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Wearing Your Arm on Your Sleeve: Studying Usage Contexts for a Wearable Robotic Forearm

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Abstract— **This paper presents the design of a wearable robotic forearm that provides the user with an assistive third hand, along with a study of interaction scenarios for the design. Technical advances in sensors, actuators, and materials have made wearable robots feasible for personal use, but the interaction with such robots has not been sufficiently studied. We describe the development of a working prototype along with three usability studies. In an online survey we find that respondents presented with images and descriptions of the device see its use mainly as a functional tool in professional and military contexts. A subsequent contextual inquiry among building construction workers reveals three themes for user needs: extending a worker's reach, enhancing their safety and comfort through bracing and stabilization, and reducing their cognitive load in repetitive tasks. A subsequent laboratry study in which participants wear a working prototype of the robot finds that they prioritize lowered weight and enhanced dexterity, seek adjustable autonomy and transparency of the robot's intent, and prefer a robot that looks distinct from a human arm. These studies inform design implications for further development of wearable robotic arms.**

I. Introduction and Related Work

The idea of extending or augmenting the capabilities of the human body has been an enduring area of exploration in fiction and academia alike. Today, prostheses and exoskeletons have reached considerable maturity in both research and commercial applications. These wearable robots serve to replace human limb capabilities that have been lost, are used as rehabilitative tools, and can enhance and augment the human load-carrying capacity [1], [2], [3].

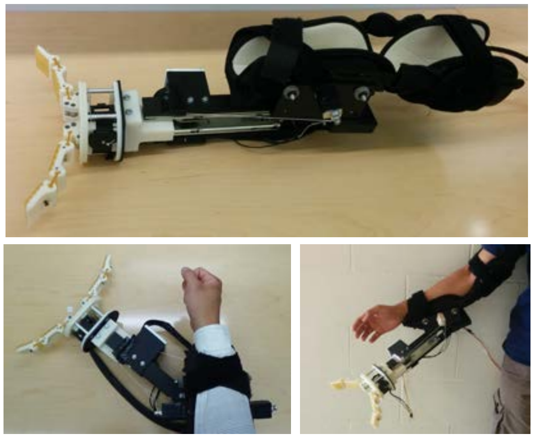

Fig. 1. The wearable robotic forearm prototype deployed in the user studies.

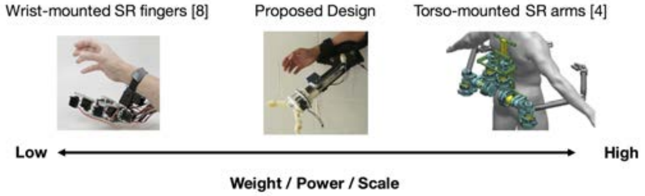

Fig. 2. The proposed design falls in between existing supernumerary robotic (SR) limb designs (wrist-mounted SR fingers and torso-mounted SR arms) in terms of weight, power, and scale.

In addition, recent years have seen work on another kind of robotic augmentation in the form of supernumerary robotic (SR) limbs (Fig. 2). These do not merely replace or support human limbs, but add degrees of freedom (DoFs) that are not naturally present in the human body. Previous work on SR limbs includes torso-mounted arms protruding from the wearer's hips or shoulders, designed to aid workers by stabilizing workpieces and balancing the wearer [4], [5]. Other work is concerned with SR fingers worn on the wrist or ankle, allowing users to perform two-handed tasks with a single hand [6], [7], [8], or to be used as a rehabilitation tool [9].

We explore a new wearable robot design (Fig. 1) which falls between previously suggested configurations of torso-mounted arms and wrist-mounted fingers (Fig. 2 center): a lightweight supernumerary forearm attached at the elbow for close-range human-robot collaboration. This intermediate design can provide mobility and low weight—like SR fingers—allowing the user to quickly position it in a desired reference frame. Still, it is capable of increasing the user's reach and workspace beyond their natural limits—like torso-mounted SR arms.

