A Drone Teacher: Designing Physical Human-Drone Interactions for Movement Instruction

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ABSTRACT

Drones (micro unmanned aerial vehicles) are becoming more prevalent in applications that bring them into close human spaces. This is made possible in part by clear drone-to-human communication strategies. However, current auditory and visual communication methods only work with strict environmental settings. To continue expanding the possibilities for drones to be useful in human spaces, we explore ways to overcome these limitations through physical touch. We present a new application for drones–physical instructive feedback. To do this we designed three different physical interaction modes for a drone. We then conducted a user study (N=12) to answer fundamental questions of where and how people want to physically interact with drones, and what people naturally infer the physical touch is communicating. We then used these insights to conduct a second user study (N=14) to understand the best way for a drone to communicate instructions to a human in a movement task. We found that continuous physical feedback is both the preferred mode and is more effective at providing instruction than incremental feedback.

CCS CONCEPTS

• **Computer systems organization** → Robotics.

KEYWORDS

drone, uav, human-drone interaction, physical interaction, instruction

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1 INTRODUCTION

Drones are becoming more prevalent in human spaces [24] like the service industry [45], for personal [5] and professional [36] entertainment, and for search and rescue, to name a few. However the methods for robot-to-human communication are less developed for drones than for ground robots, thus limiting their potential applications. Touch is an important aspect in human-human communication [42], and in robot-to-human communication it can help convey intent [34] and improve user sentiment towards the robot [7, 20] (depending on the cultural context[7]). New safe-to-touch enclosure designs open up an exciting opportunity to explore physical communication strategies for drones. While there has been work on physical human-to-drone communication methods [2, 11, 18, 29, 33, 35], there is a lack of research on physical drone-to-human communication [27, 41, 46]. For drones to be more useful in close proximity to humans, it is important to understand how physical interactions can be leveraged to make drone-to-human communication more clear and to expand their application space.

Some example applications include crowd control [39], emergency evacuation situations [39], and independent exercise [4, 21, 50] or therapy [8]. In the latter two applications, drones have the potential to provide an exergame experience closer to that of a fitness instructor because the drone is free to provide feedback at multiple body points without using additional equipment (wearables [6, 26, 28], hand controllers [14, 28], etc.)–potentially providing more precise pose correction than auditory or visual systems alone. While work has been done to develop visual and auditory drone-to-human communication methods similar to ground robots, there are some limitations. Visual cues such as movement patterns [43], projections [15, 31], and flashing lights [44] are subject to very strict lighting conditions, making them less useful during the daytime or in changing light. Auditory methods such as a person who is blind following the sound of a drone to navigate [4, 10, 22] are restricted in situations where there is loud ambient noise. Also, relying solely on these methods excludes people who have visual and/or auditory impairments. Naturally, to overcome the limitations of the visual and auditory methods, physical drone-to-human communication should be explored.

Unlike previously researched scenarios where the drone might communicate its internal state or intent, for this new class of applications, it is critical for the drone to provide clear *instructions* to a human to get them to take some action. Because of the capabilities of drones, there is a full body interaction space to consider.

While some work has explored physical interactions in this 3D space [9, 32, 47], none have explored them in a communication context–drone-to-human or human-to-drone. Therefore, fundamental research is needed to understand where and how people prefer to interact with drones physically to receive instruction.

Thus, to develop physical drone-to-human instruction methods, we explore the research questions: *Where on the body and in what way do people feel comfortable being touched by a drone?* And, *What physical interactions allow a drone to successfully communicate pose instructions to a human?*

To answer this question, we designed three interaction modes, Tap, Guide, and Slide. We did this by conducting a literature review, observing movement instruction classes, and through pilot studies. We then conducted a two part study to test these interactions and get feedback from participants. Study 1 (N=12) focused on understanding fundamental questions of where and how people want to physically interact with drones, and what people naturally infer the physical touch is communicating. The drone executed each interaction at seven different body locations. The participants were then instructed by the drone in a free-form movement task using the three interactions. We used these insights to modify the interactions. Study 2 (N=14) then focused specifically on the most effective way for the drone to give instructions. We grounded Study 2 in an independent exercise scenario–participants transitioned between different ballet arm poses instructed by the drone. We contribute:

(1) A new application for drones
(2) Design considerations for how to physically communicate instructions, specifically for movement tasks
(3) Insights on people's comfort level and perceptions in physical human-drone interactions

2 RELATED WORK

2.1 Drones for Communication

2.1.1 Visual Methods. A few researchers have explored lights, projections, and screens for drone-to-human communication. Szafir et. al used flashing lights to explore communicating the drone's intent to a user [44]. Knierim et. al. used a projection system to visualize arrows on the ground to help a person navigate [31]. Their system was limited to nighttime use. Scheible et. al. explored co-located displays by projecting content from a drone onto a projection screen that was affixed to the same drone [37]. They demonstrated its use in communicating information to people in indoor and outdoor settings. In Schneegass' 2014 work, they explored outdoor display screens without projections [38]. They found that when both the drone and user were in motion, it was difficult for the content to be read. Overall, light, projection, and screen communication methods can introduce visual limitations.

Other visual methods rely simply on the motion pattern of the drone to communicate to the human. These methods include uses for navigation [19], providing encouragement [21], communicating the drone's emotional state [17], the intent of the drone [43], and probing actions users would take in reaction to a drone's motion [12, 13]. All of these methods are limited to daytime use, unless a light is attached to the drone. They also rely on the person being able to track it at all times. This could be difficult in visually cluttered environments such as disaster zones or sporting events. They are also inaccessible to people with visual impairments.

2.1.2 Auditory Methods. Auditory methods for drone-to-human communication have largely been explored in the context of assistive devices, specifically for people with visual impairments. Examples include the work by Zayer et. al. to assist people with visual impairments in independent exercise [4]. Participants followed the sound of the drone to navigate while running around a track. Avila et. al. also explored navigation via the sound of a drone [10]. A participant followed the sound of the drone while walking with their white cane. Lastly, Grewe et. al. used a drone to scout ahead of a participant [21]. Obstacles were relayed to them via a bluetooth device. All of these methods show the potential when not just visual methods are used. These methods are still inaccessible to people with hearing impairments, and they are inaccessible to anyone when sufficient noise is present.

