Proprioceptive Interaction

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ABSTRACT

We propose a new way of eyes-free interaction for wearables. It is based on the user's *proprioceptive* sense, i.e., rather than seeing, hearing, or feeling an outside stimulus, users feel the pose of their own body.

We have implemented a wearable device called Pose-IO that offers input and output based on proprioception. Users communicate with Pose-IO through the pose of their wrists. Users enter information by performing an *input* gesture by flexing their wrist, which the device senses using a 3-axis accelerometer. Users receive output from Pose-IO by finding their wrist posed in an *output* gesture, which Pose-IO actuates using electrical muscle stimulation. This mechanism allows users to interact with Pose-IO without visual or auditory senses, but through the *proprioceptive* sense alone.

We developed three simple applications that demonstrate symmetric proprioceptive interaction, where input and output occur through the same limb, as well as asymmetric interaction, where input and output occur through different limbs. In a first user study, participants using a symmetric proprioceptive interface re-entered poses received from Pose-IO with an average accuracy of 5.8° despite the minimal bandwidth offered by the device. In a second, exploratory study, we investigated participants' emotional response to asymmetric proprioceptive interaction and the concept of the user's body serving as interface. Participants reported to enjoy the experience (*mean*= 4.6 out of 5).

Author Keywords: muscle actuation; proprioception; IO; **ACM Classification Keywords:** H5.2 [Information interfaces and presentation]: User Interfaces. - Graphical user interfaces.

INTRODUCTION

Wearable interfaces, such as gesture-based watches [35, 26] allow users to interact with information anywhere, anytime. In order to minimize interference with the user's primary task, such as walking or having a conversation [1], many wearable devices are designed specifically for eyes-free use.

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Unfortunately, these devices typically use auditory feedback, which interferes with auditory tasks. Haptic interfaces, such as vibrating bracelets, show promise here [26], but are limited in terms of bandwidth [25] and are hard to learn because they lack mnemonic properties [21].

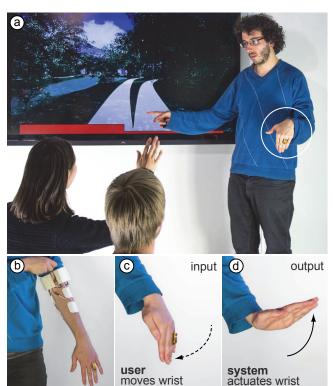


Figure 1: (a) Proprioceptive interaction allows users to interact eyes-free based on their sense of proprioception alone, allowing this user to rewind a video, while maintaining eye contact with his audience.

(b) The user is wearing our proof-of-concept bracelet called Pose-IO. (c) It reads input by sensing the same wrist's flexion using an accelerometer and (d) it sends output to the user by actuating the user's wrist using electrical muscle stimulation.

We therefore propose a different type of modality for wearable interaction, namely *proprioception*, which is the users' sense of the relative position of neighboring limbs of the body. As we demonstrate in this paper, we can use proprioception for input *and output*.

PROPRIOCEPTIVE INTERACTION

Figure 1 illustrates the concept of proprioceptive interaction. Proprioceptive interaction allows for input and output by

posing one of the user's limbs, here the user's wrist. Users enter information by performing an input gesture, here flexing their wrists inwards. The device senses this using its accelerometer. Users can perform such a gesture eyes-free, as their proprioceptive sense informs them about the position of their wrist. Users receive output from a proprioceptive interface by finding their body posed in an output gesture, here again the wrist. Also, they perceive this eyes-free by means of their proprioceptive sense.

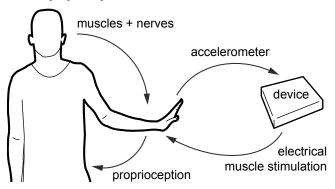


Figure 2: Symmetric proprioceptive interaction revolves around the pose of one of the user's limbs, here the wrist.

The interaction shown in Figure 2 is of the "purest" form in that input and output occur through the same limb, here the wrist. This "symmetric" interaction results in a particularly intuitive interaction [30]. However, proprioceptive input and output may also occur through different limbs, e.g., when the application requires more input than output or more output than input. We call this asymmetric proprioceptive interaction, which is depicted in Figure 3.