We envision this wearable robot to be used as an autonomous agent, which the user can dynamically position and then collaborate with in a variety of ways. The arm could pick up objects which are out of the wearer's reach, aid human-human handovers when the wearer's hands are occupied, speed up repetitive tasks through self-handovers, and stabilize tools and objects within the wearer's workspace.

Given the novelty of this human-wearable-robot configuration, we set out to explore the usage contexts and interaction scenarios that such a device may be deployed in, using a realized prototype as a reference point.

In the next section, we present the prototype used in our studies. We then report on our findings from studies employing three user-centered design methods (Fig. 3): we first conduct an online study to get feedback on the application

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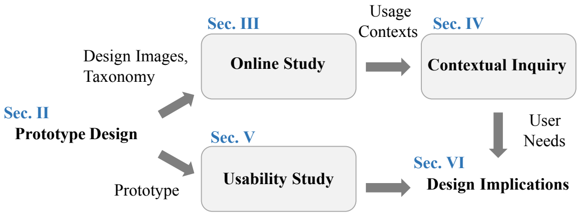


Fig. 3. Overview of the user-centered design methods applied to develop design principles for a wearable robotic forearm.

areas for a wearable robotic forearm, using a taxonomy of usage contexts and functions (Sec. III). Based on the results of this survey, we perform need-finding via contextual inquiry [10] into the specific application area of building construction (Sec. IV). We then perform an in-lab usability study through semi-structured interviews [11], [12] using the physically developed prototype (Sec. V). These studies result in design implications for future prototypes (Sec. VI).

II. PROTOTYPE DESIGN

To evaluate the usability and preferred interaction scenarios of a wearable robotic forearm, we designed and developed an initial prototype of the device, in the spirit of low-fidelity ("paper") prototypes [13]. This prototype is a fully functional, albeit non-autonomous, wearable robot. The physical realization can convey to study participants a functionality that is similar to that envisioned for the final design, and allows users to experience the device in an embodied manner, enabling design backtalk [14].

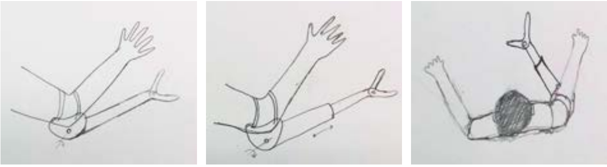


Fig. 4. Initial concept sketches for an elbow-mounted third arm robot (from left): a) Single vertical DoF, b) one vertical and one prismatic DoF, c) one horizontal and one prismatic DoF (chosen design).

Initial sketches exploring the DoFs replicated the flexion and extension of the human elbow on the robotic arm (Fig. 4a). This would allow a user to reach objects below the level of a fully extended elbow, as well as enable self-handovers. For example, when standing on a ladder, the wearable arm could reach down to bring a tool without requiring the wearer to step down. The addition of a prismatic joint further extends the wearer's reach (Fig. 4b). However, we also envision using the arm around a workbench or a desk, where its vertical movement might interfere with the workspace. We therefore explored a different degree of freedom in the form of a horizontal panning that is analogous to the horizontal adduction and abduction of the human shoulder (Fig. 4c). This side-to-side design, in addition to the prismatic extension, effectively broadens the wearer's "wing span." A gripper was chosen as the end effector to enable grasping of objects and bracing. This choice of DoFs is also suitable for two people working side by side, enabling them to stand further apart from each other during handovers.

