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Integrating Automatic Force Assistance Configuration with Mixed Reality for Active Exoskeletons

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Abstract— **Work-related musculoskeletal disorders are highly prevalent in physically demanding industries due to manual material handling tasks such as lifting, hauling, and carrying heavy loads. Occupational exoskeleton technology has emerged to help mitigate these injuries. Exoskeletons are wearable devices that replicate the structure of the human body to enable mechanical interaction between the user and the system. Active exoskeletons use powered actuators and sensors to provide versatile and adaptive assistance for demanding tasks. However, a gap remains in user interaction and intuitive control for these systems. Human-computer interaction technologies, including mixed, virtual and augmented reality, offer novel solutions to enhance user interaction and enable intuitive, customisable control strategies for active exoskeletons. This study integrates mixed-reality technologies with the XoTrunk active occupational exoskeleton to enable parameter tuning and system calibration through immersive interfaces. Two alternative mixed-reality interfaces were developed for this purpose: one that relies on manual user input and the other that incorporates computer vision for automatic adjustment. Experiments involving 15 participants were conducted to evaluate interfaces by performing setup and operational activities while wearing the XoTrunk exoskeleton. The results showed that the automatic interface achieved a higher System Usability Scale score (84.83/100) compared to the manual interface (78.5/100), indicating improved user acceptance and intuitiveness.**

I. INTRODUCTION

Industries such as transportation, manufacturing, healthcare and social assistance, retail trade, agriculture, and construction have the highest rates of work-related musculoskeletal disorders (WMSDs) [1]. Manual material handling (MMH) activities are recognised as a significant contributor to WMSDs. It involves physically demanding tasks, such as lifting, hauling, and carrying heavy items, exposing workers to low back and shoulder pain [2]. In this scenario, occupational exoskeletons present a potential solution for decreasing physical workload and fatigue [3].

An exoskeleton is a wearable device that mimics the structure of the human body with links and joints corresponding to human joints and limbs, enabling the direct transfer of mechanical power and information signals between the human and the machine [4]. Passive exoskeletons operate without powered actuators, relying instead on mechanical components such as springs, elastic bands, or counterbalance mechanisms to redistribute and support loads, thereby reducing muscular effort during specific tasks. In contrast, active exoskeletons incorporate powered actuators, such as electric motors or hydraulic systems. These last dynamically assist user movements by exerting controlled forces, enabling adaptable support that can be modulated in real-time tasks or user input demands [5].

This technical distinction results in simpler passive systems with fewer control requirements but limited adaptability, whereas active systems offer potential for enhanced, customisable assistance [5]. According to Poliero in [6], versatile active exoskeletons allow for multiple control strategies appropriate to different tasks, addressing limitations of passive exoskeleton designs.

Worker acceptance is also critical, as concerns about ease of use, comfort, and peer acceptance can hinder successful adoption; involving workers in the decision-making process can help mitigate these issues [7]. What if some domains of active exoskeletons are opened to the user to reduce the gap in terms of ease of use, comfort, and adoption? Human-computer interfaces (HCI) [8] is a field that provides a method to reach versatile control strategies for active exoskeletons. Emerging technologies, such as virtual reality (VR) [9], Mixed Reality (MR) and Augmented Reality (AR), can bridge the gap between user intent and system response. This HCI improves interaction within users and active exoskeletons, enabling users to customise control strategies more intuitively with the system.

This research presents the assessment of two novel interfaces developed in this work: the Virtual Reality Adaptive Force Assistance (VR-AFA) interface and the Virtual Reality Command User Interface (VR-UCI). Both interfaces were designed as a mixed reality application and integrated to interact with the XoTrunk active occupational exoskeleton. These systems provide a novel method of user interaction through MR, adapting the control strategy according to the scenario. The VR-AFA aims to automatically adapt the force assistance using computer vision techniques, reducing the workflow process when interacting with XoTrunk. Experiments were conducted with 15 subjects using the following methods: a) VR-UCI and b) VR-AFA interfaces to perform standard lifting tasks and XoTrunk control modification strategy. The paper is structured as follows: First, we present the motivation of this study with a brief description of our research laboratories. The method, system, and metric

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assessments used in the study are described in Section II. Section III presents the experimental evaluation, participants, and design of the experiment. Section IV presents the results of the VR-HCI assessment. Finally, Section V presents the conclusions and future work.

