Design and Evaluation of Assistive Modes in a Lower Back Exoskeleton for Sheep Shearing: a Case Study

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Abstract

Sheep shearing is an important economic activity within Australia and New-Zealand. Yet, to date sheep shearing remains a manual process involving poor lower back postures and repetitive movements leading to injuries. So far, the only commonly accepted physical assistive device in shearing is the spring-loaded ceiling harness. As such, electric-assisted sheep shearing has long been dreamed of.

We therefore propose to evaluate a lower back exoskeleton, supporting the hip flexion-extension, during shearing. We present a first two-step evaluation of the device by an expert shearer.

A preliminary lab-based evaluation allowed validation of the feasibility of the approach given simple hardware modifications of the exoskeleton and the introduction of an ad hoc Gravity Compensation controller augmented by an Asymmetric Damper (GCAD).

In situ shearing evaluation showed the compatibility of the device with the shearing task and confirmed the expert user's interest for one of the proposed assistive modes. Kinematic measures showed that wearing the exoskeleton itself reduced the lumbar flexion and hip rotations but the active assistance provided by the device did not further alter the movements.

Further quantitative evaluation of the effects of active hip exoskeletons for sheep shearing should now be conducted, specifically evaluating muscle activity in addition to the body kinematics.

1 Introduction

Wool harvesting remains a cornerstone of Australia's rural economy. The country produces about 25% of the world's wool and 90% of its fine apparel wool [AWI, 2017]. Each year, 74 million sheep are shorn by around 4000 shearers, yielding 340 million kilograms of wool and more than $3.5 billion in exports [AWI, 2018]. Out of the whole process, shearing is the largest expense for wool growers, accounting for over 60% of production costs and around 30% of wool sales revenue [Carmody, 2010].

Shearing is labour-intensive, with one expert worker typically shearing more than 200 sheep a day and spending over six hours in a stooped working posture [Gmeinder, 1986]. It carries a high risk of injury, particularly to the lower back [Pal *et al.*, 2008] [Robinson *et al.*, 2023]. The incidence rises as fatigue sets in, with nearly 68% more injuries recorded in the final two hours of a workday compared to the first. Various measures have been trialled, such as a raised shearing platform to avoid having to stoop [Gregory *et al.*, 2009], robotic shearing [Trevelyan, 1992] and chemical solutions [Hudson, 1987], each pose their own challenges such that manual shearing remains the most economical and the primary method of wool harvesting. On that front, very few advances have been made to provide assistance to the shearers in mitigating fatigue and risk of injuries. The most widespread being the back harness that uses fixed overhead spring supports to relieve strain on the shearer's torso [Robinson *et al.*, 2021].

Studies have shown that conventional back harnesses improve shearer kinematics associated with injury risk but are less effective in reducing fatigue [Robinson *et al.*, 2021]. The assistance provided by the basic spring connected to the ceiling lacks optimality for the various scenarios and body postures and was observed to shift load from a passive to an active range of muscle forces, thereby increasing muscle activity despite some reduction in joint force and spinal flexion. Thus, while they may ease certain back stresses, they can also worsen others, pointing to the need for improved harness designs.

For sheep shearing, exoskeletons can be designed to recognise what posture the human is in and what shearing task the human is performing [Robinson *et al.*, 2020] - and be programmed to modulate the assistance to suit

Figure 1: A sheep shearer, shown wearing a ceiling harness (highlighted with the outline).

the scenarios and the human body posture. There is therefore a significant potential to reduce fatigue and injury risk, and even improve productivity through the appropriate assistance provided by robotic exoskeletons in sheep shearing.

Robotic lower back exoskeletons have significantly matured in recent years, being developed for many different applications. However, a recent literature review, including 33 studies, "identified [a need] for further field studies, involving industrial workers, and reflecting actual work situations." [Kermavnar *et al.*, 2021].

The purpose of the present work was therefore 1) to evaluate the feasibility of the use of a lower extremity exoskeleton for sheep shearing and 2) to perform a first evaluation (and comparison) of possible assistive modes (controllers) during actual shearing activities. As such, this paper is a technical report of the iterative, user-based, design process to both modify and evaluate the exoskeleton for the shearing task. The process consisted of two evaluations conducted over two days: a lab-based preliminary evaluation with a lead user on the first day, followed by an in situ evaluation on an actual shearing task by the same lead user on the following day.

In this paper, we introduce the robotic exoskeleton and the proposed assistive modes (Section 2), and the preliminary lab-based evaluation and the modifications in response to the findings from the first day in Section 3. The comparison of the proposed assistive modes on the actual execution of the shearing task carried out in a shearing station in Section 4. Results and learning are discussed in Section 5.

2 Apparatus

2.1 Robotic Exoskeleton Hardware

The evaluated exoskeleton is a FIT-HV lumbar exoskeleton by ULS Robotics (Shanghai, China), as shown in Figure 2. It consists of a rigid backpack structure, holding the battery and control electronics, attached via backpack style straps above the shoulders and at the waist. For each leg, the exoskeleton has one active degree of freedom (DoF) for hip flexion-extension and one passive DoF for the hip abduction-adduction. The exoskeleton is secured at the thigh with semi-rigid cuffs, thus transmitting forces between the upper body and each leg.

Figure 2: The FIT-HV lumbar exoskeleton with hardware modifications used in this study.

Hip flexion-extension can provide a continuous torque of $24Nm$ and has a range of motion (RoM) of approximately 225°, while passive hip abduction-adduction has a range of 150°. The system has an overall mass of $5.8kg$.

For this study, the internal controller of the exoskeleton was replaced by a BeagleBone single-board computer with CANOpen capabilities and a dedicated software controller using the CORC framework [Fong *et al.*, 2020] was implemented. The new controller allowed for direct control of the motor torque in real time at $500Hz$ based on position and velocity measured at the active joints. In addition a custom Graphical User Interface (GUI) written in Python and running on a separate computer allowed for monitoring and logging of the state of the device as the operator to control the various assistance parameters.