2.1.3 Physical Methods. Using physical touch as a communication method can make drones more accessible and expands their potential applications. Some researchers have explored this area, for example, the BitDrones project [35]. However, they used physical contact with drones to mediate human-to-human communication, not for drone-to-human communication. The only examples of touch being used for *instruction* is in work by Tognon et. al [46], Huppert et. al. [27], and Soto et. al. [41]. These works focused on drone-led navigation by providing guidance via a string, or tether; the latter two focused on people with visual impairments. Tognon created a force controller to guide a person through a hallway. Huppert focused on navigating just the fingers so the participant could locate objects on a table. They found that locating objects was easier with the string drone guidance than with guidance from an audio-based system. Soto focused on navigation down a hallway–participants held a device leashed to the drone in one hand and their white cane in the other. Soto found that participants were able to navigate down a hallway faster and more accurately with the tactile feedback from the tether than with verbal instructions. However simply following the sound of the drone (with no tether) proved to be the fastest method. Also, only two out of 14 participants preferred the tethered drone method; this was largely due to the fact that participants disliked having to hold another object in addition to their white cane. They also preferred the verbal feedback over the drone sound as they were sceptical that they would be able to hear the drone in loud environments. These works were a first step in exploring physical drone-to-human instruction, but it is important to create new methods, as the tether method is limiting.

2.2 Exploring Contact Locations

Because of the 3D interaction space, it is important to understand where people are comfortable interacting physically with a drone in order to design the most effective communication. Prior works have not focused on understanding this 3D interaction space in the context of physical interactions, and none have focused on drone-to-human communication or instruction. For example, works in virtual reality (VR) have primarily focused on the drone contacting the hand [1, 25, 29, 30, 49] and are used for providing an immersive experience, not communication. Similarly, works in real life have primarily focused on the hand [32, 36]. Abtahi et. al. explored users controlling the drone directly with their hands, but there was no element of drone-to-human communication [3]. Zwann et. al explore hand interactions through boxing [50]. Tsykunov et. al. expanded to explore hand [48] and arm [47] drone landing techniques. Cauchard et. al. are the only researchers to explore touch beyond hands and arms. They explored possible scenarios for on-body drone landing [9]. In this work, they explored the head, back, and arm as landing points. However, this work was simulated in VR and the intent was not to explore physical contact as a communication strategy. More work is needed to understand where and how people want to interact physically with drones in a communication context.

3 DESIGNING PHYSICAL INTERACTIONS

3.1 Design Criteria

As no examples of "unleashed" physical drone-to-human instruction existed in the literature, we designed our own set of interactions to establish a baseline. We wanted to understand, with as close to a bare drone as possible, what kinds of physical communications were possible. We wanted the interaction modes to be distinct from each other and designed in such a way that they could properly affect a person's movement.

We also developed a drone enclosure more suitable for physical contact. We wanted the material of the enclosure to allow the drone to easily maneuver on skin or clothing. We also wanted the system to be inexpensive and easily replicable, highlighting the potential for use in home applications. For safety, we determined that the drone should not fly at fast speeds, there should be no sharp edges on the enclosure, and there should be limited access to the propellers.

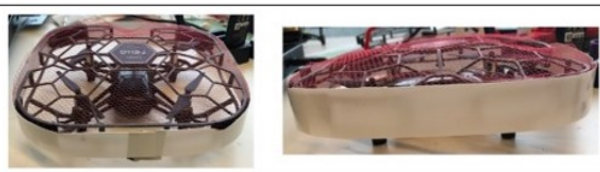

Figure 1: Drone Enclosure design

For the final design (Fig 1) we used a Tello Edu drone ($129 USD). It was 9.8×9.25×4.1 cm, weighed 108 g, and had a max speed of 100 cm/s. We modified a CYNOVA Tello cage with mesh for safety and to increase the available contact surfaces of the drone. An ABS plastic strip of 0.025 mm thickness was added around the cage to reduce friction and allow sliding motions across clothing and skin.

3.2 Interaction Modes

3.2.1 Inspiration and Exploratory Studies. To draw inspiration for the interaction modes we observed two live, and several virtual, dance classes. We took notes about the reasons instructors used physical contact, what kinds of contacts they chose (i.e., location, duration, etc.), and what the result was (i.e., student's response). We found that instructors most often used their hand to move the student's limb into the correct position, and then released.

We recruited five participants for pilot studies. We experimented with different speeds and durations to understand what kinds of interactions were possible and to tune parameters. Through this process, we created two categories of movement: 1) Continuous and 2) Instantaneous interactions.

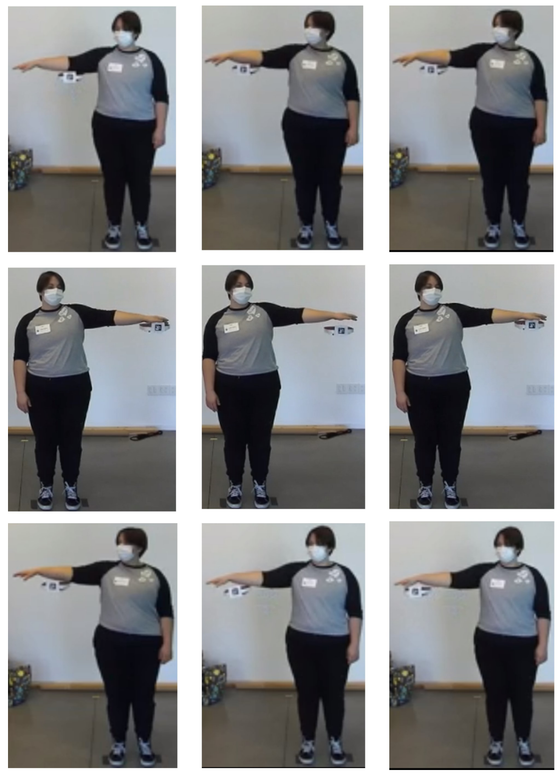

Figure 2: Drone Interaction Modes. For Guide and Slide time increases from left-to-right–Tap from right-to-left. Top: Guide. Middle: Tap. Bottom: Slide.

3.2.2 Final Interaction Modes. We chose three interactions that fit within the two classes of movement. Tap represents instantaneous interactions while Guide and Slide represent continuous interactions.

Guide was inspired by the way movement instructors give corrective physical feedback as noted in our observation phase. There was one contact point, and the drone maintained contact for four secs before retreating (Fig. 2 Top). We chose a speed of 10 cm/s to prevent the drone from rotating around the person's body during the extended period of contact.

Tap was inspired by the common way people try to get another's attention by tapping, for example, their shoulder or arm. The drone tapped at one contact point. To tap, the drone hit the intended body part and then retreated quickly (Fig. 2 Middle). The speed of Tap was 20 cm/s.

Slide is a combination of Tap and Guide. The drone tapped at one body part and then slid to another, maintaining contact for an extended period of time, (Fig. 2 Bottom). Slide also represents a new interaction made possible by our enclosure design. We determined 40 cm/s was a sufficient speed to overcome the friction caused by clothes or skin.