A. Motivation

We are the Wearable Robots, Exoskeletons, and Exosuits Laboratory (XoLab) and the VICARIOS Mixed Reality and Simulations Laboratory at Istituto Italiano di Tecnologia (IIT). XoLab develops back-support exoskeletons such as XoTrunk [10] to help workers reduce the risk of MSDs and assist workers during overhead tasks, thereby reducing MMH-associated fatigue. The VICARIOS Lab conducts research aimed at enhancing human interaction in remote and virtual environments. The group focuses on enabling real-time immersive interaction in telerobotics by integrating mixed reality (MR) interfaces [11] and extended reality (xR) [12]. At the begining of XoLab's roadmap, user interaction was achieved through an exoskeleton manager, usually a researcher in charge of adjusting and modifying the exoskeleton's parameters using a command-in-line interface (CLI). Granting users access to certain control domains in current active industrial exoskeleton systems is crucial. However, since the user is operating a powered mechanical device (as XoTrunk), ensuring that this access is provided safely, with appropriate limitations on specific actions, is essential to prevent misuse or unintended behaviour. XoLab and VICAROS Lab understand the importance of intuitive, useful, and safe user-interaction experiences between operators and exoskeletons. We aim to integrate novel applications with mixed-reality systems into our exoskeletons. The academic contribution of this work relies on the integration of MR technologies for exoskeleton user-interaction interfaces, thereby reducing the gap of access to the exoskeleton's domains and improving comfort and performance.

B. State of the art

Literature with regard to the integration of VR systems with exoskeletons has been widely explored across various application domains. Integration systems between VR and exoskeletons for haptics applications are found in [13] and [14]; both works proposed a lightweight, wearable hand exoskeleton system that provides force feedback for VR applications.

Rehabilitation technologies combining VR and exoskeletons have a wider number of studies, such as Frisoli et al. [15], who designed and clinically evaluated the upper-limb exoskeleton L-Exos, which integrates a VR application for post-stroke patients. Abbate et al. in [16] presented a mirror therapy system that integrates VR and a soft actuated hand exoskeleton to enhance the recovery of hand motor impairment.

Finally, VR systems and exoskeletons for industrial applications, in the work of Karvouniari [17] is presented a VR framework for manufacturing lines to optimise their design, evaluate workplace fit, and train operators safely.

This work closes existing gaps in adaptive interaction and control by introducing two mixed-reality interfaces for the XoTrunk exoskeleton, one employing computer vision for automatic adjustment.

II. METHODS AND MATERIALS

A. System description

1) Active Industrial Exoskeleton XoTrunk: It is a lower back occupational exoskeleton designed to assist users in MMH tasks by providing physical support and aligning the device's kinematic chain with the user's biological joints, particularly around the hip and trunk areas (see Fig. 1-A). It features a shoulder vest, belt, shoulder pads, and leg wraps that anchor the system to weight-bearing body parts, ensuring comfort and mechanical efficiency [10]. The exoskeleton contains two brushless DC motors that apply forces of up to $30Nm$. The XoTrunk control strategy is described in the following equation:

$$\tau_{acc} = K_{acc}(R^{nb}f^{b})_x M_{ub} L_{ub} \tag{1}$$

where τ_{acc} is the torque signal applied to the motors, K_{acc} is the accelerometer gain from the inertia measurement unit (IMU) sensor, $(R^{nb}f^{b})_x$ is an inverse rotation matrix constructed after the exoskeleton calibration, that rotates a vector from the navigation frame n to the body frame b; M_{ub} is the user's upper body mass, and L_{ub} is the user distance between the hip and the centre of mass. This acceleration-based strategy adapts the assistive torque in real-time to the user's trunk acceleration to better assist during dynamic phases of lifting, improving the exoskeleton's responsiveness and user experience. A comprehensive explanation of Eq. (1) can be found in [18].

2) Virtual-Reality User Command Interface (VR-UCI): Although the overall application operates in a Mixed Reality context, the user interfaces themselves (VR-UCI and VR-AFA) are fully immersive and designed within a Virtual Reality environment. The VR-UCI is a GUI based on the affordable adaptive setup system: the User Command Interface (UCI), presented in [19] and adapted for the VR headset (see Fig. 1-B). The VR-UCI interface provides a user-friendly platform for users to access and modify parameters related to the exoskeleton's operation, such as task-specific configurations (exoskelton calibration and force assistance control) and user profiles. User weight and height registration must comply with the control strategy shown in Eq. (1). The interface includes design features such as menus, submenus, cards, and decks to facilitate user interaction and task execution. All actions must be performed by the user without a guide.

