Movelet: a Self-Actuated Movable Bracelet for Positional Haptic Feedback on the User's Forearm

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ABSTRACT
We present *Movelet*, a self-actuated bracelet that can move along the user's forearm to convey feedback via its movement and positioning. In contrast to other eyes-free modalities such as vibro-tactile feedback, that only works momentarily, *Movelet* is able to provide sustained feedback via its spatial position on the forearm, in addition to momentary feedback by movement. This allows to continuously inform the user about the changing state of information utilizing their haptic perception. In a user study using the *Movelet* prototype, we found that users can blindly estimate the device's position on the forearm with an average deviation of $1.20cm$ to the actual position and estimate the length of a movemement with an average deviation of $1.44cm$. This shows the applicability of position-based feedback using haptic perception.

Author Keywords
Self-actuated; movable; wearable; haptic; positional feedback; forearm

ACM Classification Keywords
H.5.2. User Interfaces: Input devices and strategies

INTRODUCTION
Many wearable and mobile devices utilize vibro-tactile feedback for notifications. This feedback however is only momentary, so that users can miss the tactile sensation and need to invest attention. With *positional* feedback, we introduce a sustained haptic stimulus that is continuously available in the background to convey the state of low-bandwidth information. This can be used to gradually display progress, e.g. for pedestrian navigation to gradually display the distance to the next turn, for mobile notifications to provide a sense about the amount of unread messages, or for time scheduling to convey an ongoing feeling about the time left until the next meeting. We generate this feedback by presenting a self-actuated bracelet that can position itself on the user's forearm by being able to move itself up and downwards. The wearer can temporarily feel the movement (similar to other tactile feedback) in addition to an ongoing spatial haptic perception of where the device is positioned.

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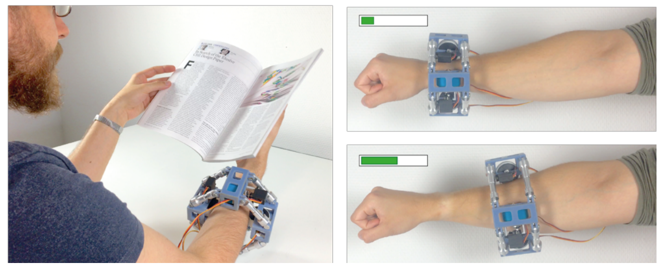

Figure 1. *Movelet* is a self-actuated bracelet that can convey haptic feedback on the user's forearm by movement and positioning.

The contributions of our paper are: (1) a novel self-actuated output device, utilizing the spatial domain of the forearm for *positional* feedback, (2) the concept of sustained background feedback without having to increase an applied stimulus, and (3) the findings of a user study investigating the users' performance in perceiving and estimating position and movement on their forearm.

RELATED WORK
To extend the feedback capabilities of wrist-worn wearables, much work has been done to visually extend the output via additional display spaces [18, 24, 19], or by illuminating the skin around [21]. Visual feedback however requires visual attention. Harrison et al. [10] found that visual alerts on the body work best when positioned on the wrist, but that the reaction time is still very slow ($\approx$ 19 seconds for the wrist).

For eyes-free feedback, vibrations are predominantly being used [16, 3]. Vibration feedback however is working in the temporal domain, so that it captures the user's attention, can be missed when the user is focused and can potentially be disruptive to the task at hand [9]. Thermal feedback can be applied to the skin to feel a change in temperature as heat or cold [29, 26], but strong and fast changing stimuli are required for detection. Another means for tactile feedback is skin drag, where a small physical tactor is mechanically moved to stretch the user's skin, allowing the user to recognize tactile shapes [12, 2]. Alternatively, a tactor can be used to poke the user's skin [13, 23]. This allows for higher bandwidth stimuli, but much like vibrations, the feedback is only momentary.

