No Need to Stop What You're Doing: Exploring No-Handed Smartwatch Interaction

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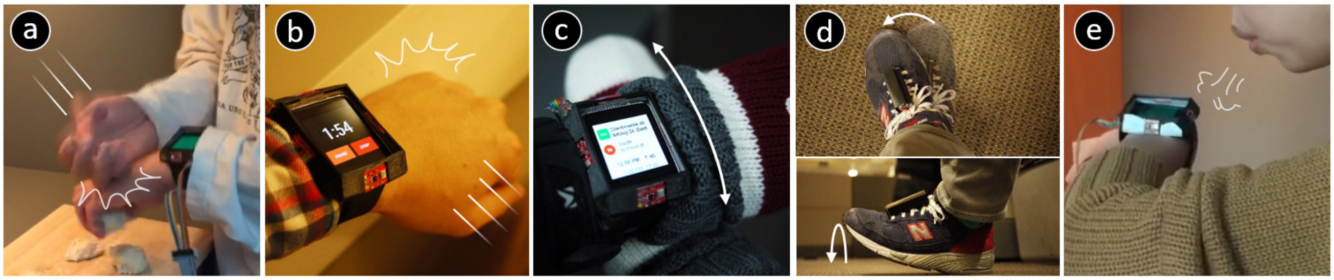

Figure 1: Examples of no-handed smartwatch interaction techniques: (a) Slap, (b) Bang, (c) Swipe, (d) Foot Tap, and (e) Blow.

Abstract

Smartwatches have the potential to enable quick micro-interactions throughout daily life. However, because they require both hands to operate, their full potential is constrained, particularly in situations where the user is actively performing a task with their hands. We investigate the space of *no-handed interaction* with smartwatches in scenarios where one or both hands are not free. Specifically, we present a taxonomy of scenarios in which standard touchscreen interaction with smartwatches is not possible, and discuss the key constraints that limit such interaction. We then implement a set of interaction techniques and evaluate them via two user studies: one where participants viewed video clips of the techniques and another where participants used the techniques in simulated hand-constrained scenarios. Our results found a preference for foot-based interaction and reveal novel design considerations to be mindful of when designing for no-handed smartwatch interaction scenarios.

Keywords: Smartwatch interfaces, wearables, no-handed interaction, body-based input.

Index Terms: H.5.2. User Interfaces: Input device and Strategies.

1 Introduction

Smartwatches are increasingly commonplace, and hold the promise of allowing users to weave short micro-interactions throughout their daily lives [42, 49]. However, the potential of these devices is constrained because they utilize both hands during operation – the hand wearing the watch positions the device for interaction, and therefore cannot touch the device, and the opposite hand is busy interacting (e.g., by touching the device's screen). Situations such as cooking [6, 49], playing musical instruments [7], or even wearing gloves [88] make interaction all but impossible, forcing the user to suspend their current task or wait until it is finished before they can interact with the device. Input using voice commands is a possibility for some hands-busy situations, but existing techniques may not be well-suited to all environments (e.g., due to social acceptability in public environments [43,84], or sensitivity to environmental noise).

When our hands are busy in everyday life, we often use alternative parts of our body to interact with the environment. For example, if your hands are occupied holding grocery bags, and you need to open a door, you might use your elbow instead. We anticipate that this strategy – repurposing physical actions executed with body parts other than the hands – can enable *no-handed smartwatch interaction* without requiring the user to suspend their current task.

With the above as motivation, we investigate the potential of alternative physical actions for smartwatch interaction. Our investigation builds on the body of literature on non-touch-based techniques for interaction, which has examined single hand gestures [8,34,50,92], subtle arm contractions [60,76,77], foot gestures such as tapping the heel or toe [19,80,86] or rotating the foot [80], gaze and facial movements [1,25,36], blowing over a device [13,68], and a number of full body gestures [16,17]. Although a range of techniques have been proposed, there is still a limited understanding of how each applies to the range of no-handed usage scenarios, and the constraints imposed by no-handed interaction scenarios for smartwatches.

This paper builds a more holistic understanding of alternative input for no-handed scenarios in three ways: First, it presents a comprehensive review of existing work to characterize the full range of no-handed interaction scenarios, and identifies interaction opportunities when the hands are busy. Next, it reports on the implementation of an example set of no-handed interaction techniques, selected from our understanding of this range of scenarios as a representative set of alternative techniques. Finally, it evaluates these techniques in two studies – an online survey and a lab study with simulated no-handed interaction scenarios.