3) Virtual-Reality Adaptive Force Assistance (VR-AFA): The VR-AFA is a GUI designed for MR applications that shows a virtual assistant (avatar) that guides the user through text dialogs the XoTrunk's setup process (see Fig. 1-C). First, the assistant requests the user to calibrate the exoskeleton by standing up and not moving for a short time. Then, the avatar indicates the user to provide the weight and height

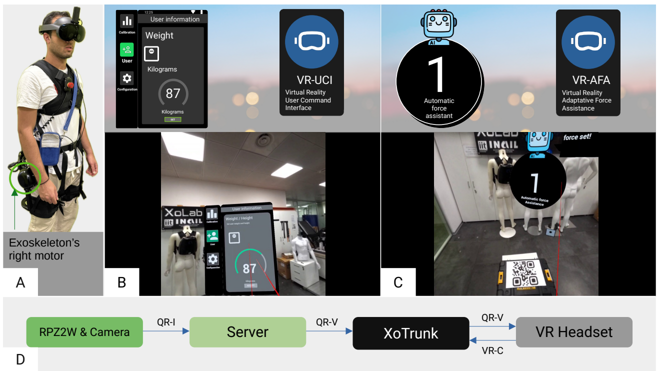

Fig. 1: Exoskeleton and MR setup. A: XoTrunk exoskeleton and the HTC Vive Pro eye VR-headset. B: VR-UCI interface GUI. C: VR-AFA interface GUI. The upper image corresponds to the rendered version of the interface GUI, and the lower image corresponds to the VR-headset point of view. D: Block diagram of the setup system; each element is conected via WIFI; arrow abbreviations are QR code image (QR-I), QR code value (QR-V), and VR user commands (VR-C).

used in M_{ub} from Eq. (1). Finally, the virtual assistant shows that the system is ready to identify the weight value of the boxes to lift, using a videocamera that is reading QR codes. Once the QR code on the box is identified, the exoskeleton's force assistance (K_{acc} in Eq. (1) is automatically modified to provide proper modulation during the lifting task.

4) Virtual-Reality Headset and Environment: The werable headset used was the HTC Vive Pro Eye VR-headset (see Fig. 1-A) with motion controllers, an integrated Tobii Eye Tracking system with an accuracy of 0.5–1.1° and a trackable field of view (FOV) of 110°. The VR-UCI and VR-AFA GUI were designed using the Unreal Engine (UE). A Raspberry Pi Zero 2W with a videocamera is mounted in the top of the VR headset to identify the QR code.

B. Assessment metrics

The assessment metrics used in this study were selected based on standardised criteria from the user-centred evaluation framework for wearable robotic devices (WRDs), as provided by the Interactive Usability Toolbox (IUT) [20].

After-Scenario Questionnaire (ASQ). This 3-item tool assesses user satisfaction immediately following the completion of a scenario in usability studies. Each item is rated using a 7-point Likert scale ("Strongly agree" at 1 and "Strongly disagree" at 7) [21].

Change in Perception Survey (CPS). The evaluation tool presented in [22] captures whether the user perceives a change in the assistive force when the overall gain of the exoskeleton controller is adjusted. The change may be perceived as an increase or decrease in force, either relative to a previous configuration or from the baseline (zero-assistance) condition defined as transparency mode.

Comfort Rating Scales (CRS). It is a set of six separate 21-point scales designed to assess the comfort of wearable computers across six dimensions: (a) emotion, (b) attachment, (c) harm, (d) perceived change, (e) movement, and (f) anxiety. Each scale ranges from 0 to 20, anchored by "low" and "high" labels, where users rate their agreement with specific descriptive statements related to each comfort aspect [23].

HAR Usability Scale (HARUS). This is a 16-item questionnaire designed to evaluate the usability of handheld augmented reality (HAR) applications by measuring two key factors: (a) manipulability (ease of handling the system) and (b) comprehensibility (ease of understanding the presented information). Users rate their agreement with each statement on a 7-point Likert scale, resulting in a final usability score ranging from 0 to 100 [24].

