Exoskeletons and Augmented Reality: Opening Pathways to Improved Coordination in Collaborative Tasks

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Abstract. Exoskeletons are designed to enhance users' strength in physically demanding tasks, such as lifting and carrying heavy objects. Despite increasing physical ability, exoskeletons can introduce mechanical constraints on joint articulation, restricting certain movements. These limitations can reduce the range of motion, alter natural movement patterns, and decrease agility. This can particularly impair collaborative tasks that require movement coordination. Since industrial applications of exoskeletons also involve teamwork, it is important to find ways to support users in maintaining coordination and mitigating the side effects that are introduced with exoskeletons. To explore solutions to this problem, we developed a system that integrates AR-based motion guidance to assist users wearing exoskeletons in collaborative object-handling tasks. Our approach leverages immersive visualizations to facilitate coordination, assisting users in maintaining alignment and executing movements more smoothly. We conducted an exploratory study involving 40 participants, divided into pairs, to examine the feasibility and challenges of this approach. Our findings uncover key considerations for motion guidance evaluation in object collaborative handling tasks, the impact of the participants' pairing strategies, and technical challenges.

Keywords: Augmented Reality · Exoskeletons · Collaboration · User Evaluation

1 Introduction

Exoskeletons are increasingly used in the architecture, engineering, and construction (AEC) industry [2, 18, 40], offering a critical solution for tasks that demand more physical strength than human workers can naturally provide. They not only extend workers' physical capabilities but also help prevent injuries, especially during solo work [5, 32]. However, these benefits come with challenges: exoskeletons can restrict body movement, requiring workers to adapt how they perform tasks [3, 8, 33].

In collaborative tasks, where coordination between two or more individuals is required, the challenge becomes more significant For example, consider two workers carrying a long heavy metal bar through an environment with multiple physical constraints. In such tasks, if a worker applies an unforeseen and sudden force, it can disrupt coordination, potentially leading to accidents or injuries for their partner. Accounting for the restricted motion range due to the exoskeleton while coordinating with the partner could be daunting. Since use cases like this are common in the AEC industry, finding ways to overcome this problem is important.

Supporting users in adapting their movements—either via training or real-time guidance—can mitigate these risks. Immersive technologies like Augmented and Virtual Reality (AR/VR) have been widely applied in training [26, 28], health [10, 17], and sports [7]. However, existing literature primarily focuses on individual use cases [6, 27], leaving a gap in addressing movement coordination for collaborative tasks. Current research also focuses more on body movement without considering external influences, such as when the person is carrying or handling an object. While VR offers a more controlled environment [24], AR enables users to remain aware of their surroundings, making it well-suited for real-world, collaborative tasks involving exoskeletons. Since movement coordination is crucial in collaborative tasks with exoskeletons, we focus on bringing AR to support movement guidance for dyadic tasks.

With that in mind, our paper explores the question: *Can movement guidance in AR be helpful for users performing dyadic tasks while wearing exoskeletons?*. Our task is inspired by a common AEC scenario: two people carrying a metal bar through a path with obstacles. We compare three conditions: AR with exoskeletons (**AR+Exo**), exoskeletons alone (**Exo**), and no support (**Exo**), to examine AR's influence on movement and coordination. We designed different AR visualizations and conducted an exploratory study with 40 participants. We collected quantitative data from electromyography (EMG) sensors placed on the deltoid and trapezius muscles on both sides of the participants' bodies, as well as motion data from the object the participants were carrying. In addition, we also collected subjective feedback about the task load through questionnaires and general feedback through interviews. Our analysis is exploratory, aiming to uncover insights into ergonomics, cognitive load, and user experience. We consider these dimensions, aiming to uncover key insights into how AR can influence task performance rather than just strictly comparing performance in an isolated way. In that sense, our paper's contribution is twofold: (1) We introduce a novel use case and exploratory evaluation of immersive motion guidance in dyadic tasks with exoskeletons, analyzing its effects from physical strain, movement variability, and user experience perspectives. (2) We identify key challenges from technical and methodological perspectives, providing insights to guide future studies on immersive motion guidance in collaborative settings.

2 Related Work

The usage of exoskeletons in Biomechanical Engineering, Ergonomics, Medicine, and related fields has been well explored, targeting mainly applications such as body rehabilitation, human support for physical tasks, and construction scenarios. The research focuses on designing the devices and studying their impact on the body in different situations. Here, we list some of the most relevant works related to our use case. Similarly, Mixed Reality applications for movement guidance have been explored in areas like sports, muscle rehabilitation, and teleoperation. We briefly review the main findings that apply to our scenario.