3.3 Experiments

We conducted two experiments to answer our research questions. The first, Comfort Study, was to gain foundational knowledge about where and how people want to have physical interactions. We also explored how people naturally infer physical communications from drones through interview questions and an exploratory phase. We used feedback from this study to refine the interactions.

Our second, Instruction Study, focused on understanding the best way for a drone to physically communicate instructions to a human. This represents scenarios where the drone would be in an authority role, for example at an outdoor concert for crowd control, for navigation, or in our case for at-home exercise.

4 COMFORT STUDY

4.1 Method

We conducted a within subjects study. We counterbalanced the order in which participants experienced each interaction. We did not control for types of clothing because in real life drone-to-human communication scenarios, people could wear a variety of clothing. We included an exploratory, untrained instruction phase as improvisation has been shown to be a good technique in the beginning stages of the HRI design process for new interactions [40].

4.1.1 Contact Locations. We identified seven contact points of interest. We chose not to go above the head or behind participants back based on prior research and for safety reasons. We determined that the arms, legs, and side would be most accessible to the drone, and most comfortable for people, as these are areas movement instructors touch. The seven locations for Tap and Guide are highlighted in Fig. 3A. Since Slide contacts multiple locations, we modified the contact points reducing it to four locations Fig. 3B.

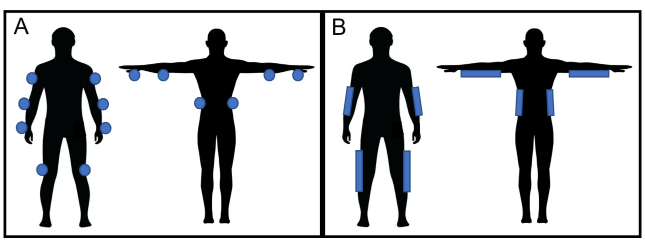

Figure 3: Study 1 Contact Points. A: Contact points for Tap and Guide. B: Contact points for Slide.

4.1.2 Participants. We recruited 12 participants (7 female, 3 male, 2 nonbinary or gender non-conforming). Participants' ages ranged between 22-32 (avg 26, std 3.2). Participants came from the University campus, the greater NYC area, and one from Japan. Occupations ranged from STEM students, business students, entrepreneurs, HR representatives, and fashion designers. We recruited via social media posts, messaging apps such as Group Me and Slack, email lists, and word of mouth. Three participants had used a drone before. Ten participants had taken a dance or movement class before and eight had received physical correction from an instructor. Participants were not paid.

4.1.3 Experimental Setup. We used a ZED 2 camera for skeleton and depth tracking. We placed an Aruco Marker on the drone and used OpenCV to track its position. On screen visualizations were rendered at the 7 contact points and a start location 5.25 cm away was rendered based on these locations. The pilot flew the drone to the starting location using a keyboard and the Tello SDK then pressed "go" and the pre-programmed flight path executed the final interaction modes as described in Sec. 3.2.2. We used pre-programmed paths to ensure consistency between participants and remove pilot error. Small variations in the contact were due to participants clothing texture. This is discussed in detail in Sec. 4.1.5.

The operator sat at a desk with the laptop and camera set up and participants stood 3 m away.

4.1.4 Procedure. Participants were brought into the experiment room and briefed. Then consent was given. We conducted a demographic interview, and asked questions about previous experience with drones, dancing, and movement instruction. We asked them to rank their fear of personal drones and their apprehension with a personal drone touching them on a Likert scale to assess their initial state. Participants then stood on a marked line. Each participant was warned when the drone was taking off. The drone hovered by their side and they were instructed to tap it a few times with their hand to get comfortable with touching the drone. The drone was then landed and placed by the participant's side. Then it took off again and began the interaction starting with the shoulder, elbow, wrist, then knee. Participants were then asked to lift their arm for the under elbow, hand, and waist interactions. We alternated sides between interaction modes. After each interaction mode, participants were interviewed. We asked what they thought the drone was trying to get them to do, to rank their comfort level at each body part on a 7-point Likert scale, and asked where they felt most and least comfortable being touched by the drone and why. After all interaction modes, we asked them to force rank the interactions, provide reasons for the rankings, and to rate their fear and apprehension once more.

For the second part of the study, participants were then instructed to stand with their arms in Ballet first position. The researcher demonstrated the pose. They were told that the drone would come over and interact with them, and they should move in whatever way they thought the drone was instructing them. The operator flew the drone to different positions on the participants' arms using the interaction modes, starting with the mode they ranked highest. We took detailed notes during the interviews. We audio and video recorded all sessions. The session lasted 1.25 hrs. We sanitized the drone between participants, and they were required to wear masks. This experiment was approved by our Institution's Review Board.

4.1.5 Analysis. Despite our efforts, there were slight variations in the interactions between participants due to the differences in clothing, the accuracy of the depth measurements, and the controller limitations of the drone. We did video analysis to quantify these variations. We noted the clothing worn for all of the participants. As Guide and Tap could potentially be perceived as the same interaction if not executed properly, we recorded the amount of time the drone was in contact with the participant during Guide and Tap for P1, P6, and P12. This represented how accurate the drone operator

	1	2	3	4	5	6	7
Shoulder	12	4	2	2	2	0	2
Elbow	12	12	0	0	0	0	0
Wrist	10	8	2	4	0	0	0
Knee	12	2	8	0	2	0	0
Under Elbow	10	6	0	6	0	0	0
Hand	8	6	6	0	0	0	2
Waist	8	8	4	0	2	2	0
Outer Arm	6	2	3	0	0	1	0
Leg	5	3	2	2	0	0	0
Under Elbow	4	5	1	1	1	0	0
Waist	4	2	2	1	1	2	0

Table 1: Study 1: The average Likert scores reported by participants for comfort at each contact location. Shoulder-Waist are the average scores for Tap and Guide combined (total of 24 data points), while Outer Arm-Waist are the average scores for Slide (total of 12 data points). 1 = "very comfortable" and 7 = "very uncomfortable".

was during the beginning, middle, and end of the experiment. The standard deviation of the contact time was 1.3 secs for Tap and 1.8 secs for Guide. We found that on average, Guide was 2.3 secs, or two times, longer than Tap. Based on this difference in contact time and the differences in speeds between Guide and Tap (10 cm/s and 20 cm/s respectively) we concluded that there was a distinct difference between Guide and Tap for all participants. Tap was a short, forceful interaction while Guide was a longer, lighter interaction. This confirmed we were aligned with our design criteria that interaction modes should be distinct from each other.