NASA Task Load Index (NASA-TLX). A multi-dimensional scale designed to estimate the workload experienced by task-performing operators. It consists of six subscales: (a) mental, (b) physical, and (c) temporal demand; and: (d) frustration, (e) effort, and (f) performance. The participant rated each of the six subscales immediately after the task performance. The scale uses a weighting scheme of 10 graduation scales (from "very low" to "very high") [25].

Net Promoter Score (NPS). This is a single-question survey tool used to measure patient experience by asking how likely a respondent will recommend a service, application, or product [26].

System Usability Scale (SUS). This is a reliable 10-item usability assessment tool for research and industrial evaluations. It rates on a 5-point Likert scale (from "Strongly Disagree" to "Strongly Agree") and includes both positively and negatively worded statements to ensure careful consideration [27].

User Fatigue Survey (UFS). The study used a subjective symptoms questionnaire consisting of 7-item to evaluate visual fatigue and related discomfort. Each question is rated on a scale from 0 to 4, with higher scores indicating greater severity [28].

III. EXPERIMENTAL EVALUATION

A. Participants

Fifteen healthy participants (weight: 70.1 ± 22.3 kg, height: 1.63 ± 0.49 m) with no history of low-back pain were part of the experiment. Among the participants, four wore glasses while viewing a screen, four had no prior experience with VR systems, and six had no prior experience with exoskeletons. The experiment was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Liguria (protocol no.: CER Liguria 001/2019).

B. Experiment design

The experimental design structure is presented in Fig. 2. There are two adaptable setup systems to assess: (a) VR-UCI and (b) VR-AFA. Each adaptable setup system performs three activities: (1) calibration, (2) user information registration, and (3) standard lifting. Results are presented as post-activity (results obtained immediatelly after performing the activity), dedicated set (results related to one of the two

VR interfaces at the end of the three activities), and post-experiment (results obtaind after completing the experiment).

First, each participant wears the XoTrunk exoskeleton and the VR headset. Next, the participant uses the interface to calibrate the exoskeleton, during which the system corrects motor bias based on the torque sensor data. The user then manually enters their weight and height. Afterward, the participant performs the standard lifting sequence three times with different K_{acc} values (see Fig. 3), adjusting these values manually. Upon completing each activity, the participant immediately fills out the post-activity questionnaires (ASQ, NASA-TLX, and TCT). After completing activity 3, the participant additionally completes the CPS. Once all three activities are finished for each VR interface condition (VR-UCI and VR-AFA), the participant completes the HARUS, NPS, and SUS questionnaires. Finally, at the end of the experiment, participants respond to the CRS and UFS questionnaires.

The standard lifting sequence has been presented in [18] and [29], it consists of a five-step sequence, as depicted in Fig. 3. To begin, the participant stands in front of an elevated weight (50 cm height from ground); then, the participant bends over and grasps the weight (1 kg); next, lifts the weight up to chest height; then, bends over and releases the weight; and finally, stands up in front of the weight. The sequence is performed three times with the same weight and same K_{acc} value (this is one trial), this activity allows the participant to use the exoskeleton in a controlled environment, resulting in a better perception of the change in force assistance modulation. In the first standard lifting trial, the participant uses a K_{acc} value of 0.0 to experience the exoskeleton in transparency mode with no force assistance. In the second trial, the gain is set to $K_{acc} = 0.1$; thus, the participant experiences a low level of force assistance modulation. Finally, the controller is set to $K_{acc} = 0.2$ to provide a moderate force assistance modulation

Second, the participant repeats the previously described activities; however, the second VR interface (VR-AFA) is used in this trial. The VR-AFA interface guides the participant during the user information calibration and registration. Finally, it automatically detects the weight of the box to be lifted by scanning the QR code placed on top of the box. The camera reads the QR code and automatically adjusts the exoskeleton controller's K_{acc} force assistance modulation when the participant looks at it. The QR codes contain the following values: $1, 2$, and 3 kg. The accelerometer gain K_{acc} is adjusted to $0.0, 0.1$, and 0.2 when the QR code values are detected. The participant is requested to answer the above-mentioned questionnaires and proceed to remove the exoskeleton.