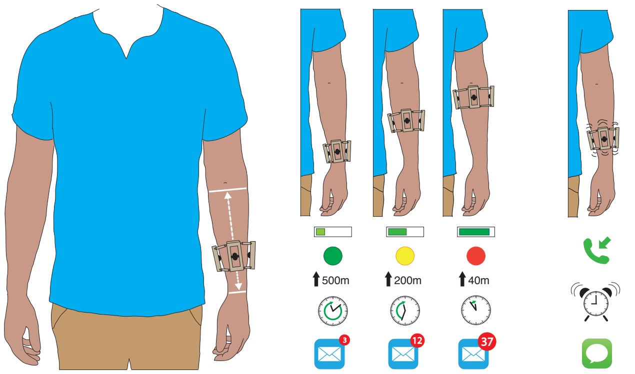

Figure 2. (Left) The self-actuated bracelet can move up and down to position itself on the user's forearm. (Center) The device's position can be used to convey abstract information, such as progress, urgency, distance for navigation, time left until an approaching meeting or the amount of unread notifications. (Right) Fast up and down movements at a location can be used as a means for a temporary notification.

Sustained Feedback

For sustained feedback, pneumatic compression can be applied [20]. Inflating straps can tighten around locations like the wrist much like a blood pressure monitor to generate compression ranged from subtle to forceful [20]. Compression can provide constant background feedback which can ramp up by slowly inflating (or deflating) the device to symbolize progress or to slowly bring something to the user's attention. Similar to thermal feedback however, this requires the applied stimulus to become stronger which with an increased stimulus can be perceived as less pleasant. With *Movelet*, we explore to provide sustained increasing background feedback without an increase in the applied stimulus by using the spatial domain of the user's forearm for *positional* feedback.

Self-Actuation and Smart Jewelry

Self-actuation in Human-Computer Interaction (HCI) was explored to change the affordances of mobile devices [22]. Dementyev et al. envisioned that in the future, wearable devices are dynamic and can move around the body. They introduced Rovables [6], minature on-body robots that can move on clothing via magnetic wheels to serve for input and output and SkinBots [5], on-body robots that can move over skin via two suction legs. Gong et al. presented Cito [8], an actuated smartwatch that can translate, rotate and tilt its face towards the user to address limitations of a fixed watch face.

An important element of jewelry and garments is to appeal and communicate with others. This has been utilized to augment fashion, e.g. a scarf altering its shape to represent emotions and attitude [27] or to dynamically change the color of fabrics on clothing [7] to display abstract information. Kao et al. [15] argued that jewelry and accessories have long been objects for decoration of the human body, but that they remain static and non-interactive. In the future however, smart jewelry could become mobile to vary shape and design [15] as we see an increase in computational jewelry [25]. We envision that such smart jewelry could utilize its motion and positioning as a means of feedback.

Haptic Acuity

Multiple methods have been introduced to measure the haptic acuity of a respective skin region. For the forearm, the haptic acuity was reported by Weinstein [28] as ~3.8cm using the two-point touch threshold (the smallest spatial seperation between two concurrent stimuli) and ~0.9cm using the point-localization threshold (of when a user cannot tell if two successive stimuli were present at the same location). While these methods are useful to compare the acuity of the receptors at different skin regions (in this case the forearm), e.g. for neurological examiniation, they only inform about the haptic acuity, but not about the capability of estimating the *position* of a haptic stimulus.

The localization of a haptic stimulus has so far been limited to multiple vibro-tactile tactors placed on respective body parts, e.g. Cholewiak and Collins [4] used a linear array of seven tactors placed on the forearm and found that the localization (i.e. the identification of the right tactor) was more precise when the stimulus was close to the wrist or the elbow as anatomical points of reference. Jones et al. [14] found that vibro-tactile sensations cause surface waves that propagate across the skin and make the localization of the locus of a vibro-tactile stimulus with tactor distances less than 6cm difficult to achieve. Luzhnica et al. [17] showed that phantom sensations using three vibro-tactile tactos along the forearm can be used to convey continuous values.

In contrast to vibro-tactile sensations, that only reach the fast adapting tactile receptors within the skin during vibration (Meissner's and Pacinian corpuscles), the constant haptic stimulus of *Movelet* via contact force and indented skin also reaches the slowly adapting receptors (Merkel's disks and Ruffini endings). These receptors have already been utilized for skin-stretch displays that utilize the contact force of a small movable tactor to inform directional cues with high accuracies [2, 1]. However this has been limited to direction and tactile shapes during tactor movement. The accuracy in assessing the *position* of a self-actuated haptic stimulus has not been investigated yet.