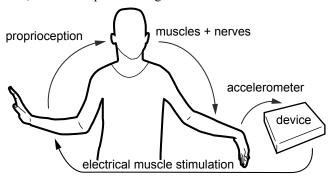


Figure 3: In an asymmetric proprioceptive interaction, input and ouput occur through different limbs.

The Pose-IO device

Figure 4 shows Pose-IO, the proof-of-concept proprioceptive device we have created. It offers input and output based on proprioception. We implemented Pose-IO in the form of a bracelet, which users wear under their clothing. Pose-IO receives input from the user by means of a wireless accelerometer attached to the user's hand. Pose-IO produces output by writing to the user's arm muscles using electrical

muscle stimulation (EMS) through four electrodes attached to the user's arm.

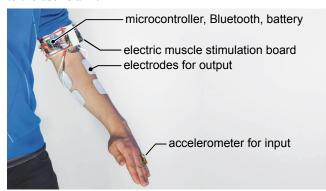


Figure 4: The main components of Pose-IO.

APPLICATIONS

We have implemented three simple applications, each of which highlights a different strength of proprioceptive interaction.

(1) Symmetric Proprioceptive Interaction

Figure 1a illustrates our video-scrubbing tool for presenters based on the Pose-IO device, which is an example of symmetric proprioceptive interaction. One of the audience members just asked whether the presenter could show the video one more time. Figure 5 shows how the presenter responds. (a) He invokes Pose-IO's video scrubber by performing an invocation gesture, here by shaking his wrist back and forth. (b) Pose-IO responds by posing the users' wrist, so as to represent the current video playback position, which the user perceives through his sense of proprioception. The user lets the video run for another moment during which Pose-IO keeps updating the user's wrist position, continuously extending it upwards, which again the user perceives through his sense of proprioception. (c) The user now rewinds the video by flexing his wrist back down to the desired play position. He uses sufficient force to override Pose-IO's control over the wrist. Pose-IO responds by scrubbing in real time, allowing the user to locate the intended position.

(b, c again) To emphasize his answer, the presenter replays the scene one more time. This time, he moves the video play head to its intended position without iterating, but by posing his wrist directly in the same position as before, based on his proprioceptive sense alone. (d) The presenter is just about to dismiss Pose-IO using a strong flick gesture, when one of the attendees throws him a marker. He catches the marker and Pose-IO interprets the abrupt movement as a dismiss gesture and deactivates itself. This is by design, so as to allow users' primary tasks to take priority whenever necessary.

This particular scenario uses the same limb for input and output, allowing us to implement a *symmetric* interaction, i.e., an interaction where the same modality and the same mapping are used for input and output, resulting in a particularly intuitive interaction that even allows users to learn input

based on output [30]. This is a benefit of proprioceptive interaction over other wearable interfaces, for example, such as vibrotactile feedback, which has to be combined with a different input modality, such as a set of buttons.

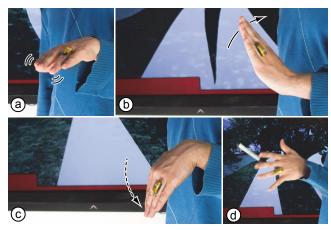


Figure 5: (a) The presenter from Figure 1 invokes the Pose-IO video scrubber by performing a shake gesture, which (b) causes his wrist to track with the video play head. (c) He scrubs backwards. (e) When someone throws him a marker, his abrupt hand movement automatically dismisses Pose-IO.

(2a) Asymmetric Interaction

Proprioceptive interaction does not have to be symmetric though. We demonstrate this at the example of the eyes-free reaction game *red hands* [29]. Traditionally, this children's game is played by two players, one of which is trying to slap the hands of the other. With the use of Pose-IO, we turn red hands into a solitaire computer game. We partition the user's body as depicted in Figure 6, which is why the interface is asymmetric. Here the user's right hand represents the computer opponent; the left hand continues to belong to the player. At every turn, the computer hand tries to slap the player's hand (i.e., game *output*); the player's objective is to evade the slap (i.e., game *input*). The red-hands application detects successful slaps based on *acoustic* recognition (similar to [13]), i.e., a wearable microphone in a small bracelet around the player's wrist.