To assess participant comfort, we averaged the Likert scores and took detailed notes during the interviews. We analyzed the notes to identify the reasons why participants ranked the three interactions, and their comfort levels at different body parts. We used grounded and inductive coding to identify themes. We chose this method as this is novel work and no prior theory for physical drone-to-human communication exists.

We did video analysis to understand people's reactions during the free movement portion. We took notes on each participants actions and grouped them into categories. These categories informed the design decisions for modifying the interactions.

4.2 Results

4.2.1 Contact Location Preferences. Understanding the contact location preferences helps us gain insights about *where* people feel comfortable interacting in physical drone-to-human communication. We report the Likert scores and common themes reported by participants.

In general participants felt comfortable with the drone touching them, as evidenced by the post-experiment average Likert score of 1.9 for both fear of drones and apprehension of being touched by a drone. The Likert scale questions ranged from 1-"very comfortable" to 7-"very uncomfortable". The low ($\leq$ 2.9) score averages across all body parts are also evidence of people's general comfort with the drone's physical contact. For specific scores at each body part see Table 1. A notable exception was P4. She was generally uncomfortable with the drone and commented, "I felt like it was biting me. Like an animal attacking me".

Though most Likert scores were low, participants reasons for feeling uncomfortable at certain locations varied. Two participants (P9 and P12) rated their knee and arm higher for medical reasons. They stated normally they would feel comfortable at these locations, but those points were more sensitive at the time of the experiment. Some participants rated shoulder higher, not because the interaction felt uncomfortable, but because the drone was closer to their ear so the noise bothered them. The waist was also not very well received. Most participants felt least comfortable with the drone touching here largely because the waist is an area only very familiar people would touch. An exception was P8. She expressed being most comfortable with the waist because it was a common contact point in Ballroom dancing. These variations show that people's prior experiences interacting with others and personal circumstances influence their comfort level with where the drone touches.

People's favorite and least favorite contact locations varied slightly by interaction. For Tap, the best ranked body part was Elbow, 1.5, and the worst was a tie between Shoulder, Hand, and Waist, 2.4. For Slide, the best were Outer Arm and Leg, 2.1, and the worst was Waist, 2.9. For Guide, the best was Elbow, 1.3, and Hand was the worst, 2.0. The hand ratings support participants' (P4, P11) comments who expressed not liking the hand interactions because they could feel the vibrations of the motors more. Since Guide was the longest interaction, the drone was on their hand for the longest time, and contacting bare skin, as opposed to Tap which contacted the bare skin of the hand, but for a shorter period of time. On the other hand, some participants expressed liking the hand the most because feeling the drone directly made them feel like they had more control over it (P3, P5). Overall the results indicate that the elbow or outer arm are the best locations for a drone to initiate physical communication, regardless of the kind of interaction.

4.2.2 Interaction Modes Preferences. The interaction modes represent different ways that the drone can physically communicate with a person. Understanding *how* people felt about each interaction is important to design communications that will be well received.

The forced ranked order was Tap, Slide, then Guide. Six participants ranked Tap first. Six ranked Slide second, and six ranked Guide last. The average Likert score independent of contact location was 1.8, 2.1, and 2.3 for Guide, Tap, and Slide respectively. While Guide was ranked the lowest in terms of preference, it was scored the highest in terms of comfort–aligning with participants' comments that Guide felt like the lightest touch. These findings indicate that people are willing to trade a bit of comfort for a more clear communication.

4.2.3 Inference of Interaction Modes. We saw common themes emerge across participants about what they thought the drone was trying to communicate with the three different interactions. These themes help us understand how to design interactions for specific scenarios and to convey specific instructions.

While Tap and Guide/Slide represented different categories of interactions, instantaneous and continuous respectively, people still found similarities between them. For example, participants commented for Slide they thought the drone was trying to measure or classify them (P4 and P12). This measurement or calibration was also mentioned by P1 and P9 for Tap and Guide. P3 also mentioned it for Tap. In our experimental set up, the drone traveled from one body part to the next. We believe this action of interacting at multiple body points in succession is what led to this interpretation.

For Guide specifically, there were a few common communications participants identified. One was that either no instruction was being given (P4 and P8), or that the drone was trying to communicate, but the instruction was unclear (P5, P6, P9). Some participants thought that the drone was trying to get their attention (P2, P3, P7, P12), either to warn them "... it needs my attention like water is boiling," P3, or to play with them (P5 and P9). P5 commented, "He's a flying animal. . . when he touched my hand, I would think he wants me to do something like a dog." Interestingly, P10 thought the drone was trying to get their attention, but not directed at the drone or something externally, rather, they thought the drone was trying to bring their attention to that particular body part. P5 and P7 also mentioned this for Tap. Some participants (P3, P6) thought that Tap felt similar to Guide, but overall people felt that Tap was more clear. The reasons given were that Tap exerted more force or that contacting twice seemed more decisive than the drone just lightly holding its position at a contact location as in Guide. Some also viewed Tap as an instruction, for example P7 noted "[If I was exercising] I'd think my arm was not high enough, or remember to pay attention to that area."

Participants generally commented that Slide meant they should prepare for something, like it was comforting them. For example, "I feel like it's breathy. I don't have an innate encoding, but the sensation is pleasant, like a light massage. It's comforting." (P2). Few participants mentioned that Slide meant an arm adjustment, and the ones who did had different answers for what that adjustment would be (ie. move arm down, up, forward). Some participants mentioned that when sliding at their leg they would think the drone was prompting them to lift it or step out. At the arms and side, people thought the drone was telling them to either relax or straighten their muscles, such as lengthen their outstretched arm or stand up taller (P1, P3, P7, P9, P10, P12).

Lastly, we noticed people had different interpretations depending on the contact location. P3 noted, "It's different based on the body part... at my hand it seems more like it needs my attention, like water is boiling." For example, at the under arm regions, people thought the drone was trying to get them to adjust their arm. At their hand, people mentioned it seemingly like a pet, and at the elbow some people interpreted it to mean they should move over.

4.2.4 Untrained Instruction Inferences. The free-form movement phase helped us understand how to design physical drone-to-human instructions by identifying how people naturally respond to instructions when no prior training is given.

We found that participants were largely confused by Slide, especially when the drone slid back and forth across their arm. Another behavior we saw was people rotated their torsos, or moved their feet, to turn all the way around when the drone pushed their arm from the side. Another observation was some participants tried to move their arms with the drone, and some participants resisted being moved altogether. Most participants moved only the arm being touched, but a few moved both arms at once. In Tap, we observed participants moved their arms in different increments–some a few centimeters, while others moved 30 cm or more, and some altered the increments throughout the interaction. This was also observed in the pilot study. While there were variations, we generally saw that people moved their arms in the desired direction during Tap and Guide.