The study results revealed preferences for foot-based techniques, underscoring the possibility of cross-modal interaction for smartwatches. The studies also revealed design considerations for the development of no-handed interaction techniques, such as the importance of social acceptability, display visibility during interaction, and concerns about cleanliness.

In summary, we contribute a *taxonomy of no-handed use scenarios* with three classes of constraints that limit the hands: physical, temporal, and social. We also derive *implications for no-handed smartwatch interaction using alternative body movements*, based on our observations and findings from two user studies.

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2 Related Work

The present research on no-handed smartwatch interaction was inspired by work to enhance the input capabilities of smartwatches, enable input in constrained scenarios, and on body-based gestures.

2.1 Enhancing Smartwatch Interaction

Researchers have explored a range of techniques to extend interaction possibilities with smartwatches. Text entry on a smartwatch, which requires a rich input vocabulary, has become more accessible by scaling targets [67] or using swipe gestures [14,42]. Xia et al. proposed using a small finger-mounted stylus to improve selection precision and reduce occlusion under the fingertip [90]. Other techniques have expanded the input space outside the watch's screen by supporting interaction along its edge or borders [65,91]. The smartwatch input space has been further expanded by using infrared sensors to measure skin deformation [66], by projecting laser buttons onto the skin to use the area around the watch for input [48], or by tracking the finger via inaudible audio signals [63]. Although these techniques served as inspiration, most are not applicable to no-handed situations due to their reliance on finger-based input.

2.2 Smartwatch Input in Constrained Scenarios

Many projects have developed smartwatch interaction techniques that do not require touchscreen finger input. Hansen et al. used gaze to navigate menus [36]. Orbits presented visual widgets on a smartwatch display and detected users' widget-following gaze movements for activation [25]. Reyes et al. developed and evaluated a sensing technique that uses non-voice acoustic input, such as blowing or shooshing [72]. When input from the non-watch wielding hand is constrained, Google Android Wear [31] enables wrist twisting gestures to scroll contents, whereas Guo and Paek used tilt-based gestures [34]. Gong et al. integrated infrared proximity sensors along the smartwatch band to detect continuous 2D wrist gestures [30]. Yamada et al. used a button-based switch on a wrist-worn device that could be pressed by wrist tilting and used the button to discriminate intentional gesture motions [93]. ViBand showed that high frequency vibration sampling from a smartwatch's accelerometer could enable the sensing of gestures, including one-handed gestures [49]. Tomo used electrical impedance tomography to recognize watch-worn hand gestures such as left, right, fist, or stretch [97]. Xu et al. also supported single hand smartwatch input by recognizing hand and finger gestures using wrist-mounted accelerometer and gyroscope sensors [92]. Finally, EM-Sense recognizes when a user has touched an object using electromagnetic noise transferred through the skin, to provide context-appropriate information [50].

The projects reviewed above demonstrate the rich potential of non-touch smartwatch input when novel sensing strategies are used. Rather than focusing on sensing innovations, the present work explores the *behaviors* such sensing enables, such as wrist and finger movements of the watch-worn hand [30, 31, 34, 49, 92, 93, 97] and gaze-based or non-voice acoustic input [13, 25, 36].

2.3 Body-based Gesture Input

Outside of smartwatch use, many interaction techniques have been developed for body-based gesture input that do not require the fingers or hands to be used on a display.

Using the Arm: Extensive research has sensed finger or hand postures using Electromyogram (EMG) [76,77,83], camera vision [9,52,85], or acoustic sensors [3,23,40]. Crossan et al. showed that wrist rotation could be used for input while in a stationary situation [21]. Costanza et al. investigated the use of isometric upper arm contractions for socially-acceptable unobtrusive interaction [18].

Using the Head, Eyes, and Face: Interaction using the head, eyes, and face has also been explored. Head movement, such as orientation and nodding [12] or left and right tilting [20], has been demonstrated for hands-free input. The eyes are also a common interaction modality for those with limited motor movements [25,36,44]. Given its protruding shape, the nose has been used for hands-free indirect pointing [32] and to perform touch interaction [71,95]. The physical movement of the tongue has also been shown to be useful for input [74,75], as has blowing with one's mouth [13,68].

