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Towards a Multimodal System combining Augmented Reality and Electromyography for Robot Trajectory Programming and Execution

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Abstract— **Programming and executing robot trajectories is a routine manufacturing procedure. However, current interfaces (i.e., teach pendants) are bulky, unintuitive, and interrupts task flow. Recently, augmented reality (AR) has been used to create alternative solutions. However, input modalities of such systems tend to be limited. By introducing the use of electromyography (EMG), we have created a novel multimodal wearable interface for online trajectory programming and execution. Through the use of EMG, our system aims to bridge the user's force activation to the robot arm force profile. Our proposed system provides two interaction methods for trajectory execution and force control using 1) arm EMG and 2) arm orientation. We compared these methods with a standard joystick in a user study to test their usability. Results show that proposed methods have increased physical demands but yield equivalent task performance, demonstrating the potential of our proposed interface to provide a wearable alternative solution.**

Fig. 1. A user demonstrates our multimodal system by following a sinusoidal force pattern (pink line). The user (at right) controls the normal force exerted on the surface (blue arrow) and the end effector linear velocity by moving his forearm and changing his muscle activation level.

I. BACKGROUND AND MOTIVATION

Current robot programming and control interfaces are often unintuitive, inflexible, and tedious. In tasks involving complex robot systems, and for specifying interactions between robots and humans, more intuitive interfaces are required to ensure safe and efficient operation [1]. AR technology offers a promising alternative and recent studies have explored its application in training, repair, and maintenance tasks. Our particular interest is in large-scale complex collaborative manufacturing operations such as vehicle door assembly [2] and aircraft composite manufacturing [3]. In these operations, the task-relevant knowledge of the human worker is indispensable, but they can also benefit from the strength and repeatability a robotic assistant can offer. In these scenarios, the worker needs to alternate between controlling the robot for parts of the task, and working manually on other parts of the task. Worker mobility in workspace is also important. Current interfaces for robot control and interaction using handheld devices such as teach pendants [4] or joysticks are not well suited for such scenarios, since the worker is required to continually switch attention between handheld interface and task. In addition, these interfaces are often tethered, and the worker must repeatedly take up and put down (or holster) the interface at each transition between robot control and hands-on work.

To provide a more intuitive and efficient user interface that can allow the user to move freely in the workspace, and support smooth collaboration with robotic assistants, we have adopted a wearable solution and created a multimodal interface using AR with EMG. Most existing AR devices provide user with rich visual information, but are limited in input modalities and bandwidth, supporting only key words (speech recognition) and simple hand gestures (limited to a small region of space in front of the user) [5]. Hence, the functionalities of robot control systems using only AR devices tend to be limited to discrete waypoint specification and trajectory preview ([6], [7]). However, in many industrial tasks such as welding, composite manufacturing, or polishing, the ability to control robot trajectory and force continuously in realtime is needed. To enable this, we combine the use of EMG with AR to create a multimodal interface capable of richer user input.

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II. RELATED WORK

We first introduce relevant methods and technologies related to our problem, and discus their benefits and drawbacks.

A. Augmented Reality

Existing studies have demonstrated the potential of AR to improving human-robot interactions and robot programming. Zaeh et al. [8] proposed an industrial robot programming interface that allows user to specify motion paths by drawing directly in AR onto the workpiece. Chong et al. [9] introduced an in-situ method for path planning, allowing user to specify trajectory key points, and provided path preview in AR. Green et al. [10] proposed an AR teleoperating system for mobile robots and achieved better task accuracy. Aside from robotics application, there are studies on use of biological signals with AR. Angrisani et al. [11] demonstrated that virtual AR objects can generate detectable electroencephalography (EEG) signals. Yoshinaga and Arita [12] found that EMG can function as an additional input channel and improve interaction with AR graphics rendered on a monitor. However, in our review, we were unable to find studies on use of EMG with AR for robotic control.