2.2 Proposed assistive modes

Before the lab evaluation with the expert shearer, three control modes, corresponding to different types of assistance, were implemented on the exoskeleton and tested during the laboratory based evaluation:

1. A Virtual Wall (VW) approach intended to offer a rigid support to the user when bent forward, inde-

pendently for each left or right hip torque ($\tau_{l,r}$):

$$\tau_{l,r}^{VW} = \begin{cases} k(q_0 - q_{l,r}) & if\ q_{l,r} > q_0 \\ 0 & otherwise \end{cases} \quad (1)$$

with $k = 100Nm \cdot rad^{-1}$ and q_0 a bending angle to be defined according to user's preference.

2. A quasi-static Gravity Compensation (GC) of the upper-body equivalent mass:

$$\tau_{l,r}^{GC} = -m_{ub} sin(q_{av}) \quad (2)$$

with $q_{av} = \dfrac{q_r + q_l}{2}$ and $m_{ub} \in [0-3] kg \cdot m^2 \cdot s^{-2}$ a factor defined based on user's preference and representing the mass-length-gravity equivalent value of the upper-body reduced to a mass-point.

3. A combination of the above two approaches (VWGC) aimed to provide both a quasi-static GC while above the virtual wall and a rigid wall support when the shearer is at the lowest point:

$$\tau_{l,r}^{VWGC} = \begin{cases} k(q_0 - q_{l,r}) & if\ q_{l,r} > q_0 \\ -m_{ub} sin(q_{av}) & otherwise \end{cases} \quad (3)$$

These modes have been developed based on knowledge of the shearing task which has both dynamic components but where the shearer spends most of the time bent forward around 90° of flexion. They were inspired by previous studies on lower back injuries with shearers and by the literature on lower back exoskeletons evaluating kinematic-based control approaches [Lazzaroni *et al.*, 2019],[Miura et al, 2018], [Huysamen *et al.*, 2018] which have the advantage of not requiring additional sensors (such as electromyography-based approaches) nor a customised-user model (such as approaches based on musculoskeletal modelling).

Each assistive torque, τ^{ASSIST}, was provided in addition to a friction compensation torque as:

$$\tau_{l,r}^{ALL} = \tau_{l,r}^{ASSIST} + \alpha \dot{q}_{l,r} + \beta sign\left(\dot{q}_{l,r}\right)\ , \quad (4)$$

with $\alpha = 0.25 Nm \cdot s$ and $\beta = 0.4 Nm$ the viscous and static (Coulomb) friction coefficients respectively.

3 Laboratory based evaluation

In order to better understand the needs from the exoskeleton in assisting shearers and to evaluate its possible suitability for the task, an expert shearer was invited for a two-day session, with the first day dedicated to preliminary testing and lab-based evaluation.

3.1 Methods

The objective was to gather qualitative feedback on the applicability of the exoskeleton for sheep shearing, define the hardware modifications required for the in situ evaluation, and define the assistive mode and associated parameters to be evaluated in situ.

An ad hoc questionnaire was developed prior to the evaluation based on the Technology Acceptance Model: Perceived Usefulness (PU) and Perceived Ease-Of-Use (PEOU) [Davis, 1989]; as well as inspired by an existing generic and validated assistive exoskeleton evaluation questionnaire [Wioland *et al.*, 2019]. This ad hoc questionnaire thus covered similar dimensions with questions more specific to sheep shearing.

The questionnaire was developed to provide feedback at separate phases of the experiment. General and personal background information on the expert and the task were obtained from the first part of the questionnaire before the device was introduced. After a brief introduction and visual inspection of the device, a questionnaire was administered using a combination of Likert-scale and open-ended questions to capture the expert's perception of the device (PU and PEOU). Another section of the questionnaire dedicated to donning/doffing and comfort was administered once the expert had worn the device and moved around with it. The questionnaire was designed such that the feedback could be used to make fitting and hardware adjustments before the device would begin to provide assistance.

Once the requirements were met, the device was turned on and the assistive modes were applied. After each assistive mode, the expert was asked to answer a series of Likert scale and open-ended questions that were assessed to evaluate the feasibility of the assistive mode as well as to inform whether any tuning of the parameters was required. The questionnaires for this section were repeated for each assistive mode.

3.2 User and task

The expert user invited for the evaluation had extensive experience as a shearer and is a qualified trainer and coach for new and experienced shearers (see Table 1 for details). He has also participated in multiple shearing competitions.

Age	41
Gender	Male
Mass	84kg
Height	181cm
Shearing experience (years)	26
Shearing work frequency	Daily

Table 1: Expert demographics and experience

The expert's own history of injuries due to his occupation included "wrist tendinitis" (both wrists) and "loss of shape spine" and he reported that his lower back was the part of his body that hurts while shearing. In general, he cited "wrist tendinitis", "slipped disks" and "lower back injuries" as common injuries for shearers. Strategies in place to limit injuries included strength training, hot/cold treatment and the use of a support harness (spring-loaded, hung from the ceiling), all left up to individual shearers to adopt.

3.3 Perception, fitting and hardware changes

The expert reported to have no prior experience with an exoskeleton. Prior to testing, his perception of the device was generally positive with some concerns about the physical compatibility of the system with the task, both in terms of physical interaction with the sheep, but also potentially with "saloon doors" often encountered in shearing sheds. Expectations were that the device could "minimise back pain", "reduce injuries", "increase [shearers] endurance" and their "longevity on the job".

Concerns about physical compatibility as well as shearer comfort were addressed directly by modifying the device. The device is originally worn much like a backpack with straps wrapping around the shoulders near the deltoids and a smaller strap linking the two shoulder straps across the chest to prevent slippage. The expert's feedback indicated that the shoulder straps significantly reduced his reach, thus affecting his ability to complete his tasks. To address this issue, a new set of straps was attached to the device that could be strapped around the chest, as shown in Figure 3a. The new chest spanning strap allowed custom shoulder straps to be attached at a more proximal point rather than wrapping around the shoulder so that the device would not rest as much on the deltoids and allow for shoulder protraction. Although the new straps made the donning slightly more complicated, it did not appear problematic to the user with donning/doffing times remaining acceptable according to the respective Likert ratings.

The expert anticipated another incompatibility of the device for sheep shearing which was a mesh strap spanning the buttocks. The strap would interfere with the sheep's leg when passed between the shearer's leg during shearing (see example in Figure 3b). Following the expert's advice, this strap was removed altogether.

The expert also reported a possible interference of the semi-rigid cuff at the legs with the sheep during shearing. Preparatory measures were taken in case this did prove to be a problem but did not end up being used.

