001$) in sEMG signal amplitude. The sEMG amplitude in this muscle is also found to decrease over the day when using a harness which is different ($P = 0.006$) from the no-harness case. This is accompanied by a slight decrease in mean frequency across the day when using a harness, which is not significantly different to the no-harness case ($P = 0.292$). This indicates that active muscle forces in L1 ES are higher when using a back-harness, and that over the course of the day it's likely that load is shifting away from this muscle. Similarly for the MF muscle, Table I and Figure 3(C),(F) shows the mean frequency is increased ($P = 0.005$) with the use of a harness, which is also accompanied by an increase in sEMG amplitude, but this is not a significant difference ($P = 0.077$). Future work with more subjects may show a significant difference here. For the harness case, there is a decrease in MF mean frequency over the course of the day, which is different to the no-harness case ($P = 0.045$). There is also a decrease in sEMG amplitude in this muscle over the day, but this is not a significant difference ($P = 0.395$) to the no-harness case. In the MF muscle it is again likely that higher active muscle forces are present with the harness, and load gradually shifts away over the day. There are no significant differences between the harness and no harness cases for the L3 ES muscle in mean frequency or sEMG amplitude.

Similar load shifting among lower back tissues has previously been observed. This has been attributed to muscle fatigue, as well as viscoelastic creep in spinal tissues [12]. As the effects differ from the no-harness group (which experience the same repeated and prolonged spinal flexion) and with higher muscle forces present, the different load shifting is likely a result of muscle fatigue in this case. The L1 ES and the MF muscle are both important for the shearing task, but the MF muscle has previously attracted research attention as it is a muscle required for providing spinal stability. Dysfunction in the MF muscle has been implicated in back injury [19]. It is also a commonly targeted muscle in rehabilitation of back injuries [20]. The back harness may therefore negatively impact injury outcomes associated with muscle fatigue in these muscles.

The harness was however found to improve spinal kinematics. Table I shows a significant reduction in spinal twisting in shearers that wore back-harnesses. Complicated spinal motion, including twisting, likely contributes to lower back injury [21], and simplifying the spinal motion in the shearing task is likely to reduce injury risk. The reduction in the axial twist parameter is in line with earlier kinematic effects reported in [4].

Previous work in [3] found a reduction in joint forces. For these results to be consistent with [3], the higher muscle activity found would imply a reduction in passive forces. A probable explanation of this is a reduction in flexion that prevents flexion-relaxation (previously observed in [6], [22]) keeping the muscles in the active region. This is plausible, as some evidence of this can be seen in figure 3(G), however caution must be applied here as this was not found to be significant in the statistical analysis, with large inter-individual differences in this feature.

It is possible that increasing the support provided by the back-harness could further reduce the joint forces, with the potential for reducing muscle activity instead of increasing it. This could further improve the kinematic benefits, while reducing the drawback of increased muscle activity. The current back-harnesses provide support through springs, and are therefore limited in the force they can provide while still allowing freedom of motion. Future work will investigate new harness designs with the potential for additional support.

V. CONCLUSIONS

The evidence suggests that the back harness does have a positive effect on sheep shearer kinematics that are important in injury reduction. This is counterbalanced by what appears to be an effect that increases the muscle activity and fatigue when using a back harness. However, sEMG measures muscle activity and does not consider passive muscle forces; so considering the previous research it is likely that the back harness causes load to shift from passive forces towards more active muscle forces, which could occur alongside a reduction in overall joint force. This is consistent with the slight reduction in spinal flexion, given that the flexion-relaxation phenomenon is seen to be present in sheep shearing. The current back harness could therefore reduce some

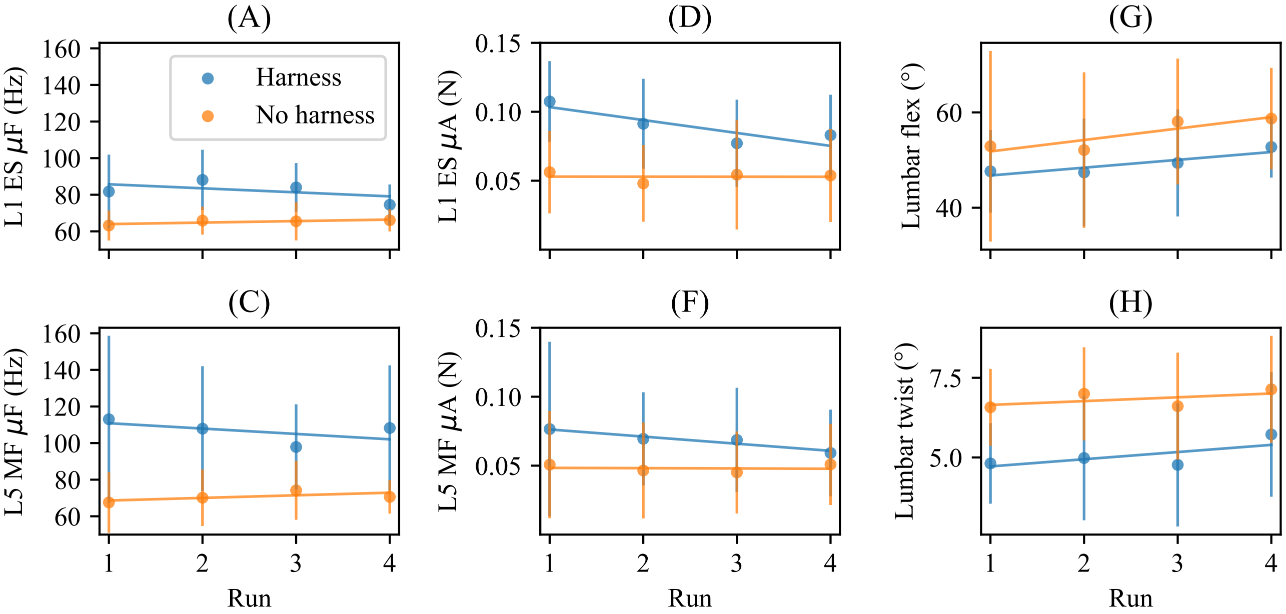

Fig. 3: Features A, C, D, F, G, and H, mean values for each run for the harness and no harness cases, with the fitted LMM.

causes of back injury, but worsen others. It is also possible that modifying the back harness to provide more support could further reduce injury risk amongst sheep shearers if the technical challenges can be overcome. Future work will consider back harness improvements, and investigating these effects on more subjects.

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