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B. Input Modalities for Trajectory and Force Control

Haptic Devices have been used to create teleoperated systems for large robots and provide accurate force feedback [13]. Similarly, force feedback mechanisms have been developed for robotic surgical systems [14]. Researchers have also combined the use of haptic device and base object for more accurate haptic rendering of needle insertion forces [15]. While haptic devices enable precise force control through direct force feedback to user, they are by nature large and stationary, and do not permit worker mobility or smooth transitioning from robot control to hands-on work.

Handheld/Hand-mounted Devices have been widely used for robot force control through force feedback. Use of various joystick forms is common. Examples include use of a haptic joystick for mobile robot control [16], and crane operation using joystick and force display feedback [17]. Various custom-built hand-mounted devices have also been proposed, including finger-worn haptic system allowing "feeling" of virtual objects [18], and hand-moutned device with motors providing grip force feedback during robotic grasping [19]. While such devices aim to provide familiarity or portability, they require the user to hold onto the device, or bulky electronics tied to the hand. Hence, they also do not support smooth transition from robot control to hands-on work.

EMG offers a hands-free method for controlling force. It also offers a closer input-output mapping compared to a joystick. Joystick maps from positional input to force output. EMG maps muscle activation level, essentially force activation, to force output. This can offer an intuitive alternative to the user, as their force activation translates to the force profile for the robot arm. However, EMG signals are known to be noisy, variable, and user-specific, and the generation of muscle activity has cognitive and physical workload implications. That said, there have been studies on the application of EMG for robot control, including the use of upper limb EMG for robot arm control [20], surface EMG for prosthesis finger control [21], and EMG-based system for exoskeleton control [22]. Using estimated muscle force, these studies were able to achieve stable human-robot interaction.

AR/EMG interface. In light of the above review, and in our proposed context of large scale human-robot collaboration for manufacturing, we have chosen to use EMG in conjunction with AR to create an arm-wearable, tether-free robot control interface to support worker mobility and smooth transition between robot control and manual hands-on work. Concerns, as mentioned, include repeatability and usability of EMG signals. Hence, our current study investigates the usability and suitability of such an AR+EMG system for robot trajectory control and execution. In addition to using arm EMG, we also evaluate an interface using arm orientation, and compare both methods with the use of a standard joystick (analogous to industrial teach pendants).

III. RESEARCH QUESTIONS

Our goal is to apply our system to large-scale composite (carbon fibre reinforced polymer - CFRP) manufacturing processes at our collaborator's facility - the German Aerospace Agency (DLR) Centre in Augsburg. Working towards this, we first seek to evaluate our proposed interface and determine whether it serves as a suitable substitute to a standard interface, such as joysticks. Our research questions are:

1) In the context of our AR system, can our proposed methods using EMG or orientation provide a suitable interface for robot position and force trajectory control, yielding comparable performance to a joystick?
2) What are the benefits/limitations of the proposed arm mounted interface (using EMG or orientation) as experienced by users when compared to using a joystick?

To answer these questions, we perform a comparative user study as described below.

IV. SYSTEM

A. Hardware

We implemented our system using a Microsoft HoloLens (the first commercial untethered head-mounted AR system) [5], and MYO armbands (the first commercial portable gesture-based input device using surface EMG worn on the forearm) [23]. The use of HoloLens and MYO band allows us to create a wearable, tether-free interface. Compared to alternatives such as motion capture systems or camera-based markerless tracking software, the MYO band is portable, relatively inexpensive, quick to setup, unaffected by occlusions, and hence, more suitable for factory scenarios.

The HoloLens permits rendering of 3D virtual objects in the physical world and provides speech recognition and gaze tracking. The MYO band provides muscle activation reading from eight sets of skin surface electrodes. It also provides recognition of six hand gestures and measures acceleration and orientation. In our current work, we use our system to control a 7-DOF robot arm (Barrett WAM [24]) as a stand-in for an industrial robot.

B. Software

We use Microsoft HoloLens SDK and Unity for developing our AR application. The Robot Operating System (ROS) is used for controlling and interfacing with the WAM and MYO bands. The software package rosbridge is used for communication between the HoloLens and ROS controlling the WAM through WiFi.