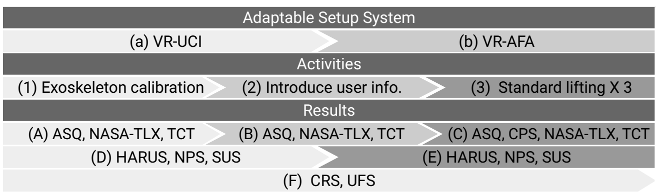

Fig. 2: Experimental design structure. Two adaptable assessment setup systems: (a) VR-UCI and (b) VR-AFA. Three activities to perform: (1) calibration, (2) user information registration, and (3) standard lifting. Results are divided into post-activity (A, B and C), dedicated set (D and E), and post-experiment (F).

IV. RESULTS

The average participant time for the experiment was $41\,\text{min}$. The results are shown in three levels: a) post-activity, b) dedicated set, and c) post-experiment results. All statistical studies were conducted with 15 participants ($n = 15$). Results IV-A.1, IV-A.2, IV-A.3, IV-B.1, IV-B.2, IV-C.1, and IV-C.2 are categorised as subjective, while IV-A.4 are objective results.

A. Post-activity

1) After-Scenario Questionnaire: The internal consistency assessment using Cronbach's alpha which returned a value of $\alpha = 0.975$. For the ASQ standard score, the lower the rating, the better the score. A Wilcoxon signed-rank test was performed to compare the three activities (calibration, user information input, and configuration) and there were no statistically significant differences when comparing the following ASQ attributes (see Table I). Abbreviations in Table I: A = ASQ task, I = interface, E = task ease, T = task time, D = task documentation, U = VR-UCI, F = VR-AFA, and S = sum of signed ranks and probability.

TABLE I: After-Scenario Questionnaire

A	I	Calibration	User info.	Configuration
E	U	2.26 ± 2.01	2.46 ± 2.06	2.53 ± 2.03
E	F	2.06 ± 2.25	2.6 ± 2.16	2.33 ± 2.43
E	S	$V = 10$,$p = 0.57$	$V = 26$,$p = 0.9$	$V = 16$,$p = 0.73$
T	U	2.13 ± 2.09	2.26 ± 2.05	2.4 ± 2.16
T	F	2.20 ± 2.21	2.46 ± 2.19	2.46 ± 2.47
T	S	$V = 5$,$p = 1.0$	$V = 22$,$p = 1.0$	$V = 15$,$p = 0.86$
D	U	2.8 ± 2.0	2.8 ± 1.85	2.86 ± 1.95
D	F	2.0 ± 2.1	2.46 ± 2.19	2.33 ± 2.16
D	S	$V = 28$,$p = 0.15$	$V = 36$,$p = 0.4$	$V = 31$,$p = 0.3$

2) Change in Perception: Participants reported a change in perception during lifting task activities when using VR-UCI and VR-AFA. Activity "Standard lifting I" was conducted with a $K_{acc} = 0.0$, indicating transparency mode. The force assistance was adjusted to $K_{acc} = 0.1$ and $K_{acc} = 0.2$ for "Standard lifting II" and "Standard lifting

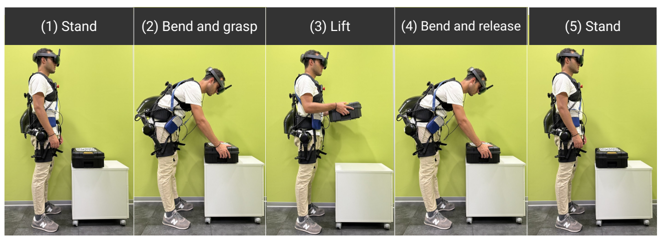

Fig. 3: The standard lifting five steps sequence.

III", respectively. Table II shows that all participants using the VR-UCI platform perceived a change in force assistance that differs from the transparency mode ($K_{acc} = 0.0$). All participants using VR-AFA perceived a change in force assistance for $K_{acc} = 0.2$.