2.1 Exoskeletons for Construction Tasks

Recent studies have highlighted the capabilities of different types of exoskeletons in the construction sector [11, 40]. However, all these studies have evaluated the advantages and disadvantages of exoskeletons within individual tasks. For instance, a comprehensive review reveals compelling evidence regarding the efficacy and effectiveness of upper limb exoskeletons designed for industrial use. These exoskeletons have shown significant potential in mitigating factors associated with the risk of Musculoskeletal Disorders [27]. Various studies have employed diverse approaches, such as the biomechanical method utilizing Electromyography (EMG) [20] and the psychological method involving Near-Infrared Spectroscopy [34]. In summary, the collective findings demonstrate the favorable outcomes and advantages of utilizing shoulder support exoskeletons for overhead individual tasks. However, more research is needed to investigate collaborative tasks. In such scenarios, each participant's movement is interconnected with their counterpart's actions, giving rise to the leader-and-follower relationship. For instance, in the transportation of objects, inadequate coordination can amplify safety hazards for the workers. Sudden, abrupt, or forceful movements, coupled with delayed reactions, harbor the potential to precipitate injuries.

In a recent study, researchers examined the collaborative process of installing ceiling panels within a modular construction factory, employing shoulder support exoskeletons [3]. The findings revealed that exoskeletons designed to aid the shoulders effectively delivered an ergonomic sense of relief during overhead positions. However, the study highlighted the absence of benefits in tasks requiring lower body and/or back support, as the exoskeleton's design posed limitations on dynamic movements. Another study examined the use of exoskeletons in collaborative tasks in the laboratory [22], evaluating subjective user feedback through metrics such as the Body Discomfort Scale and System Usability. The outcomes showed a favorable positive impact of these devices on user experience. In contrast, our work focuses on dyadic tasks, in which two workers work together and need to coordinate.

2.2 Mixed Reality for Movement Guidance

Motion guidance supported by immersive devices, such as head-mounted displays (HMDs), has gained increased attention in the past decade. Among the popular use cases where they have been studied, motion guidance for instructing physical activities has been explored a lot by the HCI community in applications such as general exercising [35], martial arts [37] and reahabilitation [31, 38]. In sports, for instance, precise body movement is an important aspect, and it needs to be repeatedly trained, which relies on the availability of physical space, time, and potentially a coach monitoring and correcting movements. Scenarios like this can benefit from immersive technologies, such as Virtual, Augmented, and Mixed Reality.

Movement guidance can be divided into different categories, and many works have dedicated their time to evaluating the differences between perspectives and granulation on feedback [36]. Yu et al. [35], for instance, analyzed how different perspectives could impact the usability of motion guidance systems, and they discovered that first-person or third-person perspectives should be adopted depending on the task. MR motion guidance has also been used for Yoga instructions [16], revealing benefits for novice users. The authors evaluated which of the guidance perspectives was more useful for correcting the poses. Other guidance scenarios include teaching music movements [29], motor learning [9], and mirror perspective studies [39].

Applications to support motion guidance in collaborative scenarios have also been explored in the literature and commercially. Dance Reality [4] is an application that allows users to visualize dance steps in situ. In this case, the users can replay the steps and practice with a dance partner. Kodama et al. [19] investigated a collaborative scenario where the teacher and learner control the avatar, performing the movement together. The authors concluded that learning in virtual co-embodiment with the teacher improves motor skill learning efficiency compared with sharing the teacher's first-person perspective or without the teacher.

In our scenario, we opted not to include a helper for simplicity, since it would add another dimension to the independent variables of our study. We also mixed a few different visualization strategies to support different user needs. So far, there is not a lot of investigation on the impact that handling objects can have on immersive motion guidance, which is an aspect we address in our use case.

2.3 Exoskeletons and Augmented Reality

We can highlight a few works that studied the integration of exoskeletons and AR headsets. Hazubski et al. [13] used AR glasses to control the visual prosthesis, capturing the user's behavior through the head position and a camera and using their input to control the movement of the prosthesis. Users also had visual feedback in real-time of the prosthesis position. Kong et al. [21] observed how

[4] https://www.dancereality.com/

we can use exoskeletons to support AR movement. The support was employed to reduce the strain on the muscles caused by having the upper limbs constantly move to operate gesture-based interactions.

Hidayah et al. [15] combined immersive motion and haptic feedback with exoskeletons for participants using a lower limb exoskeleton and analyzed its impact on the gait. The authors discovered that the visual support diminished the trajectory deviation and increased the normalized step height, indicating that AR can be useful for patients with gait impairment.

From a different perspective, AR has also been proposed as a support to avoid collisions of users wearing an exoskeleton [23]. This work proposed a computer vision approach to identify objects around users and notify them through an AR head-mounted display. The authors recognize that there needs to be more exploration of the visualization aspect of the support.

To the best of our knowledge, no work has yet explored the integration between AR and exoskeletons for motion guidance in a collaborative task. Our goal is to start filling this gap and investigate AR usage for collaborative exoskeleton usage when users need to coordinate their movement while minimizing the risk of physical injuries. We consider this work a first step into understanding the benefits of this integration.

3 An Interface for Immersive Movement Guidance in Collaborative Scenarios

Here, we present our AR-based interface for supporting motion guidance in collaborative scenarios in which users are wearing exoskeletons carrying a heavy object together. During the design process, many questions emerged: What kind of movement should be supported? What should the visualizations look like? How much support do users need? To address these questions systematically, we first identified key requirements that an effective AR-based motion guidance system should meet, which we describe below.