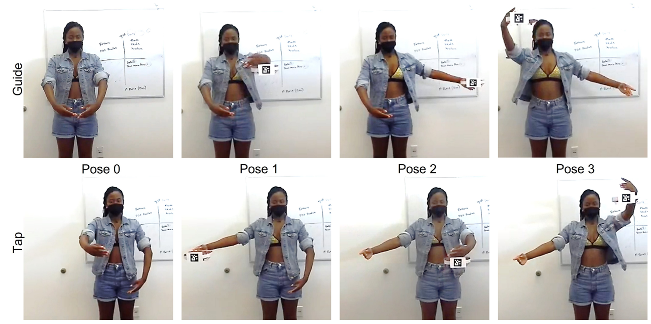

Figure 4: Study 2 Ballet pose sequences for Guide and Tap

4.2.5 General Themes. Some participants referred to the drone as an animal and others gendered the drone. One participant, P2, said the drone reminded them of a small animated assistant found in some mobile video games. As the drone approached participants slowly for safety reasons, some participants expressed wanting to help the drone reach them. Some saying encouraging things like "you can do it". Additionally, despite not designing for appearance a few participants commented that the drone was "cute".

5 INSTRUCTION STUDY

5.1 Method

Based on results from Study 1, we chose to modify Guide, and exclude Slide. We increased Guide to be 20 cm/s to match the speed of Tap since Tap was highest rated. Matching the speed also gave a more fair comparison to Tap in this instruction context. As mentioned in section 4.2.3 when asked what Slide meant, few participants mentioned an arm adjustment, and the ones who did had different answers for what that adjustment would be. Therefore, we decided that Slide was not best suited for adjusting arm poses as the direction would be unclear. Some participants mentioned that when sliding at their legs they would think the drone was prompting them to step out or lift their leg. However, as Study 2 focused on arm adjustments, this was not relevant. Based on these findings and our observations in section 4.2.4 we concluded that Slide is best for instructing people to hold or straighten a position and provide comfort. Slide might be best for fine tuning, not getting general shapes like we aimed to do in Study 2. We were more focused on the transitions between poses in a sequence rather than the engagement of the muscles. Though we excluded Slide, Continuous and Instantaneous feedback were still represented in the study with Guide and Tap respectively. We alternated the order participants were instructed with each during the study.

5.1.1 Participants. We recruited 14 participants (8F, 6M) ages 18-35, (avg 28, std 4). We recruited using the same methods as Study 1 and posted flyers around the surrounding University neighborhood location. Four participants had used a drone before and 13 had taken a dance or movement class. Of those, 12 had received correction in the form of physical feedback.

5.1.2 Procedure. The same experimental setup was used except participants stood 2 m away. Participants were brought into the room for briefing and given the same demographic interview as Study 1. Before each mode, there was a training period so participants could get used to the instruction. There were three poses in each sequence. If participants did not get the correct position, the next pose was attempted. When this happened if the participant was in a position that would prevent the drone from attempting the instruction, the operator demonstrated the failed pose so they could start from a neutral position. After each mode, participants were asked if there were any points of confusion. After the experiment, participants were asked which interaction mode was their favorite and why. They were asked to rate their fear and apprehension again and what applications they could see for the drone.

5.1.3 Analysis. We did video analysis to identify how long the drone contacted the participant in each pose, the amount of time it took to correct each pose, the number of times the drone made contact, and how many participants failed to reach the correct pose. The sum of the contact time was counted as "correction time". The time it took for the operator to fly the drone to the correct position was not included so an even comparison could be drawn across participants. We took detailed notes during the interview and analysed them to find common themes. We also analysed the videos to observe human behaviors during the instruction.

We again used open coding and grounded method. Before coding two researchers discussed the data and decided on preliminary codes. We then coded 2 participants (12 video clips) together. We defined what counted as a touch by looking at the clear physical reactions evident when the drone collided with a participant (ex: the drone bouncing and tilting). We came to a consensus about what counted as a touch. Then researcher 2 coded participants 3-14 alone. As they saw some behaviors not previously discussed, both researchers discussed them and agreed before adding the code. Researcher 1 then looked at participants 3-14 to confirm failures counted by researcher 2. Researcher 1 then wrote a script to count the contact time, the average number of contacts, the average duration of each contact, and the number of fails.

To analyze the interview responses Researcher 1 grouped similar answers into themes and Researcher 2 reviewed the notes and themes to ensure the findings were properly captured.

5.2 Results

5.2.1 Pose Accuracy. Determining the accuracy of each pose helped us understand which category of feedback, Continuous or Instantaneous, was best for correctly communicating an instruction. Pose accuracy essentially translates to how clear the instruction was by measuring how many people comprehended it. Similar to the first study, we used on screen visualizations so the operator knew where to start the drone. The visualizations also indicated when the participant had reached the correct pose. We compared the number of times a participant failed to reach the correct pose in the sequence (Table 2). Most participants were able to reach the correct pose. However, no participants failed in Guide while there were five fails for Tap.

	Pose	Avg CT (s)	Avg No. Contacts	Avg Contact Length (s)	Total No. Fails
Guide	1	5	4	2	2
	2	12	12	0	0
	3	10	8	2	4
Tap	1	12	2	8	0
	2	10	6	0	6
	3	8	6	6	0

Table 2: Study 2 comparison between instructing with Guide vs Tap. Note: Data for P4 Guide pose 1 and 3 were not saved and have been excluded from the results. CT = Correction Time.

5.2.2 Instruction Mode Preferences. While a clear instruction is very important, we also wanted to understand user preference. Most (11) participants preferred Guide over Tap. The general consensus was that Guide was more clear as it gave continuous feedback. The three who preferred Tap thought it was more clear because the incremental feedback let them know they were on the right track. P13 for instance said Tap was encouraging–like the drone was saying "good job".

Overall, the preference for Guide in this movement instruction task was not surprising considering its design was inspired by observing movement instructors. The modification learned from Study 1 to increase the drone's speed to match that of Tap's probably increased the likelihood of Guide being preferred, as well as its likelihood of success.

5.2.3 Sources of Confusion. Understanding the reasons participants failed or were confused helps us know what to avoid when designing future drone-to-human instructions. The biggest source of confusion for Tap was participants (P5, P6, P8, P10, P11) were not sure how far to move their limb. This echos our observations in Study 1. This confusion might be what lead to one of the observed behaviors. Essentially, participants did not break contact with the drone, but instead moved with it until it retreated. They then waited for it to tap again before continuing to be corrected. This was different then what we expected the interaction to look like. We anticipated people would move as soon as they were tapped, essentially breaking contact with the drone almost immediately. These participants effectively used Tap as a smaller step-sized Guide.