TABLE I

TECHNICAL SPECIFICATIONS FOR DOFS OF THE PROTOTYPE

DoF	Motor	Range of Motion	Stall Torque	No-load speed
Panning	Dynamixel MX-64	˜120°	6.0 Nm	63 rpm
Extension	Dynamixel MX-28	˜160mm	2.5 Nm	55 rpm

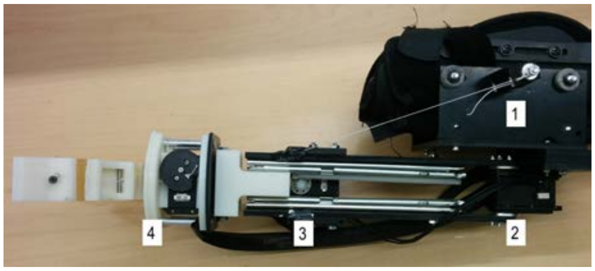


Fig. 5. Structure of the prototype: 1) Mounting Platform, 2) Motor for panning, 3) Motor, rack and pinion for prismatic extension, 4) Gripper

The assembled 3-DoF prototype is shown in Fig. 5. Weighing ˜2kg, its body is realized out of laser-cut acrylonitrile butadiene styrene (ABS) sheets (shown in black) and 3D printed ABS components (shown in white). Stainless steel rolling slides enable prismatic extension. The DoF specifications are presented in Table I. The pan DoF is direct-driven, and the prismatic DoF is actuated using a rack-and-pinion transmission. The gripper is based on the Yale OpenHand Model T42 [15], modified to constrain both fingers to move together by attaching their cables to a single motor.

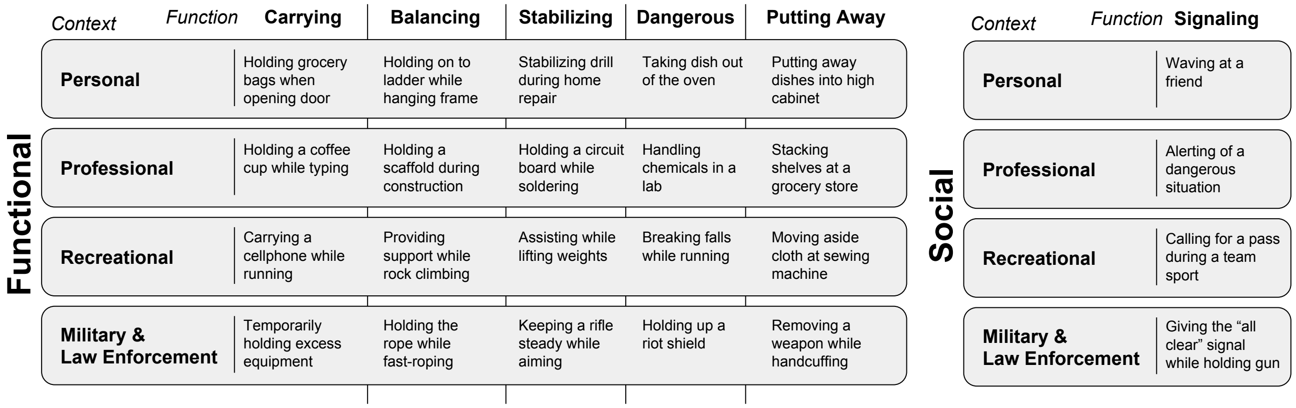
III. ONLINE STUDY: CONTEXTS AND FUNCTIONS

After constructing the prototype, we conducted a brainstorming session [16] with colleagues to produce a large number of possible usages for a wearable robotic arm. We also shared pictures of the prototype on social media and collected open-ended responses, through snowball sampling [17], to the question: "What would you use a wearable robotic third arm for?" We then categorized the collected usages into a taxonomy of usage contexts and functions (Fig. 6).

Usage **contexts** are groupings of *where* a wearable robotic arm would be useful. Usage **functions** are groupings of *what* such a device would be useful for.

Clustering the usages via affinity diagrams lead to the identification of four usage contexts:

- **Personal:** Error-tolerant tasks in environments familiar to the user, supporting daily activities.
- **Professional:** Tasks performed in office and industrial contexts, requiring more robustness from the robot.
- **Recreational:** Hobby or fitness related tasks, possibly outdoors or in unfamiliar environments.
- **Military and Law-Enforcement:** High-risk tasks in uncertain environments.