3.1 Requirements

With an iterative design process in mind, we analyzed previous work that evaluated exoskeletons [2, 20, 22] and the use cases that could be generalized to our interface. For simplicity, we will assume a metal bar as a placeholder for the object addressed in the collaboration, and we refer to it accordingly throughout the text, but this can be changed according to the needs of different use cases. From this analysis, we identified key requirements for our interface: the task should align with the physical constraints of the exoskeleton, support natural coordination between users, and provide clear motion guidance through AR. Here we describe the requirements in more detail:

Task design aligned with hardware. Based on the available exoskeleton model, we knew that targeting an example where an overhead movement was necessary would be ideal. We opted to support a situation where the users would have to carry an object together while lifting and lowering it, sometimes by showing the users the trajectory they would have to follow in space with AR. The overhead movement is also interesting for studying the collaboration between the participants since (depending on the size and weight of the object) it can affect an individual's balance and their peer in the case of a dyadic scenario. Yet, with a different type of support, the AR guidance can be adapted and still work in the same way, given the specific task requirements, making this requirement independent of the guidance.

Motion guidance in AR. Then, considering how to support the movement, we decided what kind of visualizations would be best for the users by testing them and implementing incremental improvements. We based our design decisions on previous research by implementing three first-person perspective visualizations [35] in a combination of static and dynamic feedback. Finally, we considered that an AR HMD would be the best alternative for displaying the guidance since it offers hands-free interaction.

Assessment of user experience and collaboration. To have a deeper understanding of how the support could alter the behavior of the users, we considered tracking the target object as a first measure. To make sure we could track an area large enough where participants could walk, we employed a camera-based motion capture system with a total of 8 cameras. Furthermore, we also wanted to observe how each individual would perform the task. Therefore, we decided to measure the muscle activation of the participants' trapezius and deltoid muscles through EMG sensors to see how they vary between the conditions. This is usually a metric used in previous evaluations with exoskeletons [22]. We considered tracking the body movement of each participant, but that would demand time and resources that were not easily available.

Determining the motion path. Since we decided to give guidance based on the object trajectory, we also needed to calculate the trajectory movement that the users should follow. Due to the complexity of calculating the next best movement based on the body position, we decided to simplify the setup, tracking only the object being carried and basing the calculation for the trajectory only on it. We acknowledge that our approach simplifies the guidance in a way, but given the complexity of our system, we decided to calculate the movement like this as a first step. Considering these metrics and the visual guidance, we had a system integrating 1) two AR head-mounted displays to provide guidance, 2) an EMG system to measure the muscle activation, and 3) a video-based motion capture system to track the object carried.

3.2 Visualization Design

We debated whether visualizations should be shared or individual, if they should be anchored to the HMD or the environment, and how best to compare different visualization strategies. These decisions were crucial to ensure effective guidance while maintaining spatial awareness and coordination between participants. We derived the answer to these questions after prototyping and testing the system with a few external users and with ourselves. As a result, we decided to have three different visualizations, each one for a different movement perspective: **Ghost Bar**, **Guidance Arrow**, and **Trajectory Dots**. Figure 1 illustrates the visualizations together in the final interface. The guidance arrows and dots were updated in real-time according to the bar's position, while the ghost bar visualization was static according to the predefined trajectory. Our choice here was mainly based on having different perspectives for the guidance: a dynamic approach targeted towards a single user, a dynamic one shared between the pair, and a static one based on the general trajectory, segmenting the task into shorter steps.

Fig. 1: Visualizations used for guidance of the movements. On the left side, the arrow is positioned above the real bar. On the right side, we can see the trajectory dots and ghost bars.

- **Ghost bar:** A series of semi-transparent geometries with the same size and shape as the original object being handled. For our use case, we are dealing with a metal bar, which is the one represented in Figure 1. Each one is positioned along the ideal trajectory over the space, from the starting position to the end position. We also attribute a sound to the visualization that is played whenever the ghost bar and the real one match positions. The ghost bars are displayed for both participants in the same way.
- **Guidance Arrow:** We include an arrow on each side of the object to give participants an individual first-view perspective. The arrows indicate the coordinates X, Y, and Z, and they gradually change colors (from red (furthest) to green (closest)) the closer the participants are to the correct position.
- **Trajectory Dots:** To give a better overview of the bar position, we display three dashed curves using small spheres along the trajectory: one positioned on each bar tip and one in the middle. The three curves reflect how well-balanced the object is being held. It also gives a better overview to one participant on how their partner is holding the bar.

3.3 Implementation

Since our setup was collaborative, we implemented a system that connected two Microsoft HoloLens 2 headsets simultaneously and updated the visualizations in real-time based on the object position, which was tracked by a Vicon camera-based motion capture (mocap) system. In the early stages of development, we used marker-based tracking, but the accuracy was too low, and it was more complicated to synchronize the position between the two devices and the bar.

To address these limitations, we implemented a server application that bridged the communication between the mocap system and the HMD, streaming the position of the shared object.

The server and the HoloLens applications were developed using Unity and a framework called Riptide [5] that handles the network connection. We used four markers that served as world anchors to synchronize the tracking coordinate system with the HoloLens. We placed four markers in a rectangular layout across the room to improve the tracking accuracy and reduce the error margin. By averaging all markers, we created a world anchor centered in the room. After scanning, we calculated the transformation between the marker and camera coordinate systems, aligning the HMD visualizations based on tracking information from the mocap system.