(a) Custom modified straps.

(b) Sheep's leg passing between the shearer's legs.

Figure 3: Possible interferences with the exoskeleton were identified for sheep shearing, a) shows how straps were modified and b) shows a possible incompatibility with the original device and the shearing task.

3.4 Assistive modes preliminary evaluation and iteration

Following the above hardware modifications and after qualitatively validating the physical compatibility of the exoskeleton with the task, the different assistive modes were evaluated in the laboratory.

After short testing at different settings of the Virtual Wall (VW) and the Gravity Compensation (GC) modes, the user clearly identified that only the GC was suitable. Specifically, the VW assistance made it extremely difficult for the user to reach low enough (close to ground level) to access under the sheep during some portions of the work. The support otherwise provided by this mode was also not appropriate as it was localised at a specific angle (q_0). The GC mode was generally found supportive and potentially helpful for the task. However, the expert noted that he "need[ed] to fight to go down" and that it "goes back up a bit too fast".

Following this feedback, an additional assistive mode was developed and evaluated on the actual shearing task the next day. This mode incorporated an additional Asymmetric Damper (AD) in addition to the Gravity Compensation as follows:

$$\tau_{l,r}^{GCAD} = \begin{cases} -m_{ub} sin(q_{av}) + b\dot{q}_{l,r} & if\ \dot{q}_{l,r} > 0 \\ -m_{ub} sin(q_{av}) - b\dot{q}_{l,r} & if\ \dot{q}_{l,r} \leq 0; \end{cases} \tag{5}$$

with $b \in [0-1] Nm \cdot rad \cdot s^{-1}$ a damping coefficient, providing damping in the upward direction and a positive viscosity assistance in the downward direction. Such an Asymmetric Damper is intended to mitigate the effect of the Gravity Compensation in the most dynamic sections of the activity (moving back up and lowering down) where the Gravity Compensation approach alone was leading to uncomfortable movements according to the preliminary evaluation.

In order to compare the interest of this new approach more thoroughly, an approach with Asymmetric Damping alone was also tested:

$$\tau_{l,r}^{AD} = \begin{cases} b\dot{q}_{l,r} & if\ \dot{q}_{l,r} > 0 \\ -b\dot{q}_{l,r} & if\ \dot{q}_{l,r} \leq 0. \end{cases} \quad (6)$$

For the remainder of the study, the damping coefficient b was tuned to $0.69 Nm \cdot rad \cdot s^{-1}$ for these two approaches and the m_{ub} coefficient was set to $2.6 kg \cdot m^2 \cdot s^{-2}$ for the GCAD approach.

The laboratory-based evaluation allowed us to define the required hardware and control changes to make the device acceptable for field testing. Following these changes, the expert did not foresee any other difficulty, agreeing that he could wear the exoskeleton for a full day of shearing. Testing was thus carried out with the exoskeleton with two possible assistive modes: Gravity Compensation augmented with an Asymmetric Damper (GCAD) and an Asymmetric Damper alone.

4 In situ evaluation

4.1 Settings and protocol

To get the expert user to qualitatively evaluate the effect of the device during the actual shearing task, a protocol involving six steps was defined as shown in Figure 4. The experiment was conducted on a sheep farm in Victoria and involved a total of 24 sheep over a period of 5 hours.

For each condition after the familiarisation steps, subjective evaluation from the user was obtained using the NASA-TLX [Hart and Staveland, 1988]. In addition, the full-body kinematics were captured using the Xsens Awinda suit (Movella Inc., El Segundo, USA). Comparisons of relevant static and dynamic metrics were performed across the conditions to evaluate the possible effect of the device on the shearing pose and movements. An illustration of the full setup is visible in Figure 5.

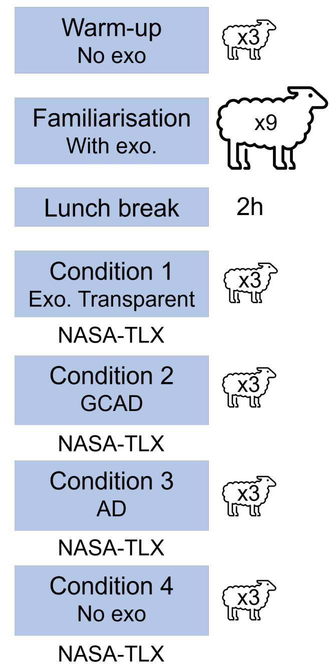

Figure 4: Protocol of the in-situ evaluation with number of sheep shorn at each stage.

4.2 Qualitative observations and subjective evaluation

No physical incompatibilities between the exoskeleton and the sheep or the environment were observed. During the familiarisation phase, the expert was able to carry out his task without specific visible limitations and reported that the device was overall comfortable to wear and the weight was acceptable.

The NASA-TLX ratings of each condition are shown in Figure 6. It appears that the proposed GCAD control approach had the expert's preference for all dimensions. It is also interesting to note the comparatively high Effort and Frustration ratings for the Transparent and AD conditions. In those cases, the user explicitly wondered what assistance the exoskeleton provided or whether it was assisting at all.

Quantitatively, the shearing time did not directly reflect the user Performance rating, with the fastest condition being without the exoskeleton (2 mins/sheep), followed by the AD condition (2.5 mins/sheep), the GCAD (2.7 mins/sheep) and the Transparent condition (3 mins/sheep). However, these results should be interpreted with caution given the single user and low sample size (only three sheep per condition).

4.3 Quantitative analysis

For the full-body kinematic analysis, the exoskeleton did not interfere with sensor placement for the Xsens Awinda suit (as seen in Figure 5), however, additional measures were taken to ensure minimal sensor movement during shearing, such as when the hand passes underneath the shorn wool.