MOVELET CONCEPT

In this work we present *Movelet*, a self-actuated bracelet that can move along the user's forearm to convey feedback via its movement and positioning. While the movement can be used for momentary haptic feedback to notify the user, the device's *position* provides sustained haptic feedback continuously in the background.

Positional Feedback

The positioning of *Movelet* on the forearm can be seen as an output channel for one-dimensional information. It is thus particularly suitable to convey the state of gradually changing information with a defined endpoint. This can span varying abstract information such as progress (e.g the ongoing completion of a download, a working task, or activity), for urgency (to slowly make the wearer aware when it is increasing), for time awareness (e.g. the time remaining until an approaching meeting), for pedestrian navigation (e.g. the slowly decreasing distance towards the next turn), or for awareness

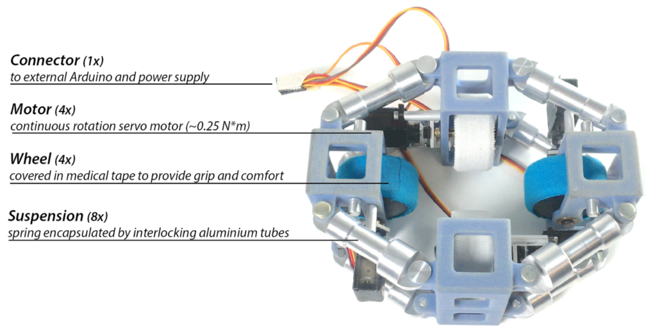

Figure 3. The *Movelet*-prototype consists of four segments that are interlinked, each containing a wheel that is powered by a small servo motor. The interlinkage includes suspension that mechanically expands or contracts to adjust to the varying circumference of the user's forearm. The mechanical wheels were covered in medical tape which showed to provide grip and comfort.

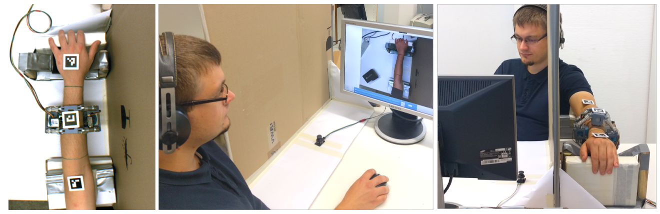

Figure 4. (Left) Marker-based camera tracking of movement and positioning. (Center) A user estimating and marking the *Movelet's* position on a previously taken image of his empty forearm, (Right) while his left arm wearing the device is hidden behind a visual cover.

of quantity (e.g. a feeling about the amount of unread emails) (see Fig. 2).

These information can be displayed eyes-free to subtly have an effect on the user. In contrast to other haptic feedback, such as vibro-tactile notifications, the *position* can work as a sustained background feedback that is always available. Unlike visual feedback, perceiving the *position* does not require visual attention and unlike a notification it does not necessarily disrupt the task at hand. These properties can be useful to convey information when the user is engaged in important activities, like a conversation or meeting, where the user then does not get disrupted or has to look onto a display, but can still perceive a feeling about the state of information.

Implementation

For the implementation of the *Movelet* prototype, we first started with design considerations that had to be met to enable self-actuation on the user's forearm. The prototype would need to be capable of moving up- and down the arm and otherwise keep its position, so that a certain amount of pressure or cling to the arm would be required. The arm's shape however heavily differs between users as well as at different forearm position, so that usually the upper forarm has a broader circumference than the user's wrist, which needs to be compensated for by the device. Another importance is that when moving the device along the user's forearm, skin or hair irritations need to be prevented. For the latter reason we designed the prototype so that only little surface area would be in contact with the user's skin.

This led to the design of four mechanical wheels (2*cm* wide; 4*cm* diameter) that contact the user's skin, are evenly distributed around the arm and serve to actuate the device, to stabilize for each direction and to provide the haptic stimulus for the user. To prevent skin or hair irritation we tested different surface materials like plastic, pearl and rubber and found in medical tape the most suitable combination of grip and comfort.

For the *Movelet* to be capable of moving up and down the forearm, the device needed to be able to adjust to the varying circumference from wrist to upper forearm, fit tightly at these different positions and yet be flexible enough to ascend an increasing arm thickness. For this reason, we interlinked the wheel segments via suspension consisting of a spring encapsulated by interlocking aluminum tubes contracting the segments. The design is modular so that users with different arm sizes could wear the device. We provided interlinkage with three different sizes (40, 44, 48mm in length) that could be exchanged for each segment.