5.2.4 General Themes. We observed that people either moved together with the drone, waited until a bit after it touched them, or moved before it touched them. Some of the ways in which people moved together with the drone, almost seemed as though they were trying to work with it, not simply receive instructions from it. The findings for this are not conclusive from this study as collaboration was not the focus, but this is an interesting area for further exploration. Additionally, a few participants expressed not needing to wait for the drone to touch them before knowing what to do. This was shown in the data as 12 participants moved before the drone made contact at least one time.

Some participants commented on the general experience. Some noted that the drone was louder than they expected, P8 thought that the drone could look more friendly, and four participants commented the drone was too slow and it took too long to get them into the next pose.

When asked about possible applications for drone-to-human instruction participants, unsurprisingly, thought of independent exercise. Specifically, some mentioned it could be good for virtual instruction, or for dance instruction as a game for a console such as Wii or Xbox. Others thought it could be a good application to teach people with visual impairments how to dance or help them navigate around the home or store. Two participants had ideas outside of movement instruction. P1 thought it would be good for hanging level pictures. P7 thought it could be helpful for reminding her in certain scenarios like cooking (i.e., drone bumps her hand when that is enough spice) or while working (i.e., drone reminds her to stop slouching).

6 DISCUSSION

We set out to answer the research questions: *Where on the body and in what way do people feel comfortable being touched by a drone* and *What physical interactions allow a drone to successfully communicate pose instructions to a human?* by first understanding (1) where and how people feel comfortable physically interacting, and (2) how people naturally infer instructions with no prior training. We answer these questions by contextualizing our findings with respect to other human-drone interaction work and summarize our findings as design considerations.

6.1 Comparisons to Prior Work

6.1.1 Instruction. Our work and the tethered navigation method [27, 41, 46] are examples of successful physical drone-to-human instruction, but our work enables more freedom. It would be interesting to see how our system would compare to the leashed drone methods in the same hallway navigation tasks. These works and ours emphasize the potential for physical instruction to open the door for broader drone applications.

6.1.2 Comfort. It has been established that people feel comfortable controlling a drone directly by using their hands [2, 16, 32]. Our work has provided further insights into how the length and frequency of a hand interaction affects people's comfort level. Ours is also the first to explore hand interactions specifically for drone-to-human communication. The differences between our study and previous work with regard to how much control the user had, might explain the differences in user perceptions. We found that there is a limit to how long people want to interact in hand interactions and that the cage design plays a major role. Exploring customized cage designs like those explored in [23] could optimize the vibration level for each user.

In work by Auda et. al. [9], they found that the outer arm region was where people felt most comfortable with a drone landing. They also found that people were least comfortable with a drone landing on their waist. Although their work was about drone docking and not direct contact, this aligns with our findings regarding comfort at the outer arm being the best region and the waist being the worst region for physical interactions.

Lastly, several participants compared the drone to a pet or gendered it [16], or found the drone too noisy [41], aligning with prior research .

6.2 Design Considerations

We summarize the general takeaways for researchers to consider when designing physical drone-to-human communications:

- Short interactions at multiple body parts conveys that the drone is processing or calibrating.
- The drone staying at one body part for an extended period of time is good for drawing a person's attention, either to something external or internal.
- The contact surface and length of the contact affect how people feel about the interaction. Cage design can minimize vibrations, thus increasing comfort.
- Continuous contact is best for movement instruction.
- The elbow or outer arm are the best locations for people to feel comfortable with an interaction.
- A force that is too light will likely cause confusion.

6.3 Limitations

The number of participants was small, and as this was an unpaid study, we likely recruited participants who viewed drones favorably. Increasing the number of participants would give a better idea of the general population's feelings towards physical drone-to-human communication. Due to clothing, some participants did not experience two taps at each location. Though the intended application of the second study was a controlled environment (i.e., independent movement instruction), the first study was limited to a lab environment. Repeating this study in an unstructured or outdoor environment would lead to more insights about how people would perceive and feel comfortable with physical drone-to-human communication in uncontrolled scenarios. Also, this study was not truly Wizard of Oz as the operator was in the room. This could influence people's perceptions of the drone and their comfort level. Lastly, further reflection is needed regarding the broader safety implications of touch-based drone instruction in real world settings.

7 CONCLUSION

We designed novel physical interactions for drone-to-human communication. We conducted two user studies to understand people's comfort level in physical interactions with drones and how they interpreted these designs. We also introduced a new application for drones, physical instructive feedback, and established a baseline for understanding the best interaction mode for this kind of instruction. Future work should explore these interactions in other settings, and create new physical drone-to-human communications for other applications based on our findings.

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REFERENCES

[1] Muhammad Abdullah, Minji Kim, Waseem Hassan, Yoshihiro Kuroda, and Seokhee Jeon. 2018. HapticDrone: An encountered-type kinesthetic haptic interface with controllable force feedback: Example of stiffness and weight rendering. In *IEEE Haptics Symposium, HAPTICS*, Vol. 2018-March. https://doi.org/10.1109/HAPTICS.2018.8357197

[2] Parastoo Abtahi, David Zhao, Jane E., and James Landay. 2017. Drone Near Me: Exploring Touch-Based Human-Drone Interaction. *IMWUT* 1, 3 (2017).

[3] Parastoo Abtahi, David Y. Zhao, Jane L. E., and James A. Landay. 2017. Drone Near Me. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 1, 3 (9 2017), 1–8. https://doi.org/10.1145/3130899

[4] Majed Al Zayer, Sam Tregillus, Jiwan Bhandari, Dave Feil-Seifer, and Eelke Folmer. 2016. Exploring the Use of a Drone to Guide Blind Runners. In *Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility*. ACM, New York, NY, USA, 263–264. https://doi.org/10.1145/2982142.2982204

[5] Alex Heath. 2022. Snapchat's Flying Camera. https://www.theverge.com/2022/4/28/23043011/snapchat-pixy-drone-hands-on

[6] Hesam Alizadeh, Ehud Sharlin, Richard Tang, and Anthony Tang. 2014. Haptics in remote collaborative exercise systems for seniors. In *Conference on Human Factors in Computing Systems - Proceedings*. https://doi.org/10.1145/2559206.258131

[7] Thomas Arnold and Matthias Scheutz. 2018. Observing Robot Touch in Context: How Does Touch and Attitude Affect Perceptions of a Robot's Social Qualities?. In *ACM/IEEE International Conference on Human-Robot Interaction*. https://doi.org/10.1145/3171221.3171263