Red hands is an example of asymmetric proprioceptive interaction in that output goes to the right hand, while the device receives input from the left hand.

To make red hands playable, it offers multiple levels of difficulty. The first level gives players several hundred milliseconds of advance warning before slapping. It does so by briefly flicking the computer hand before actually attacking. This warning period gets shorter on subsequent levels. Since Pose-IO talks directly to the user's muscles, it can actuate the hands surprisingly fast: if we set the warning period to zero, we found player's chance to evade the slap to be no better than random (see also Study 2). This ability for *very* fast interaction stems from talking to the user's muscles directly—a key strength of our approach.

Similar to the presenter tool, red-hands for one is played through the sense of proprioception. This allows playing eyes-free, which, interestingly, most of our study participants did even though they were allowed to look (see Study 2 for details).

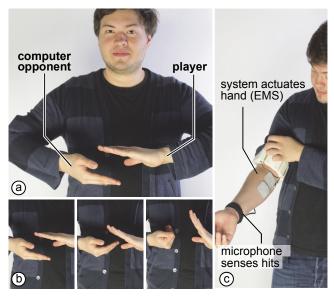


Figure 6: Red-hands for one: Under control of Pose-IO, the user's right hand is trying to slap the user's left hand. The goal is to evade getting slapped by his own hand.

(2b) Asymmetric Interaction with a Spatial Component

To demonstrate an interaction with a spatial component, we implemented *imaginary pong for one*. As depicted in Figure 7, we again partition the user's body so that the actuated hand forms the computer opponent, while the other belongs to the player.

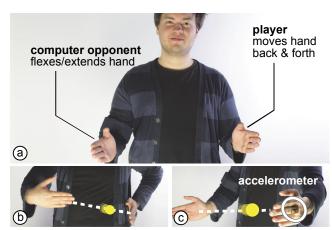


Figure 7: Imaginary pong for one: (b) The computer opponent plays the imaginary ball left by flexing its hand (c) The user returns the shots by moving his hand to where he feels the ball went.

There is no actual rendition of a ball. Instead, players have a notion where the ball should be based on their sense of physics (similar to [3]). The computer opponent may flex the user's hand to play the imaginary ball towards the player's body or it may extend the hand to play the ball away from the user's body. The user's task is to return the shots by moving his hand to where he feels the ball went.

In one version of the game, we added a second Pose-IO bracelet to the player hand in order to render recoil at the moment the imaginary ball hits his palm. This allowed us to add a timing element to the game. As with the two applications presented earlier, users play eyes-free through the sense of their proprioception alone.

CONTRIBUTION, BENEFITS, & LIMITATIONS

Our main contribution is the concept of proprioceptive interaction, here illustrated at the example of wrist pose.

In addition to being wearable, proprioceptive interaction offers four desirable properties: (1) It allows for eyes-free and ears-free use. (2) Instant invocation and dismissal allows users to invoke the device any time and also to return to their primary task immediately when necessary. (3) Symmetric setup allows implementing the same interaction "language" for input and output, resulting in a particularly intuitive interaction that even allows users to learn input based on output [30]. However, (4) this I/O symmetry is not mandatory, and we also explore an interaction modality in which input and output occur at different limbs; we denote it as asymmetric interaction. Thus, depending on the type of application, designers might place input and output freely to best fit their needs.

On the flipside, interaction based on the perception of poses is obviously very low in bandwidth compared to visual or auditory interaction. Its use is therefore only applicable for very simple tasks. Also, any solution that relies on EMS requires an initial step in which the system is calibrated. Furthermore, EMS is still undergoing improvements regarding comfort and ease-of-use (see Related Work).

HARDWARE IMPLEMENTATION

To help readers replicate our proof-of-concept device, we now provide a detailed description of it. As shown in Figure 8, Pose-IO's hardware design has the form of a bracelet with attached electrodes. The bracelet is comprised of 3D-printed sections, each housing the embedded electronics.