Context \ Function	Carrying	Balancing	Stabilizing	Dangerous	Putting Away
Personal	Holding grocery bags when opening door	Holding on to ladder while hanging frame	Stabilizing drill during home repair	Taking dish out of the oven	Putting away dishes into high cabinet
Professional	Holding a coffee cup while typing	Holding a scaffold during construction	Holding a circuit board while soldering	Handling chemicals in a lab	Stacking shelves at a grocery store
Recreational	Carrying a cellphone while running	Providing support while rock climbing	Assisting while lifting weights	Breaking falls while running	Moving aside cloth at sewing machine
Military & Law Enforcement	Temporarily holding excess equipment	Holding the rope while fast-roping	Keeping a rifle steady while aiming	Holding up a riot shield	Removing a weapon while handcuffing

Context \ Function	Signaling
Personal	Waving at a friend
Professional	Alerting of a dangerous situation
Recreational	Calling for a pass during a team sport
Military & Law Enforcement	Giving the "all clear" signal while holding gun

Fig. 6. A taxonomy of contexts and functions of use for a wearable robotic arm, developed through brainstorming sessions, open-ended snowball sampled surveys, and affinity diagram clustering (see: Sec. III), along with non-exhaustive illustrative examples.

Orthogonal to these contexts, we identified five usage functions:

- **Carrying** objects and performing human-robot handovers.
- **Balancing** the user by grasping and bracing using objects in the environment.
- **Stabilizing** an object that the user is holding.
- Handling **dangerous** objects such as chemicals and hot plates.
- **Putting away** objects to outside the wearer's reach or while hands are occupied.
- **Signaling**, for example, using the robotic arm to gesture to a coworker for assistance.

Finally, we noted a high-level distinction between functions that are purely pragmatic or "functional" and those involving social interactions. This differentiation stems from the fact that beyond its physical assistive function, a third arm offers additional modalities for expressing non-verbal behavior. We refer to this functional/social dichotomy as usage "classes".

A. Online Survey

To inform the design features and requirements of the device, we collected responses to an online survey gauging public opinion of potential usage contexts and functions based on the above taxonomy, in the spirit of [18].

We collected 105 responses (57 male, 48 female) from participants recruited using the Amazon Mechanical Turk platform [19]. The age distribution was: 18-25 (12.4%), 26–35 (45.7%), 36–50 (28.6%), 50 and above (13.3%).

The survey showed images of a 3D model of the arm and pictures of the physical prototype, as in Fig. 1, followed by the text:

> We are building a smart robotic "third arm" that attaches at your elbow. The first prototype shown below has three motors: rotation at the elbow, arm extension, and gripping. The purpose of this survey is to gauge application areas and features, which will motivate development of future prototypes.

Then, we presented participants with three sections, one for usage context and usage class, one for specific functions, and one for desired features, along with space for open-ended responses and demographic questions.

TABLE II

ONLINE SURVEY RESPONSE SCORES ABOUT CONTEXTS AND CLASSES OF USE (MEAN, STANDARD DEVIATION AND MODE)

A robotic third arm is useful for..			
Usage context	$\bar{x}$	σ	mode
Personal	4.80	1.95	6
Professional	5.00	1.61	4
Recreational	4.51	1.70	4
Military/Law Enforcement	5.02	1.68	6
Usage class	$\bar{x}$	σ	mode
Functional	5.77	1.41	7
Social	2.82	1.60	1
I can see myself using a robotic third arm for..			
Usage context	$\bar{x}$	σ	mode
Personal	4.17	2.23	1
Professional	3.30	1.93	1
Recreational	3.63	2.13	1
Military/Law Enforcement	2.38	1.98	1
Usage class	$\bar{x}$	σ	mode
Functional	5.08	2.13	7
Social	2.23	1.60	1

In each of the first two sections, we presented the context, class or function of use, alongside two activity examples. For each context, we chose one example from the functional list of activities, and one from the social list: "PERSONAL USE (e.g., holding grocery bags while opening a door, or shaking hands with multiple people)." For each of the use classes and functions, we selected activity examples from different contexts: "FUNCTIONAL USE (e.g., holding a coffee cup while typing, providing support while rock climbing, or stabilizing a firearm)." The list was preceded by the phrase: "Think about the following contexts [functions] for a robotic third arm." We asked two questions per context and class, and two questions per function, each on a scale of 1–7 ("Not at all useful" to "Extremely useful"), shown in Tables II and III.