TABLE II: Change in Perception Survey

Activity	Force assist. gain	VR-UCI	VR-AFA
Standard lifting II	$K_{acc} = 0.1$	80.0%	93.3%
Standard lifting III	$K_{acc} = 0.2$	86.6%	100.0%

3) NASA Task Load Index: The scale demonstrated an internal consistency coefficient (Cronbach's alpha) of $\alpha = 0.887$. Fig. 4 presents the NASA-TLX results. A Wilcoxon signed-rank test was conducted across three activities (calibration, introducing user information, and configuration) and there was no statistically significant difference when comparing the following NASA-TLX attributes: (a) average mental demand between the VR-UCI (2.06 ± 1.7) and VR-AFA (1.8 ± 2.12) interfaces, $V = 34.5$, $p = 0.17$; (b) average physical demand between the VR-UCI (1.71 ± 1.85) and VR-AFA (1.55 ± 1.45) interfaces, $V = 19$, $p = 0.44$; (c) average temporal demand between the VR-UCI (1.33 ± 0.79) and VR-AFA (1.22 ± 0.37) interfaces, $V = 10$, $p = 1.0$; (d) average performance between the VR-UCI (7.28 ± 3.31) and VR-AFA (7.55 ± 3.75) interfaces, $V = 16$, $p = 0.46$; (e) average effort between the VR-UCI (1.86 ± 1.42) and VR-AFA (2.13 ± 2.4) interfaces, $V = 31$, $p = 0.75$; and (f) average frustration between the VR-UCI (2.0 ± 2.0) and VR-AFA (1.24 ± 0.52) interfaces, $V = 25$, $p = 0.07$. Abbreviations in Fig. 4: U-1 = VR-UCI Activity 1, U-2 = VR-UCI Activity 2, U-3 = VR-UCI Activity 3, A1 = VR-AFA Activity 1, A-2 = VR-AFA Activity 2, and A-3 = VR-AFA Activity 3.

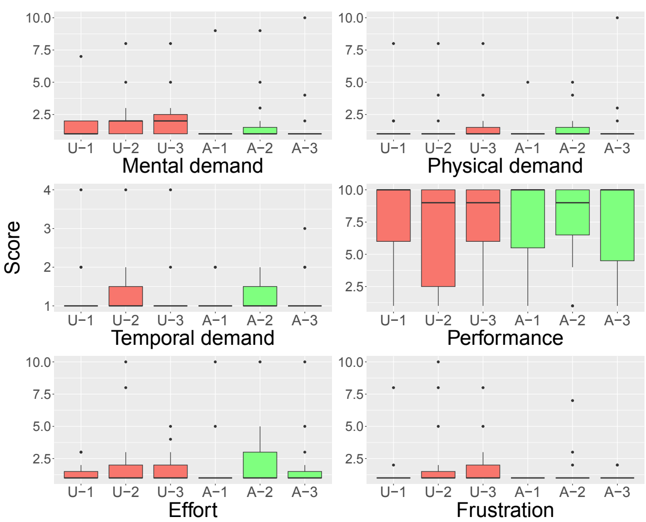

Fig. 4: NASA TLX scores. Comparison of the VR-UCI and VR-AFA interfaces in terms of six attributes. Calibration (Activity 1), registration of user information (Activity 2), and configuration (Activity 3).

4) Task Completion Time: Fig. 5 presents the TCT scores of each activity (calibration, user information input, and configuration). Activity 3 (configuration), was splitted in two parts: (a) the configuration (where the user manually adjust the accelerometer gain when using VR-UCI, or automatically set when using VR-AFA) and (b) the standard lifting. As seen in Fig. 5, activities (3-a, 3-c, and 3-e) represent the time taken by the participants to configure the accelerometer gain (K_{acc}) when using VR-UCI first and automatically set when using VR-AFA. Activities (3-b, 3-d, and 3-f) represent the time taken by participants to perform the standard lifting. This analysis discriminated the standard lifting time because this activity does not directly affect the user–exoskeleton interaction. A paired t-test showed no statistically significant difference when comparing the following task completion times: (a) exoskeleton's calibration between VR-UCI (15.0 ± 6.09) and VR-AFA (14.4 ± 4.88), $t(14) = 0.40$, $p = .69$, 95% $CI[-2.65, 3.85]$; (b) user information registration between VR-UCI (48.8 ± 19.09) and VR-AFA (48.8 ± 17.45); $t(14) = -0.01$, $p = .991$, 95% $CI[-12.43, 12.29]$. Next, a Wilcoxon signed-rank test showed no statistically significant difference in task completion times: (c) exoskeleton's configuration trial 1 (Activity 3-a) with $K_{acc} = 0.0$ between VR-UCI (11.6 ± 6.5) and VR-AFA (17.2 ± 12.5); $V = 35.5$, $p = .17$. Then, a paired-samples t-test showed a statistically significant difference in completion time: (d) exoskeleton's configuration trial 2 (Activity 3-c) with $K_{acc} = 0.1$ VR-UCI (7.9 ± 2.7) and VR-AFA (14.8 ± 6.5); $t(14) = -4.20$, $p < .001$, 95% $CI[-10.47, -3.40]$, with VR-AFA interface taking significantly longer. Finally, a Wilcoxon signed-rank test indicated a statistically significant difference in task completion time (e) exoskeleton's configuration trial 3 (Activity 3-e) with $K_{acc} = 0.2$ VR-UCI (7.8 ± 4.6) and VR-AFA (13.8 ± 8.3); $V = 21.5$, $p = .03$, with VR-AFA interface taking significantly longer. Abbreviations in Fig. 5: U = VR-UCI and A = VR-AFA.