Our system allows the user to visualize the robot, create trajectories using gaze and speech, preview trajectory, execute trajectory using gestures, and control the robot's applied force online using muscle activation or arm orientation. The system provides visual force feedback during execution. A virtual model of robot and work surface is rendered and shown to user co-located with the real robot and work surface (Fig. 1). Fig. 2 shows the workflow. The user first sets the desired trajectory way-points by looking at desired locations and giving a speech commands. A green sphere, indicating way-point location, and a blue arrow indicating surface normal, is rendered and displayed as the user sets each way point (Fig. 2A). Once the way points are set, the user constrains the robot motion to the trajectory with another speech command. The desired force profile to be applied

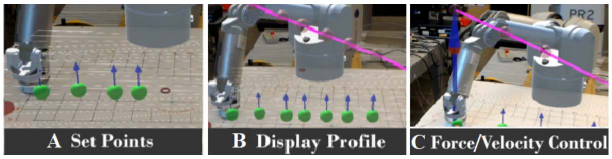

Fig. 2. During our study the user A. sets the desired path using both head orientation and speech, B. displays the path profile using speech, C. controls the robot arm force and velocity using one of our interfaces.

along the trajectory is displayed via AR in task space as a pink line (Fig. 2B). Once the user locks the robot to the created trajectory, they can control its movement along the trajectory and applied force (Fig. 2C) using one of the three control interfaces described below. The virtual robot provides a visual understanding of the system's calibration, and can be used to provided trajectory previews. A detail description of the AR programming component can be found in [3].

Our system provides visual force feedback to the user. When the end effector applies a force to the work-surface, arrows with length proportional to the magnitude of the applied force are rendered at the end-effector to provide a visualization of the forces in task space.

C. Trajectory Execution

During trajectory execution, the robot arm is constrained to the path using the force controller described in [7]. The controller permits control of 1 DOF movement along the defined trajectory, and applied force normal to work surface. The user controls the robot's movement along the path using either a PS3 joystick or MYO band. The user moves the robot with the joystick by pushing the right joystick left or right. The velocity of the robot is set proportional to the joystick displacement. Using the MYO band, the user moves the robot by moving their forearm left or right. The user begins trajectory control by holding the right arm out with their forearm parallel to the ground and making a fist gesture (Fig. 1). When the fist gesture is first detected, the yaw orientation of the forearm θ'_y is recorded. As the user moves their forearm, the yaw displacement is measured as $d\theta_y = \theta_y - \theta'_y$, where θ_y is the current yaw angle measurement. A driving velocity proportional to $d\theta_y$ is then applied to move the end-effector along the path.

D. Force Control Interfaces

We created two force control methods using the MYO band, with one using EMG, and one using orientation measurement. We also implemented a joystick-based method as comparison. These methods are explained in detail below. Only downward forces are permitted for safety reasons.

EMG. User controls applied force by muscle activation level. When the system initializes, the user first squeezes the right hand into a fist with maximum force, and a maximum EMG reading $\bar{\varepsilon}_{max}$ is recorded. The average EMG activation level $\varepsilon_{avg}(t)$ at time t is computed by averaging the readings from the eight electrodes on the MYO band at time t. A smoothed average is obtained by averaging $\varepsilon_i(t)$ over a time window:

$$\bar{\varepsilon}_{avg}(t) = \frac{\sum_i \varepsilon_{avg}(t-i)}{n} \tag{1}$$

Fig. 3. Workers removing wrinkles from plastic sheets placed over a large composite fibre layup workpiece. (Image courtesy of DLR.)

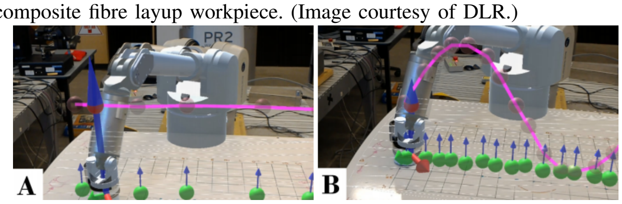

Fig. 4. User's point of view. Pink line indicates force to follow: A - Constant force profile. B - Sinusoidal force profile.