4 User study

To evaluate the impact of the AR movement guidance on collaborative scenarios with exoskeletons, we conducted a within-subject evaluation where users performed a physical task in pairs.

4.1 Methods

Scenario and tasks We propose a collaborative task involving two individuals who must work together to lift, carry, and position a 250 cm-long bar with a square cross-section measuring 15x15cm and weighing approximately 30 kg onto a metal structure. Because it is challenging to assess how physically fit each individual is, we also planned for a second bar weighing 15kg, with the same dimensions, made of wood, for participants who could not lift the metal one. We defined the tracking area of the scenario to be approximately 7x4m, given the tracking configuration we had available, but this requirement can be adjusted according to the space and number of cameras. The bar has to be transported following a trajectory from the starting point (**SP**) to an endpoint (**EP**) where it is securely placed. Throughout this trajectory, the participants must avoid an obstacle, adding complexity to manipulating the bar. After positioning the bar in the final position, the participants wait for 10 seconds and then proceed to pick it up again to return it to **SP**, doing the overhead movement throughout the whole path. A graphical description of the task is shown in Figure 2. While

[5] https://github.com/RiptideNetworking/Riptide

this task is physically specific, it captures common elements among a range of collaborative tasks: shared motor coordination, effort regulation, and mutual awareness. These elements are present in many joint activities, such as carrying objects together, assembling large parts, or assisting others during physical tasks. This task also allows us to test the effects of visual support under conditions where bodily coordination is critical, which can help identify principles that apply to physically intensive and collaborative contexts.

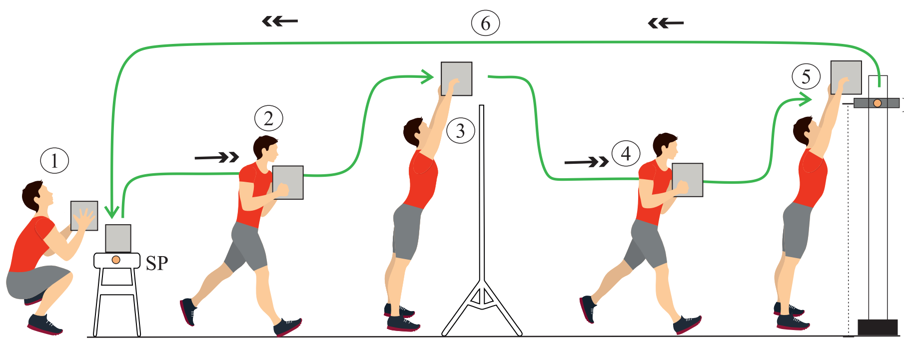


Fig. 2: Graphical representation of the setup (shown for one participant, but equivalent for both): The task begins from the starting point (SP), where a bar is positioned. Coordinating their movements, both participants transport the bar to an endpoint (EP) on a metal structure that can be adjusted to the height of the participant. We positioned an obstacle between SP and EP, represented in the middle of the figure, requiring participants to lift the bar above them.

Conditions and Randomization: Due to the physical nature of our task, there are unavoidable ordering effects based on physical exhaustion. We applied block randomization regarding the starting support condition to deal with these effects fairly and feasibly. Participant pairs were equally assigned to one of two groups. For the first half of the participants, all pairs conducted the conditions in the following order: **No Support**, **Exo**, and **AR+Exo**. The second half did the conditions in reverse order: **AR+Exo**, **Exo**, and **No Support**. We assigned participant pairs to one of the two groups according to their schedule availability. We tried to ensure balance in gender by having the same number of female participants in each of the groups.

The preparation of the participants was influenced by the condition they performed. Putting the exoskeleton on was tricky for some participants: depending on their body type, the straps had to be repositioned multiple times. Therefore, putting the exoskeleton on and off more than once during the study would lead to a longer session and more disturbance for the participants. Therefore, we decided on having participants doing the tasks in one of the following orders: 1) **No**

Support, **Exo** and **AR+Exo**, or 2) **AR+Exo**, **Exo** and **No Support**. Our counterbalancing strategy preserves the validity of our two main comparisons: (a) Conditions involving exoskeletons (**Exo** and **AR+Exo**) versus **No Support**. (b) The effect of AR within exoskeleton use (**AR+Exo** vs.**Exo**). This design ensured a fair distribution of conditions while minimizing setup errors and participant fatigue.

Measurements and Calculations:

Optimal Trajectory Calculation: To ensure participant safety, we analyzed shoulder and elbow movements to determine the maximum safe extension height. The complete extension or flexion of these joints is ergonomically incorrect and potentially hazardous when lifting heavy objects. We followed the ergonomic guidelines of the German Social Accident Insurance [6], which analyzed the acceptable joint angles of the body when it comes to work safety. Therefore, the target movement range was set below the maximum extension capabilities of the participants. Before starting the experiment, we measured participants' arm and forearm lengths, maximum shoulder height, and the highest point reached by the palm when the arm was raised parallel to the body. These measurements were used to compute a tailored trajectory and determine the corresponding obstacle height. To further ensure safety, a security margin of 15 cm was subtracted from the calculated trajectory height when setting the obstacle position.