Data from both the exoskeleton state and human kinematics were used for the analysis, and Figure 7 shows how the GCAD assistance (in the form of torque τ_r) follows the change in angle of the shearer's hip flexion. It can be seen that torque is provided to the motors whenever the shearer is bent at the hips. Since GCAD combines GC and AD it was expected to provide more torque than the other assistive modes during the shearing task. This was confirmed by the torque time integral (TTI) for each assistive mode as given in Table 2. The Transparent and AD assistive modes have somewhat similar

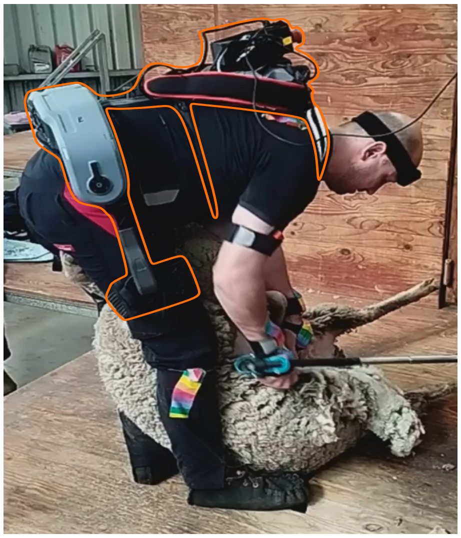

Figure 5: Expert user shearing with the exoskeleton and Xsens sensors. The exoskeleton is traced in orange, not shown in the image is how the shoulder and chest strap connect at the front.

values due to the built-in friction compensation of the actuators in Transparent mode and the quasi-static nature of the shearing task (in terms of hip flexion), not adding considerable torque on top of that friction compensation. However, it should be noted that the task was completed faster with the AD assistive mode.

Assistive mode	**TTI per sheep** $(N \cdot m \cdot s)$
No exo	0.0
Transparent	6.518×10^3
AD	5.655×10^3
GCAD	4.709×10^4

Table 2: TTI values of both exoskeleton joints for each condition for the entire task, including the catch-and-drag phase.

The RoM for the lower limbs for each condition is visualized in violin plots. The RoM for flexion of the hips and knees is largely unaffected by the exoskeleton or the different assistive modes, as seen in Figure 9. Differences between conditions were expected for the remaining DoF of the hip and, as expected, the largest difference in RoM can be observed for the internal-external hip rotation (as seen in Figure 10) because this DoF is not present in the exoskeleton. Furthermore, there is notable asymmetry for hip abduction-adduction and hip rotation between the legs. An example of this asymmetry can be observed in Figure 8, where the shearer exhibits greater internal rotation of the right hip during shearing.

In addition to hip angles, the angles of the lumbar

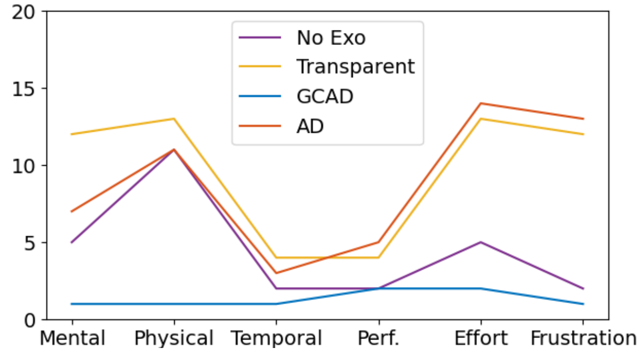

Figure 6: Results of the NASA-TLX evaluation of each condition. Rating of each dimension from Low demand (0) to High demand (20). Performance measure has been reversed according to NASA-TLX interpretation.

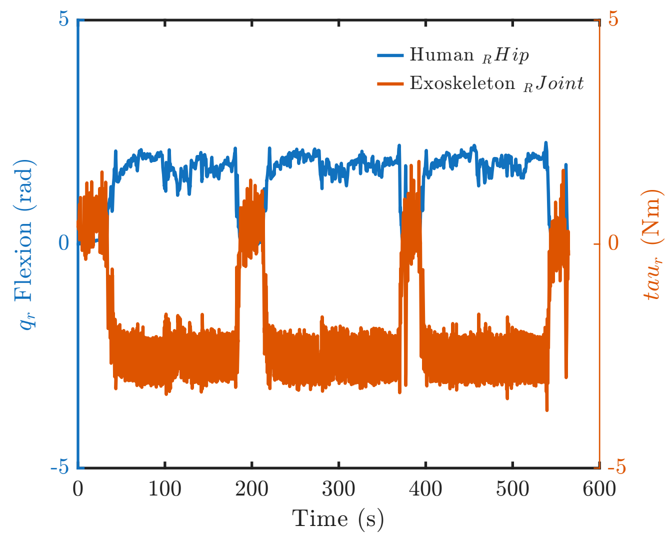

Figure 7: Biological hip flexion angle plotted with exoskeleton joint torque over time for GCAD assistance.

joints were expected to be affected by the introduction of the exoskeleton, since the rigid structure should restrict flexion regardless of the assistance mode. This is indeed reflected in Figure 11, where more negative angles represent higher flexion angles. It can be observed that the Transparent condition results in higher (more positive) angles, along with further reductions of the RoM when active assistance is applied.

Due to the introduction of damping, the exoskeleton was expected to affect not only the RoM of the shearer, but also the kinetics while providing assistance. The cyclograms plot the data points taken from when the shearer begins bending (which precedes the start of shearing) to when the shearer straightens out to the neutral pose after shearing. The data is plotted in Figure 12 for No Exo., Transparent and GCAD conditions to assess

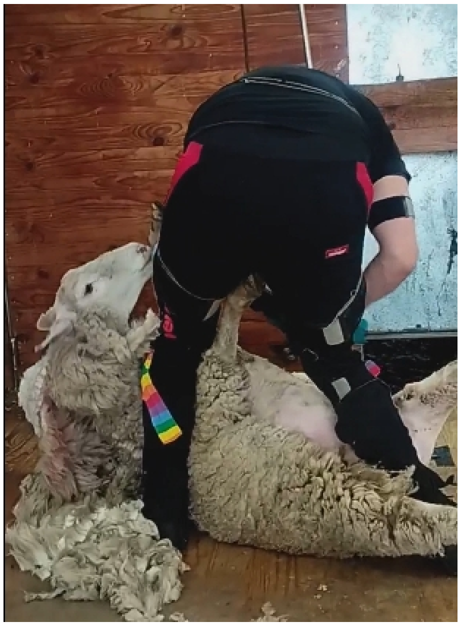

Figure 8: Shearer's posture exhibiting exaggerated internal hip rotation of the right leg. The shearer consistently adopts this posture for each sheep both with and without the exoskeleton (shown here without exoskeleton).