Figure 8: The 3D printed Pose-IO bracelet

Figure 9 shows the opened-up bracelet. Pose-IO writes output to the muscles using a medically-compliant electrical muscle stimulation unit (TruTens V3) connected to four pregelled electrodes (50x50mm). The amplification for the Electrical Muscle Stimulation is regulated by two CMOS digital potentiometers with non-volatile memory (X9C103, 10KOhm) controlled by an Arduino Nano using a three-wire serial interface.

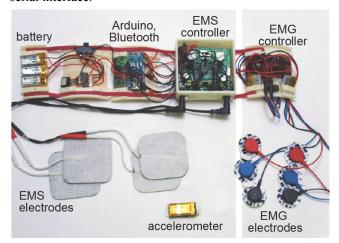


Figure 9: A Pose-IO bracelet unrolled and with the top enclosure removed. On the left side, the additional EMG unit.

Electrical Muscle Stimulation

Pose-IO creates its EMS signal as a biphasic waveform. Its signal pulsates at 120Hz with a pulse-width of 150µs. The current is limited to 100mA, allowing for safe operation. Given that the lowest power settings of the EMS unit did not achieve muscle actuation with the users we tested with, we stepped up the control curve by adding a 10K resistor in parallel to the EMS unit's variable output and input pins. This allows Pose-IO to achieve a smoother output current curve.

Upon first use, users calibrate Pose-IO's EMS device by specifying the lowest stimulus that still leads to a recognizable sensation (there is no visible hand motion at this level) as well as the maximum signal that the user perceives as comfortable. At all times, Pose-IO use is pain-free.

Figure 10 shows the placement of the EMS electrodes on the *extensor digitorum* (wrist extension) and on the *flexor digitorum superficialis* (wrist flexion).

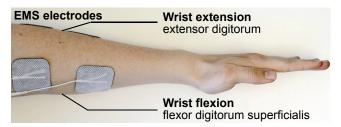


Figure 10: Placement for Pose-IO's EMS electrodes for wrist flexion and extension.

Accelerometer

Pose-IO uses the accelerometer's Y-axis to determine the user's wrist position as the tilt of the user's hand against the horizontal, sampled at 50hz. We also made an extended version of the device that determines the wrist pose with respect to a second IMU worn on the forearm. This allows users to operate Pose-IO in any body posture.

Users invoke and dismiss Pose-IO by holding the hand horizontally and then shaking it, which Pose-IO senses by looking for acceleration along any of the other accelerometer axes. Pose-IO sends commands to its applications, such as aforementioned games, which it runs on the Arduino microcontroller. Pose-IO talks to software running on other computers, such as the video player in the presenter tool scenario, via Bluetooth.

Depending on version, Pose-IO either uses an Axivity WAX3 or WAX9 3-axis wireless accelerometer that users wear on their ring fingers. After removing them from their casing, both measure 34.5mm × 16mm × 15mm and offer 4mg resolution [15]. The WAX-3 sends data over IEEE802.15.4 radio, which we convert using a laptop computer with a radio dongle; we resolved this issue with the newer WAX9, which sends data directly to Pose-IO's Arduino via Bluetooth.

Pose-IO is powered by a 9V power supply comprised of three 3.7V lithium ion rechargeable batteries connected in series and regulated using an L7809CV. Under continuous use, Pose-IO offers around 4 hours of battery-life on the bracelet and 8 hours on the accelerometer.

Control Loop for Symmetric Input & Output

When tracking an external signal, such as the video play position, Pose-IO actuates the user's muscles using a PID control loop. We obtain oscillation-free behavior using the gain factors: Kp=1.2, Kv=1.1, Ki=0.5 (Figure 11). Pose-IO calculates the error derivative on a moving average over the 10 last measured velocities.

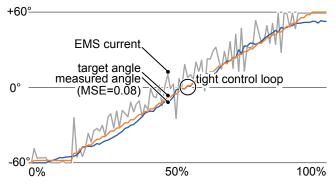


Figure 11: Behavior of Pose-IO's PID control.