[8] Tomas Ascensao and Anahita Jamshidnejad. 2022. Autonomous Socially Assistive Drones Performing Personalized Dance Movement Therapy: An Adaptive Fuzzy-Logic-Based Control Approach for Interaction with Humans. *IEEE Access* 10 (2022). https://doi.org/10.1109/ACCESS.2022.3143992

[9] Jonas Auda, Martin Weigel, Jessica R. Cauchard, and Stefan Schneegass. 2021. Understanding Drone Landing on the Human Body. In *Proceedings of MobileHCI 2021 - ACM International Conference on Mobile Human-Computer Interaction: Mobile Apart, MobileTogether*. https://doi.org/10.1145/3447526.3472031

[10] Mauro Avila Soto, Markus Funk, Matthias Hoppe, Robin Boldt, Katrin Wolf, and Niels Henze. 2017. DroneNavigator. https://doi.org/10.1145/3132525.3132556

[11] Christopher Banks, Antonio Bono, and Samuel Coogan. 2021. Physical Human-UAV Interaction with Commercial Drones using Admittance Control. In *IFAC-PapersOnLine*, Vol. 54. https://doi.org/10.1016/j.ifacol.2021.11.184

[12] Alisha Bevins and Brittany A. Duncan. 2021. Aerial Flight Paths for Communication. *Frontiers in Robotics and AI* 8 (2021). https://doi.org/10.3389/frobt.2021.719154

[13] Alisha Bevins and Brittany A. Duncan. 2021. Aerial flight paths for communication: How participants perceive and intend to respond to drone movements. In *ACM/IEEE International Conference on Human-Robot Interaction*. https://doi.org/10.1145/3434073.3444645

[14] Felix Born, Maic Masuch, and Antonia Hahn. 2020. Ghost Sweeper: Using a Heavy Passive Haptic Controller to Enhance a Room-Scale VR Exergame. In *IEEE Conference on Computatonal Intelligence and Games, CIG*, Vol. 2020-August. https://doi.org/10.1109/CoG47356.2020.9231867

[15] Anke M. Brock, Julia Chatain, Michelle Park, Tommy Fang, Martin Hachet, James A. Landay, and Jessica R. Cauchard. 2018. FlyMap: Interacting with maps projected from a drone. In *PerDis 2018 - Proceedings of the 7th ACM International Symposium on Pervasive Displays*. https://doi.org/10.1145/3205873.3205877

[16] Jessica R. Cauchard, Jane L. E, Kevin Y. Zhai, and James A. Landay. 2015. Drone & me: an exploration into natural human-drone interaction. *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing - UbiComp '15* (2015). https://doi.org/10.1145/2750858.2805823

[17] Jessica R. Cauchard, Kevin Y. Zhai, Marco Spadafora, and James A. Landay. 2016. Emotion encoding in human-drone interaction. In *ACM/IEEE International Conference on Human-Robot Interaction*, Vol. 2016-April. https://doi.org/10.1109/HRI.2016.7451761

[18] Alexandre Cherpillod, Dario Floreano, and Stefano Mintchev. 2019. Embodied Flight with a Drone. In *2019 Third IEEE International Conference on Robotic Computing (IRC)*. IEEE, 386–390. https://doi.org/10.1109/IRC.2019.00070

[19] Ashley Colley, Lasse Virtanen, Pascal Knierim, and Jonna Häkkilä. 2017. Investigating drone motion as pedestrian guidance. In *ACM International Conference Proceeding Series*. https://doi.org/10.1145/3152832.3152837

[20] Henriette Cramer, Nicander Kemper, Alia Amin, and Vanessa Evers. 2008. The effects of robot touch and proactive behaviour on perceptions of human-robot interactions. In *Proceedings of the 4th ACM/IEEE International Conference on Human-Robot Interaction, HRI'09*. https://doi.org/10.1145/1514095.1514173

[21] Eberhard Graether and Florian Mueller. 2012. Joggobot. In *CHI '12 Extended Abstracts on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1063–1066. https://doi.org/10.1145/2212776.2212386

[22] Lynne Grewe and Garrett Stevenson. 2019. Seeing eye drone. In *Proceedings of the ACM Turing Celebration Conference - China*. ACM, New York, NY, USA, 1–5. https://doi.org/10.1145/3321408.3321414

[23] Hooman Hedayati, Ryo Suzuki, Daniel Leithinger, and Daniel Szafir. 2020. PufferBot: Actuated Expandable Structures for Aerial Robots. In *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 1338–1343. https://doi.org/10.1109/IROS45743.2020.9341088

[24] Viviane Herdel, Lee J. Yamin, and Jessica R. Cauchard. 2022. Above and Beyond: A Scoping Review of Domains and Applications for Human-Drone Interaction. In *CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–22. https://doi.org/10.1145/3491102.3501881

[25] Matthias Hoppe, Pascal Knierim, Thomas Kosch, Markus Funk, Lauren Futami, Stefan Schneegass, Niels Henze, Albrecht Schmidt, and Tonja Machulla. 2018. VRHapticDrones: Providing haptics in virtual reality through quadcopters. In *Proceedings of the 17th International Conference on Mobile and Ubiquitous Multimedia*. ACM, New York, NY, USA, 7–18. https://doi.org/10.1145/3282894.3282898

[26] Kevin Hung, Nathan Wan, Sheung On Choy, Carlin Chu, and Daniel H.K. Chow. 2016. Design of an exergaming system with haptic feedback for the investigation of energy expenditure and muscle activities. In *IEEE International Conference on Industrial Informatics (INDIN)*, Vol. 0. https://doi.org/10.1109/INDIN.2016.7819286

[27] Felix Huppert, Gerold Hoelzl, and Matthias Kranz. 2021. GuideCopter - A Precise Drone-Based Haptic Guidance Interface for Blind or Visually Impaired People. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–14. https://doi.org/10.1145/3411764.3445676

[28] Alexandra Kalaitzidou, Nathalie Senechal, Paschalis Dimitriou, Krishnan Chandran, and Matthew Mcginity. 2022. "E-WAFE" - A Full Body Embodied Social Exergame. In *Extended Abstracts of the Annual Symposium on Computer-Human Interaction in Play*. ACM, New York, NY, USA, 286–290. https://doi.org/10.1145/3505270.3558375

[29] Pascal Knierim, Thomas Kosch, Alexander Achberger, and Markus Funk. 2018. Flyables. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, New York, NY, USA, 329–336. https://doi.org/10.1145/3173225.3173273