Additional details on the trajectory computation are provided in the supplementary material [30].

Based on the length of their arms and the position of the bar, which was updated dynamically by the tracking system, we were able to calculate the safety angle of the elbow and shoulder joints for the movement we specified for our task. From the measured values, we obtained a range of the least dangerous ones for the rotation of the joints, and that is also why it was important to have participants of similar height. The full equation for the calculation of the angles can be found in the supplementary material [30]. If necessary, we can give a shorter version of the calculation in the main manuscript.

EMG Data Collection: We collected EMG data to individually asses how users perform, following prior works in biomechanics [1, 4]. As we do not perform in-depth fatigue analysis, we compare EMG metrics across participants to assess the effect of visual support on muscle use. We collected EMG data with a Trigno Avanti[7] wireless EMG system using EMGworks Acquisition software from the Delsys system. The surface sensors were placed on the left and right upper trapezius (*TpLf* and *TpRg*) and the left and right medial deltoid (*DtRg* and *DtLf*), according to SENIAM recommendations[14].

Questionnaires and Media Recording: We also recorded all audio and video material from the sessions. These served us to 1) double-check the behavior of the participants in case there was any noise in the collected data and 2) verify

[6] `https://www.dguv.de/medien/ifa/en/fac/ergonomie/pdf/evaluation_of_physical_work_load.pdf`

[7] https://delsys.com/trigno-avanti/

their level of verbal communication. In addition, we also asked the participants to complete the NASA TLX questionnaire after each condition was completed, and finally, a standard demographic questionnaire.

Study procedure: Upon arriving, the participants were introduced to the study description, with a brief presentation of the task. After that, we asked them to fill out the demographics questionnaire and took measures of their height and arm length. Since we measured the muscle activation of the participants, we needed to place and calibrate the sensors on their bodies before starting the task procedure. For each participant, we placed four sensors on their trapezius (2) and deltoid (2) muscles. Once the sensors were placed and calibrated, the participants performed the movement used to measure the Maximum Voluntary Contraction (MVC), which was later on used to normalize the muscle activation values during the data analysis. The placement and calibration of the sensors lasted for about one hour. Then, we did a demonstration of how the movement should be performed with the real bar and explained the details regarding the placement, number of repetitions, and conditions to them. After the explanation, according to their starting condition, they would or would not be equipped with the supporting devices before starting the task.

After doing 5 repetitions with each condition, they took a 10-minute break, during which they also filled out the NASA TLX questionnaire [12] for the respective condition. Each condition took about 20 minutes to be completed, including the break. This process was repeated 3 times, and then the experiment was concluded. We asked the participants to reserve 3 hours in total to do the study in case of technical issues.

Participant recruitment and pairing: To recruit the participants, we invited people using a university mailing list. We asked the participants to fill out a form with their availability and information about their gender and height. We assigned people to the time slots based on these two pieces of information: having the same gender and not having a large height difference. We also considered asking about their physical strength to help with the pairing procedure. However, we could not find a reliable way of assessing or confirming it. In total, we recruited 40 participants split into 20 pairs. From this group, we had to exclude six pairs from part of the analysis due to technical issues that prevented us from collecting data from all the sources in our system. Only the data from 14 pairs (28 participants) were considered in the analysis of the trajectory and EMG sensors. We still used the 20 pairs for the NASA TLX and also for the users' preferences on the visualizations, since they completed the whole experiment. The participants were not required to have any previous knowledge or experience.

Data processing: We excluded data affected by noise and technical issues, such as muscle activation exceeding 100% (based on MVC calculations). For the trajectories, we excluded any coordinates that fell outside the tracked area. We excluded data from every trial that presented noises, which meant some of the conditions for which we analyzed data had fewer than five repetitions per pair. For the EMG data, we analyzed muscle activation at different levels of granularity to better understand muscle behavior based on (1) the specific muscle and (2) sensor placement on each muscle; we call these **aggregation levels: general, by muscle and by sensor**.

Due to the differences in sensors' sampling rates in different participant pairs and each type of sensor, our study data collection time series (trajectory tracking and EMG data) have different lengths/sizes. To be able to compare the different participants and conditions, we perform a data upsampling which normalizes each timeseries to a fixed length, containing values at the exact same frame. More details on the calculation of the data upsampling can be found in the supplementary material [30].

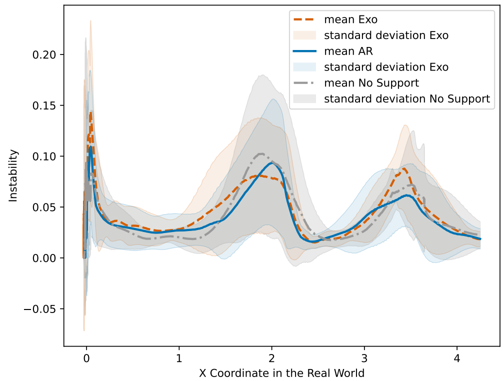
4.2 Results

Following the exploratory nature of our study, we took an inferential approach to analyze the EMG and trajectory data. We look at the average muscle activation values and the difference between the multiple movement trajectories performed by the users. We then illustrate the average values and confidence intervals as the basis of our analysis.