The motorization is optimized to vertically climb an arm and via suspension allowing the device to keep its position and exerting a steady amount of light pressure even though varying arm circumference. Using four continuous rotation servo motors (~0.25 N·m), one for each wheel, the suspension mechanically expands or contracts to adjust to the varying circumference of the arm.

Wheel segments were custom 3d printed, while the interlinkage was custom manufactured consisting of aluminum to optimize for durability, friction and weight. Overall the *Movelet*-prototype weighs 403*g* including the motors but excluding an Arduino and 6V power supply externally connected via wires.

USER STUDY

We conducted a user study to investigate the user's accuracy in estimating the device's position and length of movement on their forearm. So far, studies have been conducted to inform about the haptic acuity of body regions [28], but the accuracy of assesing the position of a self-actuated haptic stimulus has not been investigated yet.

We explored the accuracy of estimating a haptic position using the *Movelet*-prototype and used the user's visual perception as a comparison. Furthermore we were interested in whether this estimation differs for different forearm segments. The user study was conducted as a repeated measures factorial design with the means of *perception* as the independent variable and the participant's estimation of *absolute position* and *relative movement* as dependent variables.

Haptic and Visual Perception

To explore the haptic perception of position and movement, the view onto forearm and device was blocked by a visual cover for the *haptic*-perception condition (see Fig. 4). Furthermore, participants wore noise-cancelling headphones playing brownian noise.

In the *visual*-perception condition, participants would be able to visually observe the device's movement and position by slightly changing their seating posture to be not blocked by the visual cover. With vision as the primary human sense to assess position, distance and movement in the environment, the *visual* perception condition served as a best-case for comparison. We expected the *visual* perception to be more accurate than the *haptic* perception, but were interested in investigating the extent. For a self-actuating wearable like a bracelet, users would in practice be able to visually confirm and complement their haptic perception by glancing at the wearable's position, so that both conditions are important for the usage of a self-actuated wearable.

Procedure

During the study, participants would rest their left forearm horizontally on two cushioned pillars (see Fig. 4). The *Movelet*-prototype would move in-between wrist and upper forearm with outer boundaries chosen, so that the device could not reach wrist joint or elbow to prevent additional cues of feedback. This area was individually identified for each participant and in average had a length of 16.82cm (SD=1.94cm).

For each trial, the device would perform a straight movement to a random position on the forearm. Target positions were randomized following a continuous uniform distribution. We divided the forearm into four equally sized segments and aimed for an uniform distribution of landed segments. Target positions were furthermore constrained to not land within the same segment in sequence and to have a miminum movement distance of 10% of the forearm's length.

The device was automatically controlled and actuated via software utilizing marker-based camera tracking (see Fig. 4) as a ground truth of the device's position.

After each movement of the device, participants estimated the direction and length of the movement first, followed by an estimation of the device's position. Participants were seated so that their left arm wearing the *Movelet* was hidden behind a visual cover, but that they could operate a mouse and computer screen using their right hand (see Fig. 4). For the *visual* feedback condition, participants would slightly change their seating posture so that their vision onto the device was not blocked.

For the estimation of movement, participants would indicate the percentage of movement in relation to the length of their forearm on a slider bar (ranging from 0 - 100% of arm length). For the estimation of the device's absolute position, they were presented a pre-taken image of their empty forearm on which they would place an indication marker for the position. After each trial, participants would then see the actual position as a second marker on the image as well as the actual length of movement as an indication on the slider bar. Trials were conducted consecutively with the previous trial's position being the starting position of the next trial.

The two conditions (*haptic* and *visual* perception) were presented using a 2x2 latin square for counterbalancing. For each condition each participant conducted 40 trials split into two sections with a break inbetween. Conditions were further balanced, by alternating the independent variable after each section break, resulting in an A-B-A-B study design.

This was preceded by three training phases to get familiar with the haptic and visual perception. First, participants got introduced to the *Movelet*-prototype and were allowed to freely move and position the device on their forearm using a joystick. The device was then actuated to pre-defined positions five times, with the participant having to estimate movement and position, while being allowed to watch the device and its movement (i.e. the *visual* condition). Lastly, the device was hidden behind the visual cover to blindly estimate a final training set of five trials relying only on haptic perception (i.e. the *haptic* condition). The noise-cancelling headphones were handed only after the training phases, so that participants were encouraged to ask questions during training.