If the accelerometer value deviates from the system state by 10°, Pose-IO assumes that the user intends to override the system state—in the video scrubbing scenario this allows users to override the video play head position.

Extended Version Based on Electromyography

The version of Pose-IO described so far relies on the accelerometer for input, which users wear visibly on their hand. For applications in which user control and a computer-control are distributed across two hands, e.g., the two games presented earlier, we achieve a fully hidden version of Pose-IO by dropping the accelerometer and instead using electromyography (EMG) for sensing. EMG senses muscle activity, which is what the two game applications require. Users invoke the EMG version of Pose-IO by over-extending their wrist for 1.5 seconds or longer (Figure 12).

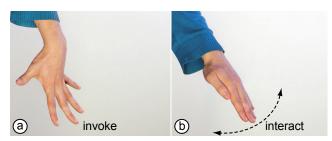


Figure 12: The Pose-IO version based on EMG uses hand-overextension as invocation gesture.

The EMG version of Pose-IO contains two additional electromyography boards shown on the right of Figure 9; they are based on the AD8221 differential amplifier. The EMG boards are connected to six electrode caps, four to sense and two references (20mm diameter), which are placed on the same muscles as for EMS, as depicted in Figure 13. The EMG boards are protected from the EMS current using two relays, which cut the EMG pathway if the EMS is active.

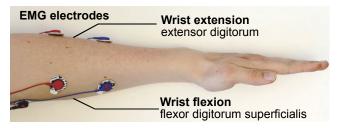


Figure 13: EMG electrode placed on wrist extensor and flexor.

RELATED WORK

The work proposed in this paper builds on proprioceptive feedback and wearable interfaces for eyes-free interaction. Furthermore it is inspired by different approaches to muscle-based input or output.

Proprioception

The human proprioceptive sense allows sensing the position, orientation, and movement of limbs, joints, and muscles [6]. Some debate has taken place whether proprioceptive and kinesthetic are two separate senses. However, the medical community points out that the term proprioception encompasses kinesthesia within [6].

More importantly, research suggests that proprioception is independent from the visual and auditory channels [6,7].

This is the reason why proprioceptive cues (position of limbs, sense of contracting muscles, etc.) are often elicited in bimanual interaction, as they provide users with a sense of where their wrists are relative to one another [19]. In our particular case, i.e., moving the wrist in mid-air, the sense of position of the wrist comes from the muscle spindles and golgi tendon organs which sense the position and movement of muscles, and the joint sensors provide a sense of flexion and extension [7,28].

Apart from research in cognitive and medical domain, proprioception has been often evoked in HCI with regards to haptic feedback. Bark et al. showed how the skin stretch sensation (part of proprioception), which is elicited once a muscle is moved, is superior to vibrotactile feedback for input tasks in which the user controls a cursor [16]. Ban et al. look at how proprioception provides a sense of weight for virtual objects, which the authors manipulate with visual hints in an augmented reality scenario [2].

Wearable Devices That Use the Body as an Input Surface

Skinput is a bio-acoustic sensor that captures the vibrations caused by users tapping on their arms [13]. Imaginary Interfaces are spatial non-visual input devices [11]. Users can operate them eyes-free by touching the palm of their non-dominant hand because the touch elicits tactile and proprioceptive senses [12]. Imaginary Phone by the same authors goes one step further and instantiates an input-device using the human hand with a small acquisition time because there is no need to reach for the mobile device in the pocket [11].

Non-Visual/Non-Auditory Output Using Mobile Haptics

For an interactive dialog to take place in an eyes-free manner, users need not only eyes-free input, but also output. The predominant eyes-free non-auditory type of output is vibrotactile output. Unfortunately, it is subject to a range of limitations. Karuei et al. found that vibrotactile output degrades in mobile situations, such as while walking [17]. Furthermore, vibrotactile output was found to offer only limited bandwidth [25] and is hard to learn because it lacks mnemonic properties [21].

The concept of unified I/O is common on touchscreen devices [38]. Recently, it was adapted to eyes-free interaction by Roudaut et al. [30]. Their prototype, *Gesture Output*, unifies input and output vocabularies in the form of 2D finger gestures on a mobile phone with an actuated touchscreen.