Using the Feet: Interaction using the feet is often used in scenarios where the hands are busy (e.g., to press the gas pedal in a car). In addition to pressing physical pedals, tapping the toes or heels has been proposed for discrete gestures [2,19,23,78,79,82], as has the lifting and rotating of the toes and heels for continuous input [80]. Kicking gestures and foot tapping locations have also been investigated to provide enriched input vocabularies [78].

Using the Entire Body: Full body movement has been widely used as input, from learning physical behavior [4] and model retrieval [41], to content generation [96] and entertainment [57]. While many of these projects rely on depth camera and vision techniques, Cohn et al. [17] sensed the electromagnetic noise received through the human body to recognize full body gestures without instrumenting the environment.

Although a range of alternative interaction techniques that do not require the hands have been developed, there has yet to be a holistic investigation of the constraints that give rise to no-handed interaction scenarios, or a comparison of alternative techniques for these kinds of scenarios.

3 No-Handed Smartwatch Interaction

In this section, we develop a taxonomy of scenarios constraining smartwatch input, based on a review of situations documented in the literature. To start, we define *no-handed interaction* scenarios as those where the hand wielding the smartwatch is unable to provide input to the watch, and the non-watch hand is also busy. This could occur, for example, when using both hands to carry a large box. In contrast, *one-handed interaction* scenarios occur when the non-watch-wielding hand is busy, but the watch-wielding hand is free. This could occur if a user is holding a coffee cup or a phone in their non-watch hand. Finally, *two-handed interaction* scenarios are those where both hands are free.

Holding / Grasping Objects
- Reading a newspaper or book [53, 69]
- Using a phone while holding a briefcase [77]
- Carrying bags [59, 77]
- Holding a coffee mug [77]
- Typing on a keyboard [35, 46]
- Answering the phone while working [15]
- Playing video games [26,69]
- Holding a strap or bar on a bus [59, 69]

Exercise
- Exercising with a bike [69]
- Operating a music player while jogging [77]
- Swimming [58]
- Hanging exercise [62]

Repair
- Soldering [11]
- Drilling a hole in the ceiling [69]
- Car repair [54, 89, 93]

Transportation
- Driving [6, 26, 29, 37, 58, 70, 81, 94]
- Riding a bike or motorcycle [37, 61, 69]
- Pushing a stroller [59]

Food and Cleanliness
- Washing dishes [53]
- Cooking [51, 69, 70]
- Eating [69, 70]
- Having unclean hands [45, 59]
- Art activities with children [69]

Job-Related
- Work where full attention is critical [59]
- Baggage handling [64]
- Teleoperation of machinery [98]
- Periodontal charting [33]
- Piloting a plane [26, 38]
- Package delivery [10]
- Anesthesia recording keeping [33]
- Surgery [26, 33]
- Parcel sorting [87]
- Wearing gloves [45, 59]

Unpredictable Circumstances
- Holding a child's hand [59]
- Breastfeeding [69]
- Animal handling [33]

User Limitations
- Motor impairments [37, 54, 55]

Multi-User
- In a presentation during class [53]
- Conversations with others [69]
- In a meeting [69]

Figure 2: "Hands busy" situations mentioned in the literature. Associated publications are indicated in brackets.

To understand the constraints that give rise to no-handed and one-handed interaction scenarios, we compiled a list of "hands busy" scenarios (Figure 2). Our list contained situations identified in past work on smartwatch usage (e.g., [69,88]), and research on no-handed interaction with other devices. In all, 40 situations were collected which revealed a rich set of scenarios, ranging from reading a newspaper [53,69] or holding a phone [15], to animal handling [33], to surgery [26,33].

Through a careful consideration of the range of no-hand scenarios, we identified higher-level themes and developed a taxonomy of no-handed interaction scenarios (Figure 3).

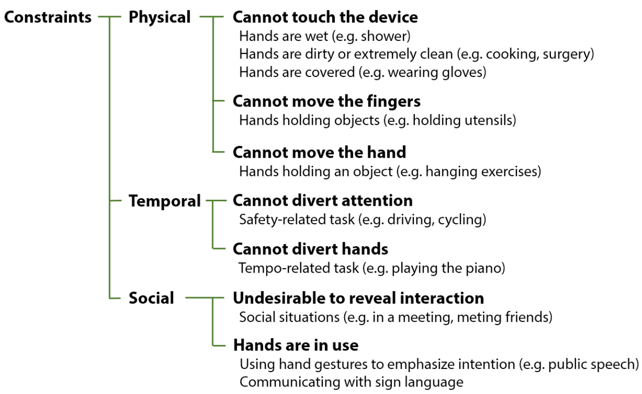

Figure 3: Taxonomy of scenarios constraining smartwatch input.