B. Dedicated set

1) Handheld Augmented Reality Usability Scale: To ensure internal reliability, Cronbach's alpha was calculated, with a resulting coefficient of $\alpha = 0.498$. Table III

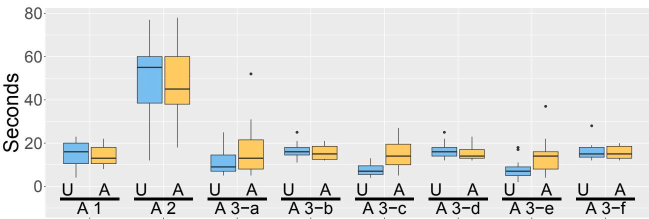

Fig. 5: The task completion time scores of each activity for VR-UCI and VR-AFA interfaces. Calibration (Activity 1), user information registration (Activity 2), Configuration 1st trial (Activity 3-a), Standard lifting 1st trial (Activity 3-b), Configuration 2nd trial (Activity 3-c), Standard lifting 2d trial (Activity 3-d), Configuration 3rd trial (Activity 3-e), and Standard lifting 3rd trial (Activity 3-f) were performed.

shows the HARUS scores. The VR-AFA interface registered higher scores than the VR-UCI. A paired-samples t-test was conducted and there was no significant difference in scores when comparing HARUS usability scores between the two interfaces: (a) total HARUS between VR-UCI (88.93 $\pm$ 8.59) and VR-AFA (90.83 $\pm$ 8.29), $t(14) = -1.71$, $p = .11$, 95% $CI[-4.30, 0.49]$; (b) "Manipulability" subscale of the HARUS between VR-UCI a(89.05 $\pm$ 10.38) and VR-AFA (90.24 $\pm$ 11.49), $t(14) = -0.77$, $p = .45$, 95% $CI[-4.53, 2.15]$; (c) "Comprehensibility" subscale of the HARUS between VR-UCI (88.81 $\pm$ 8.16) and VR-AFA (91.43 $\pm$ 7.3), $t(14) = -2.01$, $p = .064$, 95% $CI[-5.41, 0.17]$. Nomenclature for Table III: HS_{min}: HARUS score minimum, HS_{max}: HARUS score maximum, HS_{tot}: HARUS score total, "Man.": Manipulability, and "Com.": Comprehensibility.

TABLE III: Handheld Augmented Reality Usability Scale Survey

Interface	HS_{min}	HS_{max}	HS_{tot}	Man.	Com.
VR-UCI	69.64	100	88.93	89.05	88.81
VR-AFA	70.54	100	90.83	90.24	91.43

2) Net Promoter Score and System Usability Score: Cronbach's alpha was used to determine the instrument's internal reliability, which indicated a value of $\alpha = -0.255$. Table IV presents the NPS and SUS results. The VR-UCI interface reported an NPS and SUS score of 26.6/100 and 78.5/100, respectively. The VR-AFA interface registered NPS and SUS scores of 66.6/100 and 84.83/100, respectively. A Wilcoxon signed-rank test showed a significant difference in SUS scores between the two interfaces, $V = 10$, $p = 0.02$, suggesting that participants rated the interfaces' usability differently.