Participants

We randomly recruited 16 participants (8 female) from our institution with an average age of 26 (range: 21 to 29). 4 participants stated to regularly wear watch-like devices, while 2 stated to regularly wear jewelry on their forearm; 2 were left-handed. The study took 60 minutes on average and each participant received 12 *currency* and a chocolate bar as compensation.

Results

Our analysis is based on 16 participants overall estimating 1368 movements and positions. Marker-based camera tracking was used as the ground-truth for all measurements. One participant's data (P9) had to be removed from the evalation due to the results of both conditions averaging as outliers. We recruited a 17th participant as a replacement. Overall 5 estimations of position and movement were removed as outliers. All outliers were detected by using the modified Z-score by Iglewicz and Hoaglin [11].

Movement

Participants were able to indicate the correct movement direction for all but 3 trials (99.8%). Movements had an average duration of 1.61 seconds and an average length of 7.61cm. The average deviation of the users' estimation of movement length to the actual length of movement for the *haptic* perception was 1.44cm (SD=0.37cm) and 1.18cm (SD=0.46cm) for the *visual* condition, so that using their vision, participants were 0.26cm (18%) more accurate. A paired t-test showed that the difference was significant ($t(15)=2.99$, $p<0.01$).

We further seperated movements into directing *upwards* (towards the elbow) and *downwards* (towards the wrist). Participants were slightly more accurate (~8,8%) in estimating upwards movement (M=1.38cm) than downwards movement (1.50cm) under the *haptic* condition. This was potentially due to upwards movements taking slightly longer time (1.63s vs 1.52s) and participants using the duration as a cue for the distance. For the *visual* condition, participants were also more accurate (~16,4%) in estimating upwards movement (M=1.08cm; M=1.26cm). Since the participants' forearms

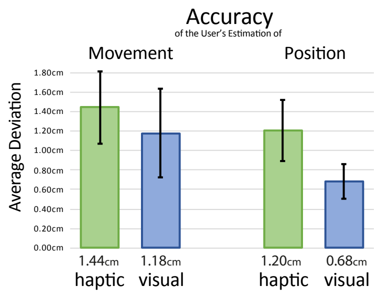

Figure 5. Accuracy was measured as the average deviation of the user's estimation to the actual movement length, resp. position. Participants were less accurate when blindly estimating movement and position in comparison to visually observing the device. Since vision is the primary human sense to assess the environment, a significant difference in accuracy between *visual* and *haptic* perception was expected. The difference was smaller than anticipated and only 18% for estimation of movement length and 43% for the estimation of position.

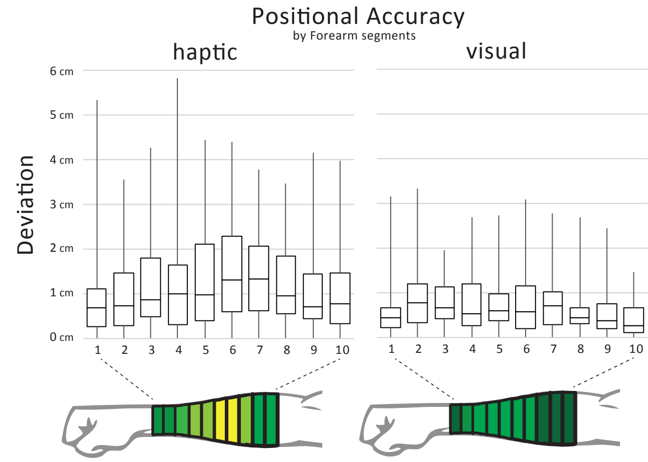

Figure 6. We divided the forearm into ten segments for further analysis of the accuracy of the users' estimated positions. Participants were most accurate at the outer forearm segments where wrist, resp. elbow, could serve as anatomical points of reference. Whiskers within the box plots represent the minimum and maximum deviation of the user's estimation from the actual position.