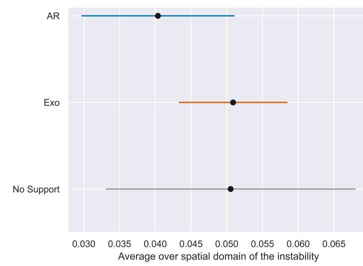
From the poll of participants, we had to exclude six pairs from part of the analysis due to technical issues that prevented us from collecting data from all the sources in our system. We also had to exclude a few trials within the repetitions, so not every condition had the 5 trials to be analyzed. We still used the 20 pairs for the NASA TLX and also for the user's preferences on the visualizations since they completed the whole experiment.

Demographics: Participants' ages varied between 18 and 46 years old, and the majority (71%) were between $18-25$ years old. Six of them identified as female, additionally 83% reported to be students, either from undergraduate or graduate levels. None of the participants had experience with exoskeletons. 52% of the participants reported no experience with AR, while 3 participants reported being experts on the topic. The average height was 179cm (STD = 8.63).

Trajectory: We focused the analysis of the trajectory of the bar for the **forward movement** since it was the one with the most variation due to the obstacles. Our results show that the variance of the movement between the 5 repetitions (instability) was lower for **AR+Exo** and **Exo** compared to **No Support**, with the visual support having a slight advantage over the **Exo** condition, as we show in Figure 3. The confidence intervals for each condition also support how participants using the **AR+Exo** performed the movement more steadily than the other two conditions, with lower average and upper and lower values.



(a) Mean and standard deviation of the instability for each spatial point. The lower the instability is, the better.

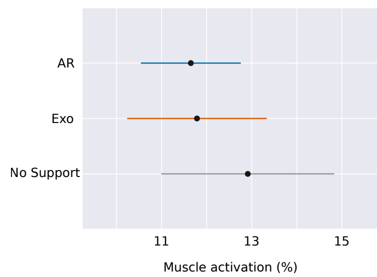


(b) Confidence interval of average over the spatial domain of the instability.

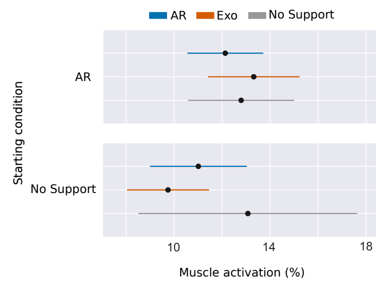
Fig. 3: Representation of the mean and standard deviation for the instability in (a) over time for the complete task movement through space. Confidence interval values are represented in (b). The **AR+Exo** condition shows a lower average deviation than the other two. **No Support** has a higher trajectory deviation and a larger confidence interval.

EMG: We employed the MVC normalization technique [25] to ensure uniformity and facilitate the comparison of muscle activity measurements for all participants. Afterwards, we calculated the confidence interval for all the sensors from both participants combined. From that, we observed that the **AR+Exo** condition registered slightly lower levels of muscle activation in general, as illustrated in Figure 4. Another interesting finding was related to the support provided to each individual muscle. We observed that the deltoid had more variance in the activation compared to the trapezius, very likely because of the exoskeleton support that we used for the study. Finally, we noticed that the muscle activation is lower for **No Support** when the starting condition was **AR+Exo**, which we believe can be attributed to the learning effect. We performed the analysis further, exploring different levels of aggregation, and to ensure full reproducibility, we provide the full description in the supplementary material.

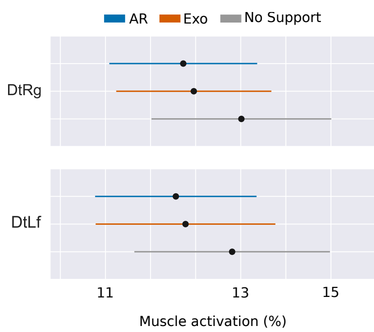
NASA TLX: To assess how the participants perceived the task load, we asked them to fill out the NASA TLX questionnaire after each condition. The NASA TLX questionnaire showed a similar response between **AR+Exo** and **Exo** conditions, but there was a higher average difference compared to **No Support**. We observed a higher Physical Demand of **No Support** (M_{ns} = 12.7) over **Exo** (M_{exo}=10.9), **AR+Exo** (M_{ar}=9.8), where the last one performed better. For Temporal Demand, **No Support** and **Exo** had similar scores (M_{ns}=7.4, M_{exo}=7.5), while **AR+Exo** scored higher (M_{ar}=8.5). This can be associated



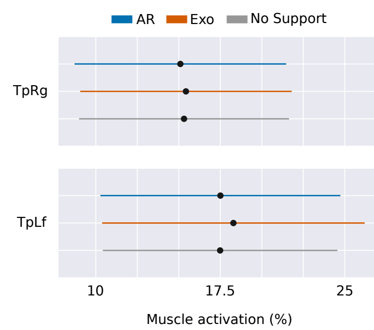
(a) General aggregation: all sensors from all participants