Reading Muscle Activity

More recently, researchers started measuring muscle activity as a means of achieving small wearable input devices that are controlled using finger flexion, such as the forearm electromyography input device by Saponas et al. [31]. This approach of sensing hand poses for input enables what Felzer et al. described as "hands-free control applications" [9]. We gathered inspiration from these findings and designed Pose-IO to be a wearable bracelet mounted onto the user's arm, which can read input signals from hand motion.

Actuating Users: Mechanically and using EMS

Actuating the user's body using mechanical actuators is common in haptics. The most common mechanical approaches actuate the body using pulley mechanisms. These mechanical actuators displace the user's body by pulling the limbs using motors; a notable example is the SPIDAR [24]. The aforementioned Gesture Output [30] is yet another example of such a system. Likewise, exoskeletons such as *Dextrous Hand* [14] or the *FlexTorque* [36] are a sub-class of pulley systems but attach the complete infrastructure to the user. While mechanical actuators are great for their accuracy and output power, they require attaching exoskeletons, motors and large batteries to the user.

As such, Electrical Muscle Stimulation (EMS) has been proposed as a mean of mobile actuation [22]. EMS originated from the field of rehabilitation medicine [33]. The technique is still under development and mostly used for rehabilitation and sports training [23]. The discomfort caused by the electrical fields passing through the skin ("tingling sensation") is being addressed by researching new tools such as multipath stimulation with large electrodes [23] or microelectrode arrays [4]. EMS found its way to artistic contexts, through Stelarc [32], and, more recently, into the field of HCI.

EMS has been applied in a range of interactive applications, ranging from gaming [8, 20] to assistive learning (e.g., *Possessed Hand* [34]). Lopes et al. demonstrated EMS as a means to implement force-feedback in mobile devices [22]. Since these systems do not use control loops, actuation works through pre-calibration [18].

STUDY OF PROPRIOCEPTIVE IN-/OUTPUT

The purpose of our first study was to verify our basic proprioception interaction concept, i.e., interaction by means of posing the wrist.

The study focuses on symmetric input/output. In the video scrubbing example presented earlier, Pose-IO informed users about the play head position by posing their wrists, allowed them to set the play head position by posing their wrist, and allowed them to recall a value by re-creating a known wrist pose. Since the first two have already been studied in the psychophysics literature [37] and [10], we decided to investigate the latter: *re-creating a wrist pose*. This interaction is particularly meaningful in the context of proprioceptive interaction in that it directly investigates symmetric input-to-output correspondence.

In this study, we used the Pose-IO device to pose participants' hands. Participants then dismissed this pose and after a pause tried to re-create that pose. Given that participants perceive both poses by means of proprioception, our expectation was to see close correspondence between the two poses.

Task

For each trial, Pose-IO posed the participant's wrist at a target angle (Figure 14) and held it stable for one second, played a sound, and dismissed the pose, causing the hand to

drop. Then, the participants' task was to recreate the previous pose. When satisfied, participants pressed a keyboard button, which caused the system to record the trial. For each trial, we recorded Pose-IO's accelerometer reading during the target pose and during the recreated pose.

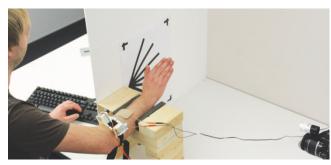


Figure 14: Apparatus for Study. A visual barrier prevented participants from seeing their wrist.

Apparatus

As shown in Figure 14, participants wore Pose-IO's electrodes on their dominant arm. The device was connected via USB to a notebook computer that ran the study script. A keyboard allowed participants to complete their trials. We recorded all trials using a camera.

An opaque screen prevented participants from seeing their hands. To make sure that participants would complete the task based on their proprioceptive sense alone, we also masked out the "tingling" sensation caused by EMS by (1) lowering skin resistance using conductive gel and (2) attaching two vibration motors to the electrodes to create a sensation similar to EMS feedback [27].

Procedure

There were 7 target angles in 20° steps between - 60° (flexion) and + 60° (extension) reflecting the biomechanical constrains of the human wrist [5]. Each participant performed (7 target positions \times 4 repetitions) = 28 trials. Target angles were presented in random order.