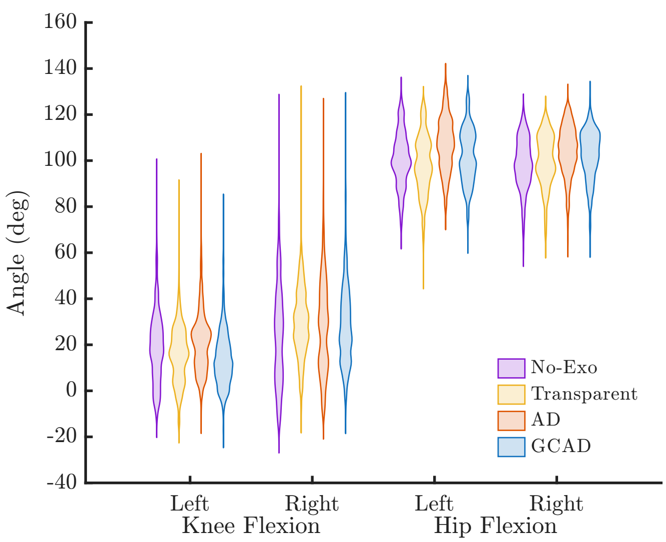

Figure 9: Violin plots of the knee and hip flexion angles of the expert during shearing for each assistive mode. Joint angles follow the International Society of Biomechanics (ISB) recommendations.

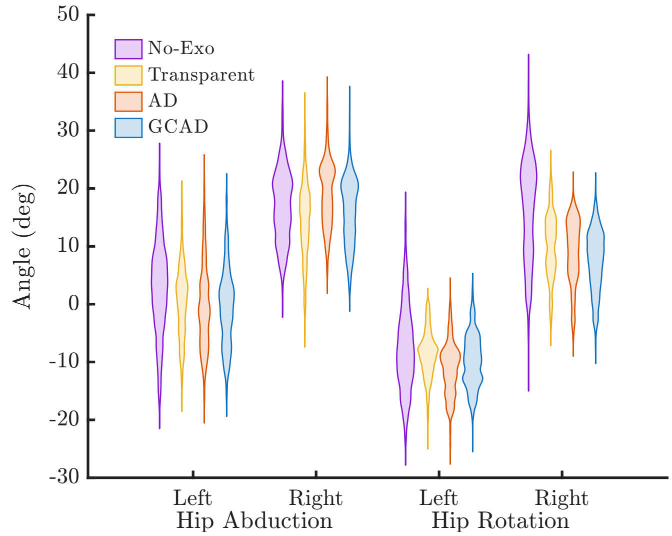

Figure 10: Violin plots of the hip abduction and rotation angles of the expert during shearing for each assistive mode. Joint angles follow the ISB recommendation.

the effect of the exoskeleton with and without active assistance compared to shearing without the exoskeleton.

5 Discussion

Overall, this first evaluation showed no incompatibility of the exoskeleton with the shearing task and the expert's evaluation suggests that a dedicated assistance might be suitable. Past the mechanical compatibility validation, user interest needs to be confirmed with additional users to provide more diversity in background and perception.

The kinematic results show that the knee and hip flexion is not greatly affected by the use of the device. Pronounced changes for the hip's internal and external rotation along with asymmetry between the left and right leg as a result of the asymmetric nature of the shearing task can be observed between the assistive modes. The exoskeleton has two active DoF for hip flexion-extension and two passive DoF for hip abduction-adduction, but none for internal-external hip rotation. Although the exoskeleton back is rigid, the thigh cuffs are not rigidly attached and interface with soft tissue at the attachment point, so some rotation is still possible.

Simply wearing the exoskeleton does appear to reduce the overall back flexion (see Figure 11) which can be explained by the rigid structure of the "backpack" and the load transfer to the legs. The passive effect of the device also led to reduced peak angular velocities of the hip and knee during shearing (Figure 12). The mass of the exoskeleton contributes to the total inertia and would thus require higher force production from the body's muscles to reach similar levels of acceleration and velocity, which could have led to these reduced velocities. These reduc-

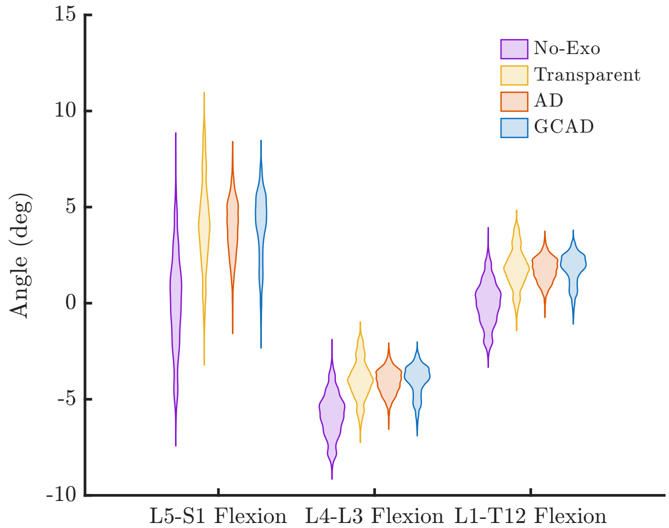

Figure 11: Violin plots for the flexion/extension angles of the lumbar spine segments. Negative values indicate increased flexion according to ISB recommended coordinate systems.