The maximum EMG reading $\bar{\varepsilon}_{max}$ is taken as the $\bar{\varepsilon}_{avg}(t)$ value measured three seconds after the user was asked to hold a fist with maximum force to avoid initial spikes in the EMG reading. The force command is computed as:

$$F_n = F_{limit} \frac{\bar{\varepsilon}_{avg}(t) - \bar{\varepsilon}_{start}}{\bar{\varepsilon}_{max} - \bar{\varepsilon}_{start}} \tag{2}$$

where F_{limit} is set to 30 N, and $\bar{\varepsilon}_{start}$ is the $\bar{\varepsilon}_{avg}$ value measured at the time when trajectory execution began (i.e., when the MYO band first detected the fist gesture).

Arm orientation. Orientation reading from the MYO band's IMU is used to control applied force. When the fist gesture is first detected, the pitch orientation of the forearm θ'_p is recorded. As the user moves their forearm, the pitch displacement is measured as $d\theta_p = \theta_p - \theta'_p$, where θ_p is the current pitch angle measurement. A force proportional to $d\theta_p$ is then applied to the worksurface at the end-effector.

Joystick. The joystick outputs a value between 1.0 (up) and -1.0 (down) corresponding to the position of the joystick. A force proportional to the output is applied in the direction normal to the worksurface at the end-effector.

V. EXPERIMENT

We recruited 12 participants (7 males, 5 females) from students at the university campus. The study was approved by the university's behavioural research ethics board (approval ID: H10-00503). In the study, each participant used our system to program a trajectory and execute a requested force profile using the three interfaces. This task of controlling the robot force along a trajectory is analogous to the pleating task found in CFRP manufacturing (Fig. 3), our target task, and representative of many other tasks such as polishing, sanding, or grinding. We tested a constant (Const) force profile and a sinusoidal (Sine) force profile (Fig. 4), with three trials each. A Balanced Latin Square design was used to mitigate carryover effects.

In the experiment, the robot arm is located in front of a 2D worksurface, and the user stands across the robot. The user first creates a 2D trajectory on the table by looking at key points on the table and speaking the command "set point". After the key points are set, the user then says "lock path" to generate a B-spline path through the key points and locking the robot's end effector to the generated path. The user then says "display force", to display the desired force profile above the trajectory. When executing each trajectory, the user is asked to first attain the target force level. Once achieved, the user then begins to move the robot through the trajectory, while controlling the robot's applied force, following the desired force profile.

For each participant, we first explained the task procedure, our AR system, and each input interface, letting them try each interface briefly. Once comfortable, we started the experiment trials. After the set of trials for each interface, the participant completed a NASA-TLX survey [25]. After all trials, we also asked for any additional comments.

VI. ANALYSIS

We computed the trial execution time, t_{exec}, maximum absolute force deviation, $|d|_{max}$, and average absolute force deviation, $|d|_{avg}$. Execution time is defined as

$$t_{exec} = t_{end} - t_{start}, \tag{3}$$

where t_{start} is the time when the robot first moves beyond 5 cm into the trajectory, and t_{end} is the time when the robot first reaches within 5 cm of trajectory end point. Maximum absolute force deviation is defined as

$$|d|_{max} = \max\{|d|(t), t \in [t_{start}, t_{end}]\}, \tag{4}$$

while the average absolute force deviation is defined as

$$|d|_{avg} = \frac{\sum\limits_{[t_{start}, t_{end}]} |d|(t)}{n}. \tag{5}$$

where $|d|(t) = |F_{applied}(t) - F_{target}(t)|$. The robot control PC was used to measure time, and force sensor on robot wrist to measure force. Data was recorded at 100Hz with 80 mN resolution. To answer our first research question, we test whether our proposed interfaces yield results equivalent to a standard joystick by performing equivalence tests as recommend in [26], [27] using two one-sided t-tests. We used an equivalence margin of $\delta = 20\%$ for t_{exec} and the survey scale according to common practice found in literature [28] for time and survey response measurements, and a δ = 5N for force deviation measurements determined empirically based on our target application (CFRP manufacturing) requirements. To answer our second research question regarding proposed interface drawbacks, we looked for measures which yielded worse results than joystick. This was done via ANOVA analyses and Bonferroni corrected *post hoc* analyses ($\alpha = 0.05$) on measures that failed to reach significance in the equivalence test.