(b) General aggregation split by the starting condition



(c) Deltoid muscle sensors



(d) Trapezius muscle sensors

Fig. 4: Confidence intervals for the EMG activation values.

with the device sometimes blocking the other participant's view and the immersive content displayed, making them slower to adjust to the space, but also with participants being more mindful of their movement and taking longer to perform it. A similar effect can be observed in the Mental Demand category, where **No Support** and **Exo** scored similarly (M_{ns}=3.5 and M_{exo}=3.6), while AR scored higher (M_{ar}=4.8). Surprisingly, participants rated Frustration similarly (M_{ns}=4.3, M_{exo}=4.0, and M_{ar}=4.9) in all three conditions. Performance was also rated similarly through all conditions (M_{ns}=4.9, M_{exo}=4.3, and M_{ar}=4.6). Finally, participants rated their Effort slightly lower in the **Exo** condition than in **AR+Exo** and **No Support** (M_{exo}=8.6, M_{ar}=9.5, and M_{ns}=9.9). Figure 5 summarizes the results.

Communication: We recorded audio data during the study and took written notes about the participants' communication behavior. We observed no verbal communication between the participants during the task, except for one of the pairs. In this specific case, they were friends and mostly communicated about how they felt after completing the tasks. They did not talk about their movements or give instructions to each other. We noted that it was easier to coor-

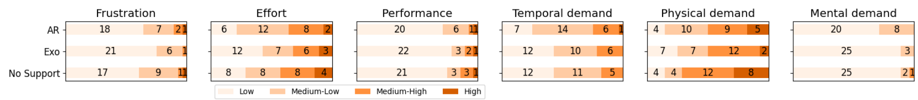


Fig. 5: Plots reflecting the results of the NASA TLX questionnaire for all three conditions.

dinate the movement between the already acquainted pairs, but this did not involve verbal communication during the task.

Preference for visualization guidance: Since we implemented three different visualizations to guide the participants' movement, we verbally asked if they felt the visualizations were helpful and which one was their favorite. In terms of preferences, participants (17/40) mentioned preferring the **Trajectory Dots** and **Ghost Bars** more than the **Guidance Arrow**. Two of them particularly mentioned being satisfied with the sound feedback whenever the real bar matched the ghost one. Five participants mentioned the arrow being too close to their faces, making it ineffective when performing the task. Four participants mentioned being confused by the amount of information displayed. They suggested that less visual clutter would be better, for example, reducing the number of dots in the trajectory visualization or the number of ghost bars. Five participants felt bothered about the visual clutter when positioning the real bar on the rack. They would prefer it if no ghost bars were shown in the final position.

One participant mentioned that they tended to forget that the bar should be kept overhead when doing the backward movement, since this was not the most comfortable pose for them. In this case, seeing the visualization helped them to remember the position and maintain coordination with their peer. A few participants also mentioned feeling discomfort when the tracking had some offset, and the visualizations had between 2 to 3 centimeters of displacement from where they should be. In these cases, we always recalibrated the system in the pauses between the conditions to reset the positions of the visualizations.

5 Discussion

We divide our discussion into two parts, by first analyzing the takeaways we can derive from the user studies results, followed by the lessons learned

5.1 Interpretation of the Results and Implications

According to the data analysis, we could observe that **AR+Exo** had an advantage over **Exo** and **No Support** in terms of movement accuracy and user preference, but it caused higher mental effort. This suggests that visual motion cues can support compensating for the movement constraints caused by the exoskeleton. Participants may have relied on these cues to better coordinate their actions and follow the intended trajectory, reducing errors in execution. However, it is important to consider whether this improvement is a result of enhanced spatial awareness or a shift in cognitive strategy. Further investigation should be done by evaluating different body movements, for example, in a less repetitive way.

While our EMG data did not reveal strong or conclusive trends in muscle activation, we observed some variability across participants, suggesting that movement strategies may have differed when following AR guidance. It is possible that some participants adjusted their muscle engagement in response to the visual cues. A further analysis of the ergonomic behavior could reveal more about their strategies, but it is out of the scope of this paper.

Our results align with previous literature that studied the benefits of using exoskeletons, where we also observed the benefits from the muscle activation and trajectory, and open the discussion to how visual guidance can also be beneficial to users, even if just for supporting the training of novice users.

5.2 Lessons Learned

Here we summarize the lessons learned through conducting our user evaluation.

Implementation and Technical Aspects

- **Combining tracking methods extends the workspace but requires frequent recalibration** Using Microsoft HoloLens for AR guidance introduced well-known tracking challenges. To mitigate this problem, we implemented a hybrid approach combining custom image markers and a camera-based motion capture system. While this expanded the workspace, it required complex marker arrangements and frequent recalibrations of the devices. Additionally, the HoloLens battery would from time to time get depleted mid-session, forcing repeated system resets and disrupting both the data collection and the participants who had to repeat the task. Future research should explore more stable tracking solutions to minimize interruptions in long sessions.
- **Exoskeleton Sizing Limitations Impact Comfort and Performance** Along the same lines as not having the best movement to evaluate the coordination between pairs, we also encountered issues when using an exoskeleton model with different participants. During the experiments, a single model and size of a commercial exoskeleton designed for a specific body type were used. Participants whose body dimensions deviated from this standard often experienced discomfort and inadequate support, making it difficult to use the device effectively. The bias of standard bodywork in industrial settings ended up being one of the weaknesses of our study; furthermore, it highlights the necessity of considering diverse body types when selecting exoskeletons in future studies to ensure that participants can engage with technology without these barriers.