3.1 No-Handed Situational Constraints

Seven canonical constraints that can affect smartwatch input were identified (the leaves in Figure 3). Further consideration of the scenarios classified under each constraint yielded three higher-level classes of constraints that can impede smartwatch interaction: *physical* constraints, *temporal* constraints, and *social* constraints.

3.1.1 Physical Constraints

In some situations, physical constraints make it impossible to interact with a smartwatch. Physical constraints were classified based on the part of the body that is constrained.

Cannot touch the device: Being unable to touch the screen of a smartwatch could occur, for example, while wearing gloves or mittens. In this case, the material covering one's hands impedes the ability to generate touch input. In other cases, one may be unable or unwilling to touch their watch for hygienic or sanitary reasons (e.g., while cooking, a user's hands may be dirty from touching ingredients [51,69,88]).

Cannot move the fingers: A user's hands could also be constrained while performing manual or bi-manual interactions (e.g. while building or repairing something, a user's hands may be holding tools [11,69,89,93]).

Cannot move the hand: A user's entire arm may also be restricted, preventing them from moving their arms towards each other to interact with a smartwatch. This could occur when carrying a large object or performing synchronous actions with both arms (e.g., hanging exercises [62]).

3.1.2 Temporal Constraints

Cannot divert attention: In some cases, the user may be unable to divert their attention from their current task. While driving, for example, taking one's eyes off the road could have disastrous consequences [26,29,45,70]. In other scenarios, such as playing a video game [26,69], the results may be less dire, but are still undesirable.

Cannot divert hands: The user's hands themselves only be able to be diverted from the primary task for a short duration, such as while playing a piano [7] (e.g., at the end of a phrase or while flipping to the next page of a score), or giving a presentation [53] (e.g., to maintain flow, long actions that take away from attention from the audience are not possible). In these scenarios, interaction needs to be quick and seamlessly interleaved with the actions required by the primary task.

3.1.3 Social Constraints

Finally, there are cases where the social activities the user is engaged in restrict use of the smartwatch. In these situations, the user's hands are not busy per-se, and they have time to interact, but social factors constrain the interaction.

Undesirable to reveal interaction: In a meeting with co-workers, it may be unacceptable to check sports scores on one's watch. Past work on enabling subtle [5] or candid [24] interaction has investigated how to enable interaction within such constraints.

Hands are in use: Hand gestures are often used during conversation to emphasize points and act as a supplementary communication channel [47], or as the main communication channel for those with hearing impairments. In these scenarios, smartwatch-based hand movements are constrained.

3.2 No-Handed Interaction Opportunities

Although no-handed interaction scenarios restrict the use of the hands, there are a range of other parts of the body that could be used for smartwatch interaction. In this section, we discuss five alternative communication channels that we see as having potential.

Forearm: The degrees of freedom afforded by the shoulder, elbow, and wrist joints enable a range of movements, even when the hands themselves are constrained. Limited amounts of forearm movement are already integrated into modern smartwatch platforms to detect when the user is looking at a watch screen or to advance notifications [31]. The advantage of forearm gestures is that they can be performed quickly, making them suitable for scenarios with temporal constraints. Their disadvantage is that it is common to use the arms expressively during conversation, increasing the difficulty of recognizing such movements.

Head, Eyes, and Face: The user's head, eyes, and face can also provide interaction opportunities. The nose or chin [88] could generate input to touchscreens without special hardware, and could receive passive haptic feedback as well, though these approaches would limit view of the screen. Other techniques such as eye gaze [25] or head movements [20] can be performed while maintaining full view of the screen, but require specialized hardware. Indirect physical contact, such as blowing on the watch display, is another possibility, and would enable the screen to still be seen. As the face and eyes play a key role in social interactions [28], the head, eyes, and face may not be appropriate in all social situations.

Feet: The potential benefit of foot-based techniques is that they can be performed subtly and quickly. In contrast to the head and hands, the feet are often hidden under a table or not the focus of one's attention, making social constraints less of a concern. Foot gestures can also be performed in parallel with tasks involving other parts of the body, overcoming potential temporal constraints.