VII. RESULT

Fig. 5 shows example plots for position and force deviations recorded during the experiment. Measured, t_{exec}, $|d|_{max}$, and $|d|_{avg}$, for each force profile, and combined averages, are

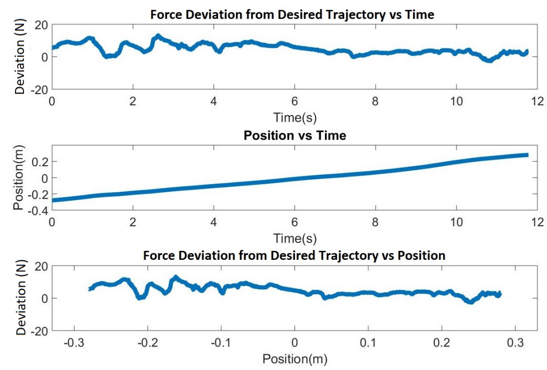

Fig. 5. Data from a trial executing Sine force profile using EMG.

shown in Table I, while Fig. 6 shows the box plot for the combined data. Table II shows NASA-TLX survey results (21 point scale) [25], while Fig. 7 shows the bar chart. Significant results are reported below.

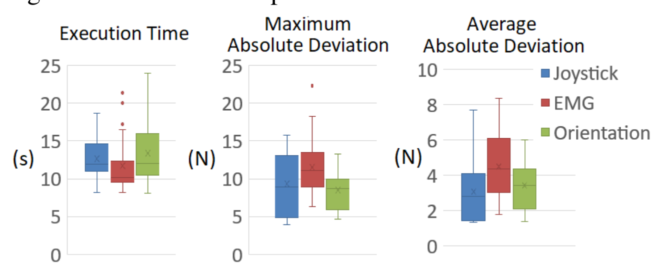

Fig. 6. Box plot of data for execution time, maximum absolute force deviation, and average absolute force deviation.

A. Equivalence Test

All three measures of t_{exec}, $|d|_{max}$, and $|d|_{avg}$ for EMG achieved equivalent performance compared to joystick ($t(23) = 2.28, p = 0.016$; $t(23) = 4.07, p < 0.001$; $t(23) = 14.8, p < 0.001$). Similarly, t_{exec}, $|d|_{max}$, and $|d|_{avg}$ for orientation achieved equivalent performance compared to joystick ($t(23) = 1.09, p = 0.034$; $t(23) = 5.63, p < 0.001$; $t(23) = 16.9, p < 0.001$). Furthermore, $|d|_{max}$ and $|d|_{avg}$ for EMG were also found to be equivalent to that for orientation ($t(23) = 3.01, p < 0.003$; $t(23) = 12.4, p < 0.001$).

Analysis of NASA-TLX responses showed both EMG and orientation achieved equivalent results to joystick for temporal demand ($t(11) = 2.90, p = 0.007$; $t(11) = 3.16, p = 0.005$). Furthermore, orientation achieved equivalent results to joystick for mental demand ($t(11) = 2.84, p = 0.008$), temporal demand ($t(11) = 3.16, p < 0.005$), and performance ($t(11) = 2.20, p = 0.025$).