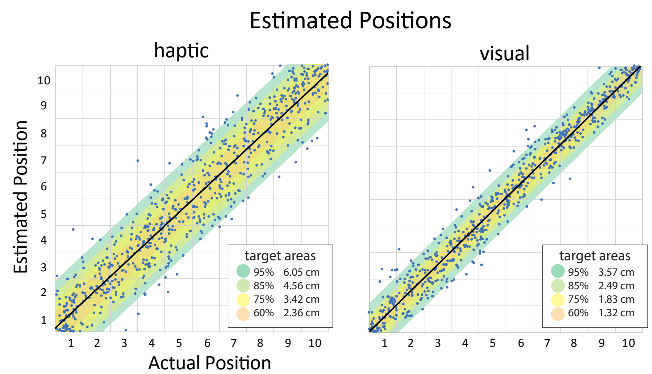

Figure 7. All user estimations for the device's *position* in relation to the actual position of the device as measured by the camera tracking.

would be facing away (see Fig. 4), the upper forearm was closer within the user's field of view.

Position

For the estimation of the device's position, the average deviation to the actual position was 0.68cm (SD=0.18) for the *visual* perception and 1.20cm (SD=0.31cm) for the *haptic* perception, so that using their vision, participants were in average 0.52cm (43%) more accurate. A paired t-test showed that the difference was significant ($t(15)=6.35$, $p<0.001$).

For further analysis, we divided the forearm into ten equally sized segments. Participants were more accurate at the outer regions, i.e. wrist and upper forearm, than within the middle of the forearm (see Fig 6). This can be explained by wrist and elbow serving as positional landmarks for the user, which could benefit the user's perception as points of reference when the device was close to either cue. Also, users could benefit from haptic experiences at the wrist by previously wearing watches and jewelry. The upper forearm had a distinctive haptic feeling in that the *Movelet* was mechanically expanding to adjust to the arm's circumference, which could help as an additional haptic cue for the upper forearm.

For the *haptic* perception, 60% of estimations for the position fell within an area of 2.36 cm along the center of the device, while an area of 6.05 cm along the center covered 95% of all estimations (see Fig. 7). For an average forearm length of 24 cm, this implies that 4 distinct target positions could be placed along the arm without an overlap to be reliably distinguishable by the user. For the *visual* perception, 95% of all estimations fell within an area of 3.57 cm, so that when glancing at the device, user's could distinguish ~6-7 distinct target positions reliably.

QUALITATIVE FINDINGS

Participants were encouraged to provide feedback about their perception. Multiple participants stated that estimating the position blindly was more difficult than under the visual condition, but that estimating movement was easier. While the results do not confirm that users were more accurate under the *haptic* condition for assessing movement, participants were nearly as accurate. A possible explanation is that for estimating the length of a relative movement, a temporal demand is involved that requires the user's attention. Under the *haptic* perception condition, participants would focus on the haptic stimulus during movement, while under the *visual* perception they would primarily trust in their visual assessment of new and previous position, which involved having to memorize the previous position of the device.

Participants were asked which advantages and disadvantages they see with the introduced *Movelet* concept. Appreciated was foremost that users do not need to look at the device (P4, P5), especially in situations where it is not possible to look at (P1). Also, that information can be perceived incidentally in the periphery (P11), which might give users the impression of an additional perceptual sense (P3). Mentioned downsides were that the device might conflict with clothing such as long-sleeves (P15) and that sudden movement could have an irritating effect on the wearer (P11).

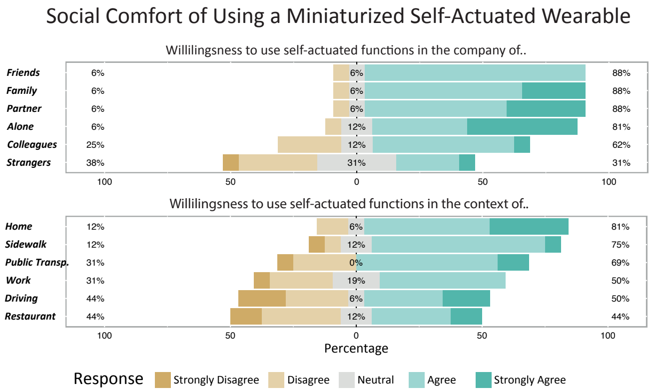

Figure 8. Participants were asked about their willingness to use the functions of a miniaturized self-actuated wearable. There was assent for private social contexts. In public scenarios some participants disagreed and were afraid the device might draw unwanted attention.