[30] Pascal Knierim, Thomas Kosch, Valentin Schwind, Markus Funk, Francisco Kiss, Stefan Schneegass, and Niels Henze. 2017. Tactile drones - Providing immersive tactile feedback in virtual reality through quadcopters. In *Conference on Human Factors in Computing Systems - Proceedings*, Vol. Part F127655. https://doi.org/10.1145/3027063.3050426

[31] Pascal Knierim, Steffen Maurer, Katrin Wolf, and Markus Funk. 2018. Quadcopter-Projected In-Situ Navigation Cues for Improved Location Awareness. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–6. https://doi.org/10.1145/3173574.3174007

[32] Marc Lieser, Ulrich Schwanecke, and Jorg Berdux. 2021. Evaluating distances in tactile human-drone interaction. In *2021 30th IEEE International Conference on Robot and Human Interactive Communication, RO-MAN 2021*. https://doi.org/10.1109/RO-MAN50785.2021.9515313

[33] Marc Lieser, Ulrich Schwanecke, and Jörg Berdux. 2021. Tactile Human-Quadrotor Interaction: MetroDrone. In *TEI 2021 - Proceedings of the 15th International Conference on Tangible, Embedded, and Embodied Interaction*. https://doi.org/10.1145/3430524.3440649

[34] Dylan P. Losey, Craig G. McDonald, Edoardo Battaglia, and Marcia K. O'Malley. 2018. A review of intent detection, arbitration, and communication aspects of shared control for physical human–robot interaction. https://doi.org/10.1115/1.4039145

[35] Calvin Rubens, Sean Braley, Antonio Gomes, Daniel Goc, Xujing Zhang, Juan Pablo Carrascal, and Roel Vertegaal. 2015. BitDrones: Towards self-levitating programmable matter via interactive 3D quadcopter displays. In *UIST 2015 - Adjunct Publication of the 28th Annual ACM Symposium on User Interface Software and Technology*. https://doi.org/10.1145/2815585.2817810

[36] Scarlett Entertainment. 2020. Aerial Drone Dance. https://scarlettentertainment.com/acts/aerial-drone-dance

[37] Jürgen Scheible and Markus Funk. 2016. In-Situ-DisplayDrone: Facilitating Co-located interactive experiences via a flying screen. In *PerDis 2016 - Proceedings of the 5th ACM International Symposium on Pervasive Displays*. https://doi.org/10.1145/2914920.2940334

[38] Stefan Schneegass, Florian Alt, Jürgen Scheible, and Albrecht Schmidt. 2014. Midair displays: Concept and first experiences with free-floating pervasive displays. In *PerDis 2014 - Proceedings: 3rd ACM International Symposium on Pervasive Displays 2014*. https://doi.org/10.1145/2611009.2611013

[39] Stefan Schneegass, Albrecht Schmidt, Florian Alt, Haifeng Su, and Jürgen Scheible. 2014. Midair displays: Exploring the concept of free-floating public displays. In *Conference on Human Factors in Computing Systems - Proceedings*. https://doi.org/10.1145/2559206.2581190

[40] David Sirkin, Brian Mok, Stephen Yang, and Wendy Ju. 2015. Mechanical Ottoman: How Robotic Furniture Offers and Withdraws Support. In *ACM/IEEE International Conference on Human-Robot Interaction*, Vol. 2015-March. https://doi.org/10.1145/2696454.2696461

[41] Mauro Avila Soto, Markus Funk, Matthias Hoppe, Robin Boldt, Katrin Wolf, and Niels Henze. 2017. DroneNavigator: Using leashed and free-floating quadcopters to navigate visually impaired travelers. In *ASSETS 2017 - Proceedings of the*

19th International ACM SIGACCESS Conference on Computers and Accessibility. https://doi.org/10.1145/3132525.3132556

[42] Juulia T. Suvilehto, Enrico Glerean, Robin I.M. Dunbar, Riitta Hari, and Lauri Nummenmaa. 2015. Topography of social touching depends on emotional bonds between humans. *Proceedings of the National Academy of Sciences of the United States of America* 112, 45 (2015). https://doi.org/10.1073/pnas.1519231112

[43] Daniel Szafir, Bilge Mutlu, and Terrence Fong. 2014. Communication of intent in assistive free flyers. In *Proceedings of the 2014 ACM/IEEE international conference on Human-robot interaction.* ACM, New York, NY, USA, 358–365. https://doi.org/10.1145/2559636.2559672

[44] Daniel Szafir, Bilge Mutlu, and Terry Fong. 2015. Communicating Directionality in Flying Robots. In *ACM/IEEE International Conference on Human-Robot Interaction*, Vol. 2015-March. https://doi.org/10.1145/2696454.2696475

[45] Tessa Wong. 2015. Drone waiters to plug Singapore's service staff gap. https://www.bbc.com/news/world-asia-31148450

[46] Marco Tognon, Rachid Alami, and Bruno Siciliano. 2021. Physical Human-Robot Interaction with a Tethered Aerial Vehicle: Application to a Force-Based Human Guiding Problem. *IEEE Transactions on Robotics* 37, 3 (2021). https://doi.org/10.1109/TRO.2020.3038700

[47] Evgeny Tsykunov, Ruslan Agishev, Roman Ibrahimov, Luiza Labazanova, Taha Moriyama, Hiroyuki Kajimoto, and Dzmitry Tsetserukou. 2019. SwarmCloak: Landing of a swarm of nano-quadrotors on human arms. In *SIGGRAPH Asia 2019 Emerging Technologies, SA 2019.* https://doi.org/10.1145/3355049.3360542

[48] Evgeny Tsykunov, Ruslan Agishev, Roman Ibrahimov, Taha Moriyama, Luiza Labazanova, Hiroyuki Kajimoto, and Dzmitry Tsetserukou. 2020. SwarmCloak: Landing of Two Micro-Quadrotors on Human Hands Using Wearable Tactile Interface Driven by Light Intensity. In *IEEE Haptics Symposium, HAPTICS*, Vol. 2020-March. https://doi.org/10.1109/HAPTICS45997.2020.ras.HAP20.89.9286fc30

[49] Evgeny Tsykunov and Dzmitry Tsetserukou. 2019. WiredSwarm: High resolution haptic feedback provided by a swarm of drones to the user's fingers for VR interaction. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology, VRST.* https://doi.org/10.1145/3359996.3364789

[50] Sergej G. Zwaan and Emilia I. Barakova. 2016. Boxing against drones: Drones in sports education. In *Proceedings of IDC 2016 - The 15th International Conference on Interaction Design and Children.* https://doi.org/10.1145/2930674.2935991