B. ANOVA Analysis

Significant differences were found for physical demand ($F(2,33) = 15.15, p < 0.001$), performance ($F(2,33) = 6.09, p = 0.006$), effort ($F(2,33) = 5.78, p = 0.007$), and frustration ($F(2,33) = 3.88, p = 0.031$), but not for mental demand ($F(2,33) = 0.168, p = 0.846$). *Post hoc* analysis showed significantly higher physical demand ($t(10) = 7.24, p < 0.001$) and less favourable responses for performance ($t(10) = 4.00, p < 0.006$), effort ($t(10) = 3.42, p < 0.017$), and frustration ($t(10) = 2.65, p < 0.067$) when comparing EMG to joystick. Orientation also had significantly higher physical demand compared to joystick ($t(10) = 2.46, p < 0.095$).

TABLE I

EXECUTION TIME, t_{exec}, MAXIMUM ABSOLUTE FORCE ERROR, $|e|_{max}$, AND AVERAGE ABSOLUTE FORCE ERROR, $|e|_{avg}$, MEASURED IN EACH TRIAL.

	t_{exec}(s)			$|d|_{max}$(N)			$|d|_{avg}$(N)		
Force Profile	Const	Sine	Avg	Const	Sine	Avg	Const	Sine	Avg
Joystick	11.4±2.4	13.9±2.6	12.6±2.7	7.3±4.2	11.4±3.2	9.4±4.2	2.5±2.0	3.7±1.4	3.1±1.8
EMG	10.4±2.1	13.1±4.4	11.7±3.6	9.4±2.3	13.7±3.7	11.5±3.7	4.0±1.9	5.0±1.6	4.5±1.8
Orientation	11.2±2.3	15.6±4.7	13.4±4.3	7.9±2.7	9.0±2.5	8.5±2.6	3.3±1.7	3.6±1.0	3.5±1.4

TABLE II

NASA TASK LOAD INDEX (TLX) [25] RESULTS (21 POINT SCALE).

	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration
Joystick	9.7±4.3	5.4±3.3	8.0±4.5	8.8±3.2	9.1±2.9	5.3±3.2
EMG	9.9±5.8	15.4±4.4	9.3±3.4	13.5±3.3	14.2±3.5	11.6±7.3
Orientation	8.8±4.2	9.5±5.4	8.2±3.2	10.3±3.7	11.8±4.4	8.1±5.2

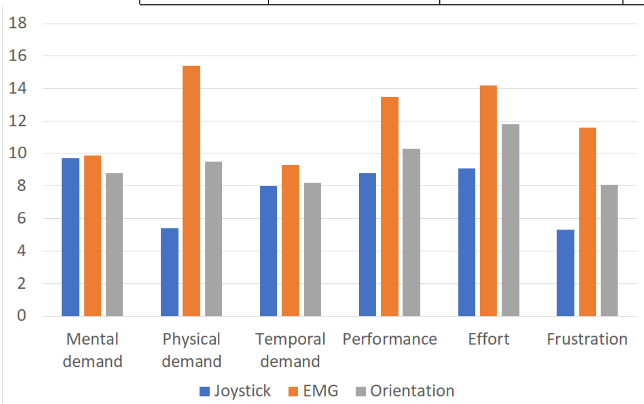

Fig. 7. Survey results of the NASA Task Load Index (TLX) [25].

VIII. DISCUSSION

A. Suitability of Proposed Interfaces

Results show that both our interfaces using EMG and orientation achieved execution times and force deviations equivalent to those using a joystick, thus, supporting that our proposed interfaces can serve as suitable alternative methods for controlling robot positional and force trajectories in our system. Furthermore, results showed that use of EMG and orientation required no higher temporal demands than joystick, and use of orientation required no higher mental demand than joystick from the user, suggesting that similar level of ease of use as a joystick is provided. This is important as interface should not distract user from task [1].

Results also showed that using EMG or orientation yielded higher physical demand when compared to using joystick. Thus a drawback of our proposed interfaces is that they may induce fatigue more easily. Using EMG, in addition, also has the drawback of inducing a lower sense of performance, and higher amounts of effort and frustration. However, it should be noted that although participants reported lower sense of performance, actual measured performance (t_{exec}, $|d|_{max}$, and $|d|_{avg}$) are equivalent to using the joystick in this first experience trial. We discuss possible explanations for these observations about our proposed interfaces below.