TABLE III

ONLINE SURVEY RESPONSE SCORES ABOUT FUNCTIONS (MEAN, STANDARD DEVIATION AND MODE) IN DECREASING ORDER OF MEANS.

How useful is a robotic third arm for..			
Function	$\bar{x}$	σ	mode
Handling dangerous objects	5.87	1.58	7
Carrying things	5.47	1.70	7
Stabilizing an object	4.77	1.74	6
Putting things away	4.19	1.91	5
Signaling to others	3.56	1.72	4
Balancing the user	3.41	1.89	4
I can see myself using a robotic third arm for..			
Function	$\bar{x}$	σ	mode
Handling dangerous objects	5.06	2.14	7
Carrying things	5.02	2.20	7
Stabilizing an object	4.17	2.11	1
Putting things away	3.75	2.14	1
Balancing myself	2.73	1.97	1
Signaling to others	2.66	1.83	1

B. Results

Table II shows the means, standard deviations, and modes for each context and usage class. A wearable robotic third arm was considered more useful as a functional tool than for social uses by a wide margin. Moreover, people thought it was more useful in professional and military settings, and least in recreational contexts. Similarly, respondents could generally see themselves using a third arm more for functional use, but chose the personal context as more likely for their own use. Overall, respondents saw themselves less likely to use such a robot compared to how useful they rated it to be overall.

This discrepancy between general usefulness and respondent-use could be explained by the fact that respondents thought of the robot more as a professional or military tool and it is unlikely that they would have worked in particular settings in which a wearable robotic arm would be used. Also, it may be hard to imagine oneself using a device which is of a category that is unfamiliar to respondents.

While respondents could see the utility of the arm for general functional use, if not their own, a third arm was decidedly not considered useful for social contexts or signaling functions, either by the users themselves or in general.

Table III shows the means, standard deviations, and modes for each function. Handling dangerous objects and carrying were the highest rated functions for a third arm (mode 7 for both questions in Table III), with stabilizing objects and putting things away being rated as generally useful (if not for own use). Again, we see a low usage expectation for social use. Respondents also did not feel that balancing the user was a useful function.

IV. CONTEXTUAL INQUIRY: BUILDING CONSTRUCTION

Our findings in Section III suggest that a wearable robotic arm can be a valuable tool in a professional setting, where carrying things, handling hot or dangerous objects, and stabilizing and putting objects away are key functions. Informed by these results, we proceeded to conduct a need-finding inquiry [10] to guide the design of specific capabilities. We chose the domain of building construction, which includes many of the above-mentioned functions. Importantly, this trade involves a range of activities that are strenuous, repetitive and present some degree of hazard to a worker. For example, in the United States, about 40% to 65% of worker's compensation costs in construction result from musculoskeletal disorders and soft-tissue injuries which develop over time [20]. A robotic third arm may be deployed to reduce this risk from repetitive injuries in tasks classified as handovers, pick-and-place, and stabilization of a worker or tool.

Fig. 7. Observations from the construction site: a) Roof paneling installer climbing a ladder, b) plumber welding copper pipes, c) collaborative drywall installtaion.

We ran the contextual inquiry with a construction crew working on building renovations on the Cornell University campus. We were guided through the site by a supervisor who provided a brief description of each task and offered expert testimony during and after our observations of each worker. Since we are interested in building a physical augmentation device, we documented the body motions and ergonomic states of a worker while performing a task along with the hazards and loads associated with the task. We also elicited comments from the workers about the cognitive loads and common frustrations involved in their tasks.