TABLE IV: Net Promoter Score and System Usability Score Survey

Interface	SUS_{min}	SUS_{max}	SUS_{tot}	NPS
VR-UCI	50	100	78.5	26.66
VR-AFA	57.5	100	84.83	66.66

C. Post-experiment

1) Comfort Rate Scale: The reliability of the scale was evaluated using Cronbach's alpha, resulting in a coefficient of $\alpha = 0.932$. Fig. 6 presents the results of the CTS survey. The highest rated score for XoTrunk and the VR-Headset was "Attachment" with a mean value of 4.73 ± 2.40 and 2.6 ± 2.87, respectively. The lowest rated score for XoTrunk and the VR-Headset was "Emotion" with a mean value of 0.53 ± 0.91 and 0.8 ± 1.42, respectively.

2) User Fatigue Survey: Table V shows the UFS results. The maximum and minimum scores represent a single score for each symptom. The attribute clear vision recorded the highest rated symptom as in "too clear" vision after the experimental protocol. Half of the participants reported having experienced fatigue equal to or below the average symptom

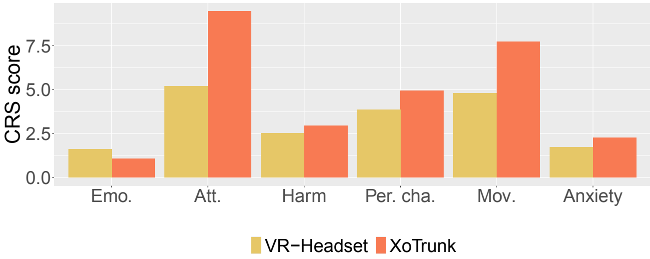

Fig. 6: Comfort rating scores for the occupational active exoskeleton XoTrunk and the VR-Headset HTC Vive Pro Eye. Abbreviations: Emo. = Emotion, Att. = Attachment, Per. cha. =Perception of change, and Mov. = Movement.

score. Nomenclature for Table V: A & B: average and below average.

TABLE V: User Fatigue Survey

Symptoms	Max	Min	Mean	SD	A & B
Tired eyes	3	0	0.733	0.883	46.6%
Clear vision	3	1	2.666	0.617	26.6%
Eye dryness	2	0	0.600	0.736	53.3%
Tired back	3	0	0.733	0.961	53.3%
Tired neck	3	0	0.333	0.816	80.0%
Severe headache	3	0	0.266	0.798	86.6%
Sleepy feeling	2	0	0.266	0.593	80.0%

V. CONCLUSIONS AND FUTURE WORK

Active exoskeletons are more adapted to specific MMH tasks. Using emerging technologies, such as mixed reality systems, we provide a bridge for user interaction between the operator and the exoskeleton. The VR-UCI and VR-AFA interfaces presented a solution to calibrate, register user information, and configure the XoTrunk exoskeleton in a demanding scenario where the exoskeleton rquires a configuration platform. Participants best rated the "Task documentation" attribute from the ASQ survey for the VR-AFA interface when performing exoskeleton calibration. Users may had a positive user experience when the VR-AFA avatar guided the activity. In the CPS results, most participants reported a change in perception for the second trial of configuration and standard lifting with $K_{acc} = 0.2$ when the force assistance was slightly higher. However, in the NASA TLX results, participants reported a higher degree of temporal demand and effort in Activity 2 (user information registration) when using the VR-AFA interface, suggesting that the interaction was less effective and the task needed more user attention. The participants experienced a significant time lapse during the second and third trials when configuring the exoskeleton's gain (K_{acc}). This was because the detection time of the camera to recognise the QR code value and set it to XoTrunk was longer. Users rated the VR-UCI and VR-AFA interfaces highly on the HARUS scale, indicating good usability. Nevertheless, VR-AFA had a higher comprehensibility rating, suggesting that it may have offered a more intuitive user experience. The

SUS scores for VR-AFA were higher than those for VR-UCI, suggesting a greater degree of usability for VR-AFA. Participants rated VR-AFA with a higher recommendation level in the NPS survey. Participants reported a high score in attachment and movement attributes for XoTrunk in CRS results, which suggests a lack of fit with users' body and movement restriction. User fatigue scores showed a slightly skewed distribution, with 46% of participants scoring below the mean; this suggests that most users experienced a degree of visual fatigue during the session. In the future, we plan to eliminate the use of VR controllers during the sessions, making all the activities, such as using QR codes or visual elements to accomplish them, visual dependent.

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