Prior to the first trial, we calibrated the device for the respective participant. However, participants received *no* training on the task, as our expectation was that the unified correspondence between input and output would allow participants to complete the task based on their natural sense of proprioception alone. The study took about 30 minutes per participant.

Participants

We recruited 10 participants (3 female) from our local organization. All were right-handed.

Results

Participants recreated poses with an average error of 5.8° ($SD = 5.1^{\circ}$) across all trials. A linear regression found the overall model fit to be R2 = 0.954. As shown in Figure 15, tilting the hand up further (shown on the left of Figure 15) resulted in slightly larger errors (mean = 6.49, SD = 5.93)

(mean = 5.19, SD = 4.18). Furthermore, we found no statistical significant difference between any of the angles. For simplicity we present the results for the pairs with larger deviation, e.g., +40° vs. -60° (Z=-1.886; p=0.059) and +60° vs. -60° (Z=-1.274; p=0.203).

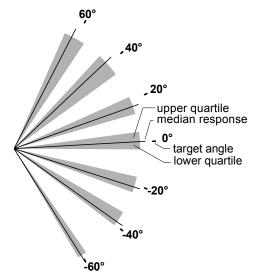


Figure 15: Differences in angle between target pose and recreated pose. Participants recreated poses with an average error of 5.8° ($SD = 5.1^{\circ}$).

Interestingly, we observed several participants recreating not only the target wrist angle, but also the entire hand pose including the artifacts caused by electrical stimulation, such as the slightly overextended middle finger (Figure 16). This suggests that proprioception was at work on a broader scale.

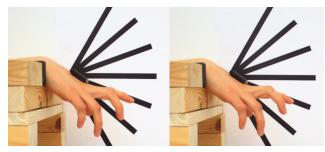


Figure 16: (a) Wrist actuated by Pose-IO (b) Pose recreated by participant in response.

Discussion

Our results show that the interaction did actually use and benefit from proprioception. As observed participants reposing was accurate and included reposing of fingers. The results suggest that proprioceptive interaction's ability to allow for symmetric input & output offers benefits when it comes to recreating poses, as users can perceive and re-pose their wrist using their proprioceptive sense.

On a practical level, participants acquired the target poses with comparably high accuracy, i.e., 5.8° error on average. With respect to the motion range of -60° to +60° = 120° this represents an error of under 5%. If we map these values back

to the motivating example of video scrubbing, this means that Pose-IO would allow users to jump to a spot in a 1-minute video clip with ± 3 seconds accuracy, which we argue to be a useful level of performance. Obviously, these values were obtained under idealized conditions, i.e., user was sitting down and immediately recreated the pose, and thus it should be interpreted as a lower bound for error.

AN EXPLORATORY STUDY OF THE PROPRIOCEPTIVE INTERFACES

While our discussion so far was focused on the technical aspects and abilities of proprioceptive interaction, one of its aspects that we are personally intrigued about is its way of representing the computer as part of the user's body. Very unlike traditional human computer interaction systems, where computers are outside and different from the user, proprioceptive interfaces make the user's limbs *themselves* serve as the interface, which we argue is the very essence of proprioception—after all, the word stems from Latin "proprius", meaning "one's own". Our video-scrubber application makes the hand partially "owned" by the user and partially owned by the machine. The two games we showed earlier push this approach even further by questioning that notion of "ownership" in that they cause one's hand to be fully owned by the machine.

We were wondering how users perceive this aspect of proprioceptive interaction and what emotional response it might produce. This is what we investigated in this second, exploratory study. We had participants play the red hands game described earlier. We recorded participants' response to the interface on video and had them fill in a questionnaire.

Setup

We recruited 12 participants (3 female) from our local organization, which did not partake in the previous study, and asked them to play the red hand game for about 5 minutes. As discussed earlier, participants' objective was to evade getting slapped by the computer-controlled hands. All participants received candy as a small incentive to participate and we promised additional candy to whoever would score highest.