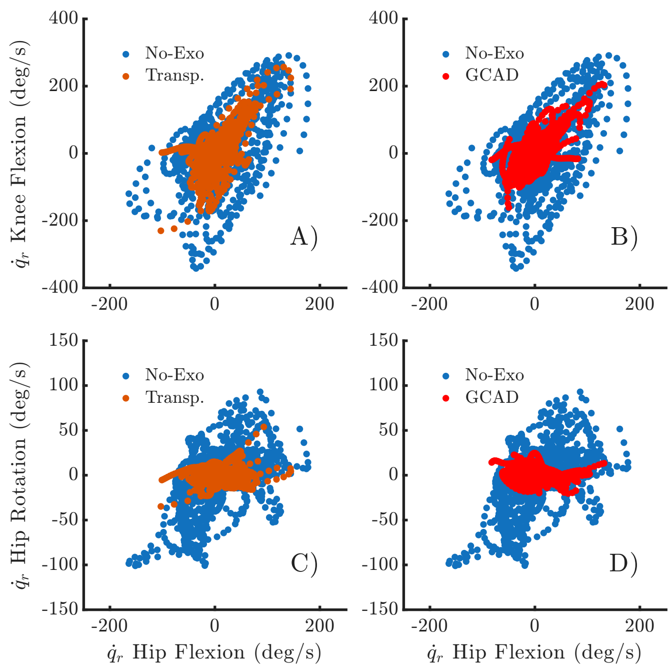

Figure 12: Various angular velocity cyclograms of the joints on the shearer's right leg. A) and B) compare the transparent and GCAD assistive modes respectively with No-Exo for the angular velocities of hip flexion and knee flexion. C) and D) compare the transparent and GCAD assistive modes respectively with No-Exo for the angular velocities of hip flexion and rotation.

tions are also more pronounced when GCAD assistance is applied, likely due to the presence of a damping term.

Overall, the kinematic data reflects reductions in the shearer's freedom of movement while wearing the exoskeleton, but the qualitative assessment seems in favour of the GCAD assistive mode, hinting at an acceptable trade-off between movement and assistance with a hip exoskeleton.

To confirm this, further evaluations with electromyography measurements of the trunk and leg muscles should be conducted to evaluate how the GCAD assistive mode may reduce physical effort and muscle fatigue in sheep shearing.

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References

[AWI, 2017] AWI. The australian wool supply chain. *Australian Wool Innovation*, 2017.

[AWI, 2018] AWI. Annual report 2017-18. *Australian Wool Innovation*, 2018.

[Carmody, 2010] S. Carmody. Sheep's back to mill. *Australian Wool Innovation Technical Report*, 2010.

[Davis, 1989] F. Davis. Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly*, pages 319–340, 1989.

[Fong *et al.*, 2020] J. Fong, E.B. Küçüktabak, V. Crocher, Y. Tan, K. Lynch, J.L. Pons, and D. Oetomo. CANopen robot controller (corc): An open software stack for human robot interaction development. In *Int'l Symp on Wearable Robotics*, pages 287–292, 2020.

[Gmeinder, 1986] G.E. Gmeinder. Back complaints among shearers in western australia: A pilot study. *Aust J Physiother*, 32:139–144, 1986.

[Gregory *et al.*, 2009] Diane E. Gregory, Carla Laughton, Allan Carman, Stephan Milosavljevic, and Jack P. Callaghan. Trunk postures and peak and cumulative low back kinetics during upright posture sheep shearing. *Ergonomics*, 52(12):1576–1583, 2009.

[Hart and Staveland, 1988] S. Hart and LE. Staveland. Development of NASA-TLX (task load index): Results of empirical and theoretical research. In *Advances in Psychology*, volume 52, pages 139–183. 1988.

[Hudson, 1987] P. R. W. Hudson. High technology options for sheep shearing III: Chemical and biological defleecing. *Outlook on Agriculture*, 16(2):68–76, 1987.

[Huysamen *et al.*, 2018] K. Huysamen, M. de Looze, T. Bosch, J. Ortiz, S. Toxiri, and L. O'Sullivan. Assessment of an active industrial exoskeleton to aid dynamic lifting and lowering manual handling tasks. *Applied Ergonomics*, 68:125–131, April 2018.

[Kermavnar *et al.*, 2021] Tjaša Kermavnar, de Vries , Aijse W., de Looze , Michiel P., , and Leonard W. O'Sullivan. Effects of industrial back-support exoskeletons on body loading and user experience: an updated systematic review. *Ergonomics*, 64(6):685–711, June 2021. Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/00140139.2020.1870162.

[Lazzaroni *et al.*, 2019] M. Lazzaroni, S. Toxiri, D. Caldwell, S. Anastasi, L. Monica, E. De Momi, and J. Ortiz. Acceleration-based Assistive Strategy to Control a Back-support Exoskeleton for Load Handling: Preliminary Evaluation. In *2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR)*, pages 625–630, June 2019.

[Miura et al, 2018] K. Miura et al. The hybrid assisted limb (HAL) for Care Support, a motion assisting robot providing exoskeletal lumbar support, can potentially reduce lumbar load in repetitive snow-shoveling movements. *J. Clin. Neurosci*, 49:83–86, March 2018.

[Pal *et al.*, 2008] P. Pal, D. Gregory, S. Milosavljevic, A. Carman, and J. Callaghan. A review of risk factors associated with low back injury in wool harvesting. *J. Occup. Health Saf. Aust. NZ.*, 24:435–453, 2008.

[Robinson *et al.*, 2020] M. Robinson, L. Lu, Y. Tan, K. Goonewardena, D. Oetomo, and C. Manzie. Enabling context-aware data analysis for long-duration repetitive stooped work through human activity recognition in sheep shearing. In *Procs. Int'l Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, pages 87–90, 2020.

[Robinson *et al.*, 2021] M. Robinson, Y Tan, K Goonewardena, D Oetomo, and C Manzie. Evaluation of ceiling-supported back harnesses in preventing injury in sheep shearing. In *Int'l Conf. IEEE Eng. in Med. Biol. Soc. (EMBC)*, pages 6957–61, 2021.

[Robinson *et al.*, 2023] M Robinson, L Lu, Y Tan, D Oetomo, and C Manzie. Feature identification framework for back-injury risk in repetitive work with application in sheep shearing. *IEEE Trans Biomed. Eng.*, 70:616–627, 2023.

[Trevelyan, 1992] J. P. Trevelyan. *Robots for shearing sheep: Shear magic*. 1992.

[Wioland *et al.*, 2019] L Wioland, L Debay, and JJ Atain-Kouadio. Processus d'acceptabilité et d'acceptation des exosquelettes: évaluation par questionnaire. *Références en Santé au Travail*, 160:49–76, 2019.