Based on these observations, we identify three usability "need themes" informing promising functional requirements of the robot.

A. Reaching and Self-Handovers

We observed multiple instances where a worker would reach for a tool or work piece in a way that impedes their current task. For example, a worker installing roof panels while standing on a ladder would frequently bend down and pick up tools placed on the ladder or in his utility belt. He also had to step down from the ladder to consult his plans.

Another instance involved an electrician who had to modify a control panel that had been installed in the midst of ventilation piping in the ceiling. To reach the panel in the tightly enclosed space, he had to climb up a ladder and take off his safety helmet to be able to unfasten the screws on the panel. He mentioned that the task would have been much easier if a tool could reach into the enclosed space and bring the screws to him after removal.

This suggests that a third arm would need to function as a tool for handovers and as a temporary storage space, while extending the reach of the wearer. Depending on the dexterity, it would allow a user to perform complex operations in constrained workspaces. The ability to bring nearby objects to a user would reduce the time and effort expended to bend, or to climb up and down to fetch objects.

B. Stabilization of Objects and Self

We found numerous tasks where adding another point of support for bracing a worker would enhance their safety and comfort. The supervisor mentioned that safety regulations require a worker to have three points of contact with a ladder at all times (Fig. 7a). In practice, this is difficult to achieve, especially in bi-manual tasks. When both hands of a worker were occupied, we noticed that they braced against the ladder with their stomach or hip.

A plumber installing copper piping for heating units described a challenge during soldering operations. He would lay down on the floor and have to hold his blowtorch in one hand, and attempt to feed more solder to the joint while also holding the pipe steady with his other hand (Fig. 7b). Another instance was of a cement-layer who constantly had to brace against the floor while spreading a layer of cement.

This suggests that a wearable third arm should be able to stabilize objects and provide for additional contact points for workers when balanced in uncomfortable positions.

C. Coordination of Repetitive Actions

In tasks performed in pairs, workers tend to develop coordination strategies as a result of repetition. For example, one person would cut a gypsum board for drywall installation, while his colleague would hold it in place and brace it against a wall frame. The first person would then get up on a ladder and nail the board into place at positions marked out by the colleague (Fig. 7c). They would perform this series of tasks fluently with minimal communication and acknowledgement from each other, as a result of having done these tasks together multiple times.

Another example of collaborative activity performed in pairs was by window installers: one worker would bring nails and ties from a bin to the worker installing the window panel. This repeated handover task proceeded with fluency and coordination to the point where the installer was able to anticipate the handover without even looking at the other worker.

This suggests the need for a robotic device deployed in such scenarios to not just be physically robust and capable, but also be able to coordinate fluently in repetitive activities, leading to a reduction in the cognitive load of a worker.

V. LABORATORY USABILITY STUDY

The two studies described thus far provide us with a selective focus for contexts and functions, and with specific user needs in a potential application area. However, both the online study and the contextual inquiry were conducted on a purely conceptual basis, with participants imagining the use of a wearable third arm. To generate actionable design principles grounded in physical interaction with the device, we also conducted a user study with participants wearing and using the prototype arm, followed by semi-structured interviews.

Fig. 8. Tasks performed by users: moving a cup on a table while seated, and handing over a cup to the interviewer while standing.

A. Study Design

This third usability study had three phases: a preliminary interview, interaction with the device, and debriefing. In the initial interview, participants began by describing a typical day in their lives. After identifying some activities at home, at work, and performed for recreation, we asked them to imagine if having a third arm attached to their body would affect these activities. We questioned them about the structure, appearance and capabilities of the hypothetical third arm. In order to narrow down their thought process towards forearm mounted devices, we showed the participants pictures of a 3D model of the prototype. We then repeated the questions about their daily activities and elicited suggestions for changes or improvements to the device at this stage.