B. Participant Feedback

Inspecting participant comments revealed bimodal responses toward use of EMG. One group was positive, commenting "Myo-band generally felt intuitive", "prefer orientation mode, than EMG mode", and "definitely the most intuitive", while the other group was negative, commenting "EMG force control was very difficult, frustrating", "using the myo band to control the force was ... a lot of frustration". Indeed, data show 33% indicated very low levels of frustration (<4 out of a 21-point scale), while 58% indicated moderate to very high levels (>15). This bimodal response was not seen in joystick or orientation as both are somewhat normally distributed. During calibration, a few participants had trouble getting the MYO bands to recognize their hand gestures. Also, while most subjects have an $\bar{\varepsilon}_{avg}$ of around 750, two participants have $\bar{\varepsilon}_{avg}$ only around 350. This made the available range for controlling F_n much smaller and hence, more difficult. The difficulties experienced by these participants are perhaps due to different physiological build or unfamiliarity with the concept of EMG control. Maximum levels of frustration reported were from these participants.

Indeed, most people are unfamiliar with controlling EMG activation levels. Thus, as expected, users experienced higher physical demand, effort, frustration, and lower performance when using EMG. However, with minimal training, all participants were able to complete all tasks using EMG within the same time scale, if not faster, and with similar force errors compared to using a joystick. Thus EMG does provide a quick-to-learn, promising interface. With additional training and familiarization, improved results are expected.

Use of orientation yielded higher physical demand when compared to use of joystick, but otherwise appeared to yield comparable results. Thus orientation may be the better interface out of the two we proposed. The higher physical demand may be due to the requirement that the user needs to constantly hold a fist to activate the control. Replacing this with a different "activation" method may improve the physical demand. Using EMG for force control does, however, have a few advantages over orientation. Using EMG to control force has a closer input-to-output mapping than using orientation, as EMG activation corresponds to the force exerted by the user. Also, using EMG for force control provides better decoupling between the control of trajectory playback in the tangential direction and applied force in the normal direction. As one participant commented, "in orientation mode, [it was] difficult distinguishing L/R from up/down, sometimes up felt like I was moving right."

C. Limitations

Among tested conditions, there may be asymmetrical carryover effects. While such are difficult to eliminate in any studies, we have used a Balanced Latin Square design to mitigate, as well as asked participants to perform the full task including trajectory specification as a washout and to provide task context. We have used an experiment task relevant to many robotic applications. But performance of our interfaces may differ if the task was significantly different. Hence, it may be worthwhile to investigate other task types as well. We have not explicitly modeled the relationship between arm orientation (θ_y) and arm EMG ($\bar{\varepsilon}_{avg}$). But these parameters are related, and this may have effects on robot control.

D. Overall Recommendations

Results show that both our proposed interfaces using EMG or arm orientation with AR provide suitable methods to novice users with minimal training for controlling robot trajectories. The use of orientation appears to be the best option for untrained users, and replacing the "activation" method of constantly holding a fist may reduce the physical demand. If EMG is to be used, a longer training period may be beneficial towards improving the higher levels of perceived workload in some of the NASA-TLX scales, since EMG control may be less familiar to most people.

IX. CONCLUSION AND FUTURE WORK

We have presented a multimodal system combining AR with EMG, and arm orientation, for robot trajectory programming and execution. To our knowledge, this is the first system combining the use of EMG and AR for online robot trajectory and force control. Our system aims to enable workers to move freely around the workspace and smoothly transition between robot control and hands-on tasks. Compared to a standard joystick, experiment results showed that our proposed methods provided suitable interfaces, allowing users to complete the tasks and achieve equivalent performances. However, they have higher perceived workload on some NASA-TLX scales. A different "activation" method when using orientation and longer training sessions when using EMG may improve these issues. Our next steps will involve testing our system with large-scale robots in a collaborative manufacturing setting with our industry partner.

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