– **Positioning visualizations while handling objects**
  Unlike traditional motion guidance techniques focusing on body movement in isolation, incorporating external objects adds more complexity to visualization design. Beyond body tracking, occlusion and positioning of visualizations need to be carefully considered. Guidance needs to be spatially aligned with the object while remaining visible from a first-person perspective. Our alternative to tackle this problem was to provide both static and dynamic visualizations, to counterbalance occasional occlusion caused by the environment and still ensure participants had easy access to the guidance, but this is definitely a design choice that needs to be further explored.

Design and Methodology

– **Estimating participants' fitness levels:** Physically demanding tasks require balancing the required effort from participants to prevent fatigue or withdrawal. Assessing participants' fitness levels, either through testing the participants beforehand, helps account for individual differences in strength and endurance. The variation of individual capabilities needs to be accounted for, including the differences that come with gender and age, since they affect fitness level and performance due to different factors, such as muscle mass and endurance. Tasks should be designed to avoid one-size-fits-all configurations, but still ensure comparability. Additionally, complementary feedback can provide a broader understanding of participant experience.
– **Challenges of collaborative object handling:** Motion guidance research often overlooks the complexities of handling external objects. Strength, coordination, and spatial awareness differences impact task execution, especially for inexperienced participants. To address these points, AR and other feedback modalities can be employed to facilitate synchronization and reduce the cognitive load on participants. Furthermore, the guidance design must consider ergonomics and ensure that the risk of strain or injury is minimized
– **Impact of participant selection and pairing:** Physical strength, communication style, native language, familiarity with the task, and prior experience collaborating can influence collaborative outcomes. Pairing compatible participants can improve task execution, while mismatches might bring up noise in the data. To mitigate this problem, future research should aim to have a variation of the pairing procedure to explore a broader range of interactions and document how pairing methods affect results to refine best practices.
– **Multimodal coordination in handling large objects:** Besides communication, gaze, and gestures, collaborative handling of large objects requires refined movement coordination, awareness of the partner's actions, and a shared understanding of the local surroundings. It also depends on body positioning, tactile feedback, and the anticipation of the next movements. Each person taking part in the task has to rely on the physical feel of the object to understand their partner's actions. Additionally, environmental factors such

as noise and occlusion can limit verbal and visual communication, making external support essential.

- **Measuring collaboration is a multidimensional problem** Choosing a single metric to measure how people coordinate in physical tasks is non-trivial. When designing the evaluation, we assessed individual effort (EMG, task load), group coordination (trajectory), and communication. Challenges arose from sensor limitations and tracking integration, highlighting the need for alternative approaches, therefore future studies should refine metric combinations.
- **Keeping participants engaged when having long sessions** Conducting long experiment sessions can feel straining to participants. Diminishing boredom, fatigue, and frustration is important not only to improve user experience but also to ensure a better quality of data. We offered participants regular breaks between each study condition and made sure to regularly ask the participants how they were feeling and if they were able to continue with the evaluation. Encouragement and positive feedback helped sustain engagement, creating a supportive environment and making repetitive tasks more manageable.

5.3 Limitations and future work

Besides the points already discussed in the previous section, the core part of our limitations lies in the complexity of integrating such different technologies in one evaluation. Synchronizing data from headsets, sensors, and a motion tracking system introduced additional challenges, and technical issues led to the exclusion of some participant pairs from the analysis. Another major constraint was the choice of metrics. While full-body motion capture could have provided deeper insights, it would have added complexity to participant preparation. To mitigate data loss, we recommend recruiting a higher number of participants as a buffer and continuously testing of the system components to minimize technical failures. We believe that the limitations that impaired the data collection are what prevented us from obtaining more meaningful results, both from the EMG and the trajectory data. Future work should explore diverse movements, task complexities, and AR support while bridging controlled experiments with real-world applications, ensuring methodological rigor and participant safety.

6 Conclusion

In this work, we studied the integration of AR support for guiding collaborative tasks using exoskeletons. We conducted a user study to evaluate our proposed use case, and through this process, we collected lessons learned that we hope can inspire the design of similar studies in the future. Considering previous works, we opened the path to bridge the gap existing between immersive motion guidance and the employment of exoskeletons for object-handling tasks. Our findings highlight both the potential and the challenges that we faced and present recommendations that can be applied in similar evaluations. The insights gained about coordination, visual support, and shared effort are relevant to a broader range of collaborative scenarios where synchronization and shared effort are required. Additionally, our study revealed practical limitations, such as when integrating multiple tracking technologies and measuring coordination in such settings. We hope our work serves as a foundation for refining motion guidance modalities and techniques and expanding the applicability of AR support in real-world scenarios.

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