A Task-related injuries and difficulties

- What are some hazards (physical) of your occupation? (list)
  `lower back, disc issues, rounded shoulders, golfers elbow, loss of shape of spine, wrist tendinitis, blister, bad knees, inflammation, swelling soreness, tight hamstrings and hips flexors, carpal tunnel`

- Do you have an history of work related injuries? (describe)
  `wrist tendinitis left and right, loss of shape spine`

- During shearing activity, are some part of your body hurting? List each body part, frequency of pain (all the time, every shearing day, some shearing day, some time) and rate the level of pain.
  `lower back during shearing: belly wool, undermine backbone, last side`

- Based on your expertise as a trainer, what part of body shearers complain about? List body parts and frequency of occurrence (every shearer, most than half shearers, some shearers)
  `lower back, slip discs, wrist tendinitis every 1-2 year`

- What existing strategies have you used or seen other used to limit these issues? List strategies and your estimated efficacy.
  `strength training up to individual, hot/cold treatment up to individual`

B Device perception and expectations

I have already used an exoskeleton for my work in the past. YES $\boxed{NO}$

I have already been offered to use an exoskeleton for my work in the past. YES $\boxed{NO}$

In an ideal world, what would you like the exoskeleton to do?
`minimise back pain, comfort spinal back flexion, supporting while moving down (increased resistance as you go down)`

"I think the exoskeleton will help me shearing faster."

Strongly Disagree | $\boxed{\textit{Disagree}}$ | Neutral | Agree | Strongly Agree

"I think the exoskeleton will help me shearing for longer."

Strongly Disagree | Disagree | Neutral | $\boxed{\textit{Agree}}$ | Strongly Agree

"I think the exoskeleton will reduce physical strain."

Strongly Disagree | Disagree | Neutral | $\boxed{\textit{Agree}}$ | Strongly Agree

"I think the exoskeleton will reduce the effort required for my work."

Strongly Disagree | Disagree | Neutral | $\boxed{\textit{Agree}}$ | Strongly Agree

"I think the exoskeleton will increase my mental load."

Strongly Disagree   Disagree   Neutral $\boxed{\textit{Agree}}$ Strongly Agree

What would convince you to use the exoskeleton for shearing?
`reduce injury, longevity on the job, endurance, coolness`

What would encourage others to use it?
`longevity on the job, reduce injury`

What would prevent you to use it or prevent other to use it?
`contact with sheep on legs, the butt mesh`

Do you anticipate any problems integrating this device into a typical shearing workday?
`strapping`

What would you change about the device to be able to use it? List any relevant changes.
`add padding on leg cuffs, remove butt mesh/strap`

C Donning/doffing, fitting and comfort evaluation

"The device is easy to don."

Strongly Disagree   Disagree   Neutral $\boxed{\textit{Agree}}$ Strongly Agree

"The device is easy to adjust."

Strongly Disagree   Disagree   Neutral $\boxed{\textit{Agree}}$ Strongly Agree

"The device is comfortable."

Strongly Disagree   Disagree   Neutral $\boxed{\textit{Agree}}$ Strongly Agree

"The time to don/dof the device is problematic for my intended use."

Strongly Disagree $\boxed{\textit{Disagree}}$ Neutral   Agree   Strongly Agree

"I (would) require assistance to don/dof the device."

Strongly Disagree $\boxed{\textit{Disagree}}$ Neutral   Agree   Strongly Agree

“The device impedes my movements (when turned off).”

Strongly Disagree   Disagree   Neutral $\boxed{\textit{Agree}}$ Strongly Agree

“The device obstructs me from using or wearing work-related gear. (Which ones?)”

Strongly Disagree $\boxed{\textit{Disagree}}$ Neutral   Agree   Strongly Agree

“I could wear this device for the full work-day.”

Strongly Disagree   Disagree   Neutral $\boxed{\textit{Agree}}$ Strongly Agree

“The device is easy to dof.”

Strongly Disagree   Disagree   Neutral   Agree   Strongly Agree

What would prevent you to use it or prevent other to use it?

`may impede hips movement at lower position, shoulder straps restricting undermine access, straps friction (40 blows/sheep!), velcro can't be use in sheds`

What would you change about the device to be able to use it? List any relevant changes.

`butt mesh to remove, could use eyelet on jeans to directly attach to`

D Evaluation of assistive strategies

D.1 Virtual Wall (VW)

“The VW assistance is safe.”

Strongly Disagree   Disagree   Neutral   Agree $\boxed{\textit{Strongly Agree}}$

“The VW assistance is comfortable to wear.”

Strongly Disagree   Disagree   Neutral   Agree $\boxed{\textit{Strongly Agree}}$

“The VW assistance obstructs me from completing my tasks.”

$\boxed{\textit{Strongly Disagree}}$ Disagree   Neutral   Agree   Strongly Agree

Optional: Agree: In what way(s) does it obstruct the completion of your task?

`No, I can even push through wall`

"The VW assistance assists me in completing my tasks."

Strongly Disagree   Disagree   *Neutral*   Agree   Strongly Agree

Optional: Agree In what way does it assist you in the completion of your tasks?

"I would use the VW assistance mode for my occupation."

Strongly Disagree   *Disagree*   Neutral   Agree   Strongly Agree

"I could use the VW assistance mode for the full work-day."

Strongly Disagree   *Disagree*   Neutral   Agree   Strongly Agree

"I would recommend the use of the VW assistance mode to shearers."

Strongly Disagree   *Disagree*   Neutral   Agree   Strongly Agree

"It is easy to understand what the VW assistance does."

Strongly Disagree   Disagree   Neutral   Agree   *Strongly Agree*

"The VW assistance match with my expectations of what the device should do."

Strongly Disagree   *Disagree*   Neutral   Agree   Strongly Agree

"I anticipate that the VW assistance can eliminate or reduce work-related injuries and physical complaints."

Strongly Disagree   Disagree   Neutral   *Agree*   Strongly Agree

What changes would you make to make to improve the VW assistance?

`Support earlier but let you go past, help geting back up`

D.2 Gravity Compensation (GC)

"The GC assistance is safe."

Strongly Disagree   Disagree   Neutral   *Agree*   Strongly Agree

“The GC assistance is comfortable.”

Strongly Disagree | Disagree | Neutral | $\boxed{\textit{Agree}}$ | Strongly Agree

“The GC assistance obstructs me from completing my tasks.”

$\boxed{\textit{Strongly Disagree}}$ | Disagree | Neutral | Agree | Strongly Agree

Optional: Agree: In what way(s) does it obstruct the completion of your task?

“The GC assistance assists me in completing my tasks.”