Social Comfort

In regard to social comfort, participants were asked in which social contexts they would be willing to use the functions of a self-actuated miniaturized wearable (see Fig. 8). Participants were assenting for private social contexts (e.g. alone, or with family and friends), and rather divided for public scenarios where the device could draw unwanted attention. To prevent unwanted attention, a self-actuated device should therefore prevent sudden and quick movement. Within the user study, our *Movelet*-prototype would quickly move towards a target position, however, we envision slow and unobtrusive device movement in the future, so that neither users nor bystanders are getting irritated.

Haptic Pressure

Participants rated the device's pressure on the arm neither as too weak (M=1.75; from 1 - strongly disagree to 5 - strongly agree) nor as too strong (M=2.06). The pressure allowed a localization of the device on the forearm (M=4.06), but was not always perceived as evenly distributed (M=2.5). One participants with a thin wrist joint (P6) mentioned that at the wrist position, the fourth wheel at the bottom was too loose and did not pressure the arm anymore. While the device's pressure allowed for localization, a more evenly distributed pressure around the arm could be realized by electronically synchronizing the applied force on the suspension.

DISCUSSION

The haptic acuracy in users' estimations of position and movement was higher than expected. The visual perception was significantly more accurate for the estimation of movement and position, but the difference (18%, resp. 43%) was less than expected considering that vision is the primary human sense for assessing movement and positioning in the environment.

A temporal demand was not involved for the estimation of the position, so that it was perceived as overall less demanding by the participants. As an implication, the *Movelet* is better in conveying a current *state* of information than in conveying the quantity of a *change*. Yet when using *positional* feedback, the *Movelet* is conveying both: Users can feel a *change* in information via movement and then have a continuous haptic feeling of its *state*. While the movement is temporary and can be missed, much like a vibration, the position enables sustained background feedback continuously available to the user.

While the haptic perception in average deviates only 1.20cm from the actual position, segmenting the forearm into distinct target areas would enable only four distinguishable target areas along the arm with a high distinction rate (95% success rate along 6.05cm, see Fig. 7). For this reason, the *Movelet* is less suitable in conveying *different* information depending on its position, and more suitable in conveying the *state* of a single information where knowing the exact quantity is less important than getting a close estimation about its extent, e.g. having a good sense about the time left until the next meeting or about the amount of unread notifications (see Fig. 2).

CONCLUSION

Movelet is a self-actuated bracelet that can move along the user's forearm to convey information via its movement and positioning. Using *positional* feedback of a self-actuated wearable is a novel means for a sustained haptic stimulus. In a user study, we found that users can blindly estimate the device's position on the forearm with an average deviation of 1.20cm and estimate the length of a relative movement with an average deviation of 1.44cm. This enables continuous *positional* feedback of abstract information that can be used to gradually display progress, such as the remaining time towards a meeting or the quantity of unread notifications. The accuracy is well suited to map progress that does not require the exact value, but a close feeling of its extent continuously accessible to the user.

FUTURE WORK

In the future, we are planning to conduct user studies comparing positional to vibro-tactile feedback under distraction to show that the user's attention does not need to be focused on the haptic perception when using *sustained* feedback of a self-actuated device rather than *momentary* feedback of vibro-tactile tactors. In this regard, we also want to explore how quickly users can assess the position when attending another main task.

Furthermore, We want to extend the capabilities of *Movelet* to enable for user input. Similar to rolling up sleeves, users could grab and reposition the device on their forearm to change or reset information. To enable this, the device has to be able to detect its position. Our user study was relying on camera tracking, but a more mobile approach could be realized by measuring the current expansion of the device when calibrated to the circumference of the user's forearm.

For positioning, we also explored to include the upper arm to be reachable by the device. The bridging of the elbow joint for angled arm postures as well as the increasing cirumference however introduced technical challenges that yet need to be resolved. The varying circumference of the user's arm also led to technical challenges regarding miniaturization that we want to address in future work. Technical considerations are needed for shrinking the form factor to make self-actuated wearables more practical. Hereby, *positional* feedback could be used on a variety of different body parts built into many kinds of self-actuated wearable form factors. The high haptic acuity of the finger [28] for example, makes it a promising location for a miniaturized self-actuated movable ring.

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