After responding to the pictures, participants were shown the prototype. They proceeded to wear it and perform two scripted tasks: moving a coffee cup on a table while seated, and handing over the cup to the interviewer (Fig. 8). During the task, the robot was autonomous, but ran open-loop, i.e., without feedback, sensing, or adaptation. Finally, participants were debriefed and asked for improvements and suggestions that they would like to see in future prototypes, and features they would like to see in a commercial product.

The participants were 14 university students at the graduate or undergraduate level (9 females, 5 males). We recruited participants by distributing fliers throughout the university campus, and sending out e-mails on a special interest forum for robotics. Participants received a $10 gift card for participating in the study.

B. Findings from Interviews

A qualitative analysis of audio and video recordings from the interviews revealed five recurring themes (Fig. 9):

1) Weight and Balance: The weight of the robot was a major concern for participants. Users often struggled to perform the task, and in one case, even had to hold up the third arm with their free hand. Reactions included: *"It was very heavy, very cumbersome to use,"* and *"I could not imagine holding it up for more than ten minutes."* Suggestions for the attachment point to the body highly depended on the use context: The arm should mount at the *"center [of the torso], to keep it symmetrical while running,"* or *"On the back, like a crane."* Generally, the forearm was often not considered to be a desirable location.

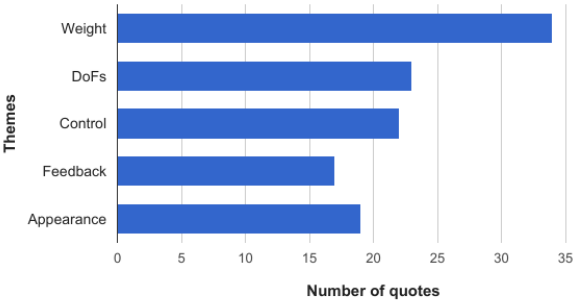


Fig. 9. Number of instances of the five recurring themes in the oral feedback from user study participants.

2) Dexterity: Participants desired more dexterity than was presented to them, especially from the end effector: *"wrist rotation would be desirable," "maybe it should have more fingers."* Many users commented that it would have been easier if the third arm were able to *"pivot in the vertical direction."*

The particular DoFs desired by participants were strongly tied to the application domain. A participant who had worked in chemistry labs said that it would be helpful if the third arm could *"scoop out [small] amounts of powders with a small spatula."* Another user who worked at a library said that the end effector should be able to *"open the cover of a book."* A longer reach during arm extension was desirable for a user who had to regularly reach up well above their head to press buttons on cameras in their lab.

3) Control and Autonomy: Many participants wanted voice-control of the robotic arm with at least some autonomy: *"I want to be able to tell it to do something, and it should just do it."* Others suggested implicit control based on movements or just intention: *"There should be some sensing so that I don't have to adapt to it, it can adapt to my position."* Some participants wanted a combination of intention-recognition and voice-override in case of errors. There was a sentiment that the arm could control itself better than the user could directly: *"I am not very good with remote controlled cars and helicopters, and would much rather have the arm control itself than have me crash it while using a joystick."* Another reason given for autonomy was the difficulty of multitasking: *"We can't really concentrate on that many things at once."*

4) Feedback: In this study, the robot was open-loop controlled, meaning that it went through a preset trajectory. Most participants commented that the arm's intentions were not clear throughout the trajectory: *"I had no sense of warning [when it was going] to pick up or drop objects."* They suggested ways for the robot to show its intention with a variety of feedback options. One participant suggested *"a light that turns on to indicate closing of the gripper,"* another *"a sequence of beeping sounds,"* and some suggested speech acknowledgments, such as *"I'm moving forward"* and *"I'm about to grip."*

5) Appearance: When speaking about the appearance of a wearable third arm device, users' imaginations were often informed by fictional characters. In a few cases, participants suggested modeling the device on existing prosthetic devices. Most prominently, however, participants found the idea of another human-like arm attached to their bodies to be *"a bit creepy,"* especially *"if it were to look like human skin or flesh."* One participant said that this would be *"[...] scary. It would feel like the arm of another person, but no one's there."*