Strongly Disagree | Disagree | Neutral | $\boxed{\textit{Agree}}$ | Strongly Agree

Optional: Agree In what way does it assist you in the completion of your tasks?
`support extension of spine`

“I would use the MG assistance mode for my occupation.”

Strongly Disagree | Disagree | Neutral | $\boxed{\textit{Agree}}$ | Strongly Agree

“I could use the GC assistance mode for the full work-day.”

Strongly Disagree | Disagree | Neutral | Agree | $\boxed{\textit{Strongly Agree}}$

“I would recommend the use of the GC assistance mode to shearers.”

Strongly Disagree | Disagree | Neutral | $\boxed{\textit{Agree}}$ | Strongly Agree

“It is easy to understand what the GC assistance does.”

Strongly Disagree | Disagree | Neutral | Agree | $\boxed{\textit{Strongly Agree}}$

“The GC assistance match with my expectations of what the device should do.”

Strongly Disagree | Disagree | Neutral | $\boxed{\textit{Agree}}$ | Strongly Agree

"I anticipate that the GC assistance can eliminate or reduce work-related injuries and physical complaints."

Strongly Disagree   Disagree   Neutral   *Agree*   Strongly Agree

What changes would you make to make to improve the MG assistance?

`need to fight to go down, goes up a bit too fast`

D.3 Combination (GCAD)

"The GCAD assistance is safe."

Strongly Disagree   Disagree   Neutral   *Agree*   Strongly Agree

"The GCAD assistance is comfortable."

Strongly Disagree   Disagree   Neutral   *Agree*   Strongly Agree

"The GCAD assistance obstructs me from completing my tasks."

Strongly Disagree   Disagree   Neutral   Agree   Strongly Agree

Optional: Agree: In what way(s) does it obstruct the completion of your task?

"The GCAD assistance assists me in completing my tasks."

Strongly Disagree   Disagree   Neutral   Agree   *Strongly Agree*

Optional: Agree In what way does it assist you in the completion of your tasks?

`support on flexed back work and extension is comfortable and takes thought of it`

"I would use the GCAD assistance mode for my occupation."

Strongly Disagree   Disagree   Neutral   *Agree*   Strongly Agree

"I could use the GCAD assistance mode for the full work-day."

Strongly Disagree   Disagree   Neutral   *Agree*   Strongly Agree

"I would recommend the use of the GCAD assistance mode to shearers."

Strongly Disagree   Disagree   Neutral   *Agree*   Strongly Agree

"It is easy to understand what the GCAD assistance does."

Strongly Disagree   Disagree   Neutral $\boxed{\textit{Agree}}$ Strongly Agree

"The GCAD assistance match with my expectations of what the device should do."

Strongly Disagree   Disagree   Neutral   Agree $\boxed{\textit{Strongly Agree}}$

"I anticipate that the GCAD assistance can eliminate or reduce work-related injuries and physical complaints."

Strongly Disagree   Disagree   Neutral $\boxed{\textit{Agree}}$ Strongly Agree

What changes would you make to make to improve the GCAD assistance?

D.4 Overall

Is there one assistance you think is more useful/beneficial?
`GC and GCAD`

"None of these assistance will be helpful for the work."

$\boxed{\textit{Strongly Disagree}}$ Disagree   Neutral   Agree   Strongly Agree

"All these assistance can be helpful for the work."

Strongly Disagree   Disagree   Neutral $\boxed{\textit{Agree}}$ Strongly Agree

"The device is comfortable to wear."

Strongly Disagree   Disagree   Neutral $\boxed{\textit{Agree}}$ Strongly Agree

"The device impedes my movements (when turned off)."

Strongly Disagree $\boxed{\textit{Disagree}}$ Neutral   Agree   Strongly Agree

"The device obstructs me from using or wearing work-related gear. (Which ones?)"

Strongly Disagree $\boxed{\textit{Disagree}}$ Neutral   Agree   Strongly Agree

"I could wear this device for the full work-day."

Strongly Disagree | Disagree | Neutral | $\boxed{\textit{Agree}}$ | Strongly Agree

What would prevent you to use it or prevent other to use it?
`chaffing, donning/doffing if you shear on your own, social pressure, judgement`

Do you anticipate any problems integrating this device into a typical shearing workday ?
`going through saloon doors, batteries life, sheep contact`

What would you change about the device to be able to use it? List any relevant changes.
`more shoulder padding for chaffing, padding on legs for sheep contact`

E Post questionnaire

Is there one assistance you think is more useful/beneficial?
`GCAD (''cloud'') is the more useful, would need more tuning levels.`

"None of these assistance will be helpful for the work."

$\boxed{\textit{Strongly Disagree}}$ | Disagree | Neutral | Agree | Strongly Agree

"All these assistance can be helpful for the work."

$\boxed{\textit{Strongly Disagree}}$ | Disagree | Neutral | Agree | Strongly Agree

"I would likely change the assistance settings/parameters during a working day."

Strongly Disagree | $\boxed{\textit{Disagree}}$ | Neutral | Agree | Strongly Agree

"The device is easy to use."

Strongly Disagree | Disagree | Neutral | $\boxed{\textit{Agree}}$ | Strongly Agree

"The device is comfortable to wear."

Strongly Disagree | Disagree | Neutral | $\boxed{\textit{Agree}}$ | Strongly Agree

"The device impedes my movements."

Strongly Disagree | $\boxed{\textit{Disagree}}$ | Neutral | Agree | Strongly Agree

"The device obstructs me from using or wearing work-related gear. (Which ones?)"

$\boxed{\textit{Strongly Disagree}}$ Disagree Neutral Agree Strongly Agree

"I could wear this device for the full work-day."

Strongly Disagree Disagree Neutral $\boxed{\textit{Agree}}$ Strongly Agree

What would prevent you to use it or prevent others to use it?

`hard to done solo but can hang on wall to done`

Do you anticipate any problems integrating this device into a typical shearing workday ?

`bumping , snagging, jammed in saloon doors, contact with downtube of handpiece, left leg contact with sheep`

What would you change about the device to be able to use it? List any relevant changes.

`improve straps`

"I would recommend other shearers to use the device."

Strongly Disagree Disagree Neutral $\boxed{\textit{Agree}}$ Strongly Agree