The game offered levels of increasing difficulty. As mentioned earlier, these were implemented in the form of barely noticeable actuation of the slapping hand before the actual slap (750ms–50ms, depending on level). We did not tell participants about this "warning" mechanism, making it part of the game to either consciously or unconsciously figure it out. For this study we used an earlier Pose-IO prototype, i.e., same hardware but not wearable yet.

To make sure participants only responded to the pose interaction, we canceled out any auditory signals by making them wear noise-cancelling headphones that played music. Each study session started by participants calibrating Pose-IO, familiarizing themselves with the game mechanics, and playing one training level with 10 slaps. They then played 5 levels with about 10 slaps each. If they got hit less than 3 times per level, they proceeded to the next level and their score

continued to go up. If not, their score stopped increasing, but we still let them finish the remaining levels to give them a chance to experience the complete game.

Findings

We had designed the game to be challenging and participants took the game quite seriously. All except one participant completed level 3; three level 4, and two made it to the fifth and final level. Participants rated the first two levels as easy (mean = 2.0 of 5; 1 = very easy, 5 = very hard) and the last levels as hard (mean = 3.92 of 5).

All participants rated the game as fun (mean = 4.6 of 5) as depicted in Figure 17 and further illustrated by Figure 18.

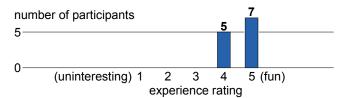


Figure 17: All participants rated playing red hands as fun (1: uninteresting, 5: fun).

When asked why, seven participants pointed to the fact that they felt as if they were "playing against themselves". Several participants went back and forth between referring to the hand wearing the device as "me" and as "computer", such as "it is weird that you lose against yourself" and "sometimes the computer hand was faster than I".



Figure 18: Participants playing red hands, an example of an asymmetric interaction.

In the last two levels, ten out of twelve participants stopped looking at their hands while awaiting the slaps. When asked about it, only two stated to have played by always looking at their hands, while five participants stated to play eyes-free and seven stated to have rarely looked. This suggests that participants operated our application by means of proprioception alone.

Most participants agreed that the muscle output had contributed to their excitement (*mean* = 4.91 of 5). One of the two participants who had continued to look at their hands explained: "it was so remarkable to see my hand moving without my intention that I could not look away".

In summary, watching the twelve participants confirmed that Pose-IO affords being operated eyes-free and that users perceived the "blurred ownership" of the user's body as compelling.

CONCLUSIONS AND FUTURE WORK

In this paper, we proposed the concept of proprioceptive interaction, which we instantiate through a wearable prototype. Proprioceptive interaction leverages the user's proprioceptive sense for both input & output, i.e., the use of pose as a bidirectional communication channel between human and computer. We demonstrated how proprioceptive interactions allows for (1) eyes-free and ears-free use; (2) invoking the device at any time and returning to their primary task immediately when necessary; and, provides (3) two modalities: symmetric, in which input and output occur in the same limb, and asymmetric (i.e., one limb for input, another for output).

A unique aspect of proprioceptive interaction is that it represents the computer using a part of the user's body, which our second study suggests that participants found this experience compelling. On a philosophical layer, this "blurred ownership" manifests itself because operating a device only through proprioception thins the boundary between human and computer, since the machine partially inhabits the human. In the case of the presented proprioceptive interface, the muscles which control the wrist are the interactive device, in contrast to most input & output devices which are external pieces of hardware, sitting outside the user's body.

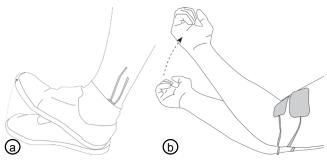


Figure 19: Extending proprioceptive interaction to other parts of the body: (a) the feet and (b) the upper arm.

Lastly, as future work, we believe the concept of proprioceptive interaction needs not to be restricted to the hands. In Figure 19 we depict two proprioceptive interaction designs, one for the upper arm (using the *biceps* for flexion) and one

for the feet (using the *gastrocnemius* for plantar flexion). These additional possibilities open up interaction spaces for scenarios in which the hands are occupied with another task. Furthermore, other input & output mapping functions are of interest for further research, such as non-linear mappings.

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