VI. DESIGN IMPLICATIONS

The following design implications emerge from the online survey, contextual inquiry, and qualitative laboratory study described above:

- The robotic arm should be designed to work in **professional**, military, and law-enforcement contexts, mainly supporting **functional** rather than social uses.
- It should enable **reaching for, storing, and handing over** an object out of the reach for a worker, relieving them from the repetitive strain of these actions.
- The arm should also be able to **handle hot, toxic, or otherwise dangerous objects**. For this purpose, the materials for the body and end-effector of the device should be resilient to electric currents, heat, and chemicals.
- The arm should **stabilize and brace** a user while they are working in precarious poses in terms of balance and ergonomics. For this purpose, the actuators and structural elements of the robot should be able to withstand forces and moments at scales produced by a human body.
- **Weight and balance** are key considerations for any wearable device. This, however, poses a trade-off with workspace and payload maximization. If material and actuation constraints require a heavier device, cable-driven systems for larger devices can help distribute the weight along the user's body by placing the heaviest components closer to the wearer's torso and thus reducing moments about the user's joints.
- Users desire high **dexterity** from the robot, especially at the end-effector, to be able to perform everyday tasks efficiently.
- Dexterity of physical design needs to be coupled with **feedback control** through different modalities: speech acknowledgments, visuals such as a screen or even a simple array of lights, or haptic feedback. The motion trajectories of the device itself should be designed to convey intent, even at the cost of task efficiency.
- Providing a wearable arm some **autonomy**, or at least a degreee of adjustable autonomy [21], is crucial for

useful collaborative activities that reduce cognitive load on the user. This is especially important during **repetitive activities**. Given the close operation to the human body, autonomy must be limited to safe operations. Designers must therefore evaluate the kinds of autonomous tasks users will trust the device to perform safely. For other tasks, they can include an option where the user can toggle to controlling it themselves, via a joystick or button.

- Finally, designers must take into account the prevailing social norms regarding robot and prosthesis **appearance**. Generally, we conclude from our interviews that a human-like appearance is undesirable, and might invoke a sense of the "uncanny valley" [22] and that a machine-like appearance would be more socially acceptable.

VII. CONCLUSION

Wearable robotic devices are becoming feasible thanks to advances in lightweight materials, sensing, and actuation technologies. These engineering developments have paved the way for prostheses and exoskeletons, but are also leading to the design of supernumerary robotic (SR) limbs—robots that add action capabilities to able-bodied wearers.

To date, the human-robot interaction scenarios and user preferences for such SR limbs have not been studied in depth, and open questions remain: How and for what purpose would a person use them? How should such robots be designed? Which capabilities are required, and in what contexts? In this paper we address these questions through the design of a SR forearm prototype and data collected in three usability studies.

We developed a new kind of wearable robotic arm: an elbow-mounted third forearm with prismatic extension and under-actuated gripping. When surveying people about the usage contexts and functions for such an arm, we find that they envision such a device mostly as a functional tool for performing tasks in professional and military settings and not as much in personal or recreational contexts. Handling hot or dangerous objects and carrying things were considered the most useful functions for such a robot, followed by object stabilization and reaching/handover tasks. Social and signaling uses were not considered useful.

Narrowing our focus following these results, we explored the possibilities for a wearable SR arm in the professional domain of building construction by conducting a need-finding contextual inquiry. There, we identified three application scenarios: reaching and handovers, stabilization and bracing, and collaboration in repetitive actions.

To ground these findings in physical interaction with the device, we conducted an in-laboratory study using semi-structured interviews. This revealed five themes of user concerns, namely weight and balance, dexterity, control and autonomy, feedback, and the appearance of the robotic arm.

In sum, we present a multi-method contextual design process, going from abstract online surveys to concrete design implications for a wearable robotic arm. Future work involves building successive prototypes based on these design implications, as well as advancing the control architecture and behavioral models toward fluent collaboration between a human and a wearable robotic arm.

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