Full Body: By bending the knees, raising or lowering the shoulders, or shifting one's weight, there are also opportunities to use the entire body for interaction. Though many scenarios constrain the hands and arms, it is often possible to move the entire body as a contiguous unit, parallel with other actions. In contrast to other input methods, full body gestures are often slower, less precise, and affected by social constraints.

External Objects: Finally, the external environment could afford opportunities for no-handed interaction. For example, objects within the user's reach could be repurposed as physical tools for interacting with a device. Placing a special capacitive material [22], a magnet [39], or an NFC tag [99] can enable an existing object to be used for interaction.

4 No-handed Interaction Techniques

We implemented a set of interaction techniques to evaluate the use of head, arm, feet, body, and external objects for no-handed smartwatch interaction. The techniques were intentionally limited to those that could be detected via the sensors that are commonly integrated within mobile and wearable devices, such as microphones, accelerometers, and optical sensors.

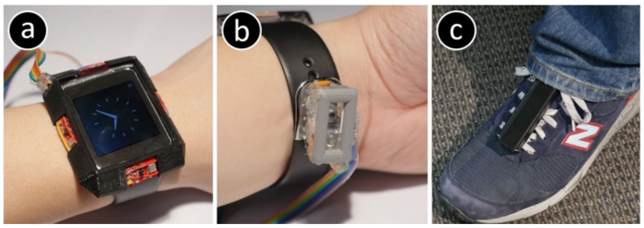

Figure 4: The sensors used to implement the interaction techniques, including (a) four MEMS microphones around the watch display, (b) the optical mouse sensor on the watchband, and the (c) 9-DOF IMU sensor with the Bluetooth module

4.1 Implementation Platform

A Samsung Gear Live Android Wear smartwatch was used as a base platform. Four MEMS microphones (Figure 4a) and an optical mouse module were integrated around the bezel and strap of the watch, respectively (Figure 4b). The microphones were connected to the PC via a USB audio interface and recorded audio at 44.1 kHz. A shoe sensor module (Figure 4c) consisting of a 9-DOF inertial measurement unit, Arduino Pro mini, and a Bluetooth module was also designed. The module was enclosed in a 77 mm × 26 mm × 17 mm 3D printed box with a clip to attach it to a shoe. The shoe module mimicked the capabilities of existing instrumented footwear (e.g., Nike+ shoes [56]), sampled orientation at 100 Hz, and sent it to a PC via Bluetooth. A Google Nexus 5 smartphone was used to collect body movement from the pocket. The smartphone sampled 3-DOF linear acceleration at 50 Hz, and sent it to a PC via Wi-Fi.

Although many technologies were employed, not every technique required all sensing capabilities. For ease of proof-of-concept prototyping, a PC collected all sensor data to recognize gestures, and sent a gesture event to the smartwatch, except for the *Slap* and *Bang* techniques, which were recognized on the watch using only inertial sensor data. The gesture recognizer program was implemented in C# and ran on a Windows 10 PC.

4.2 Using the Forearm

Three forearm gestures were implemented – two performed by tapping the forearm against the other arm or an object in the environment (*Slap* and *Bang*), and a directional technique performed by rubbing the forearm on a surface (*Swipe*).

The *Slap* and *Bang* techniques make use of the watch-wielding hand, but differ in the hand that performs the technique. With *Slap*, the non-watch hand is tapped against the watch-worn hand, whereas with *Bang*, the watch-wielding hand is tapped against the user's body (e.g., their leg) or an external object. Each of these techniques can operate in a one-handed interaction scenario and enable simple one-bit input, suitable for triggering a command such as starting or stopping a timer.

For recognition, the smartwatch used the built-in sensors to sample gravity-compensated linear acceleration and angular speed at 100 Hz. To detect the techniques, a 200 ms window was used and the recognizer attended to all acceleration peaks larger than 9.5 G in magnitude. A 400 ms window accumulating the gyroscope and acceleration magnitudes were used to discriminate *Slap* from *Bang*.

The *Swipe* technique harnesses a scratching metaphor, where the watch-worn hand is rubbed against an external surface or the user's own body. It can be performed while both hands are occupied, if forearm movement is not constrained, and enables discrete or continuous 2D control. For example, this technique would be suitable for flipping through pages of a news article or scrolling a long page.

To realize the *Swipe* technique, a PAW3504 optical mouse sensor (Figure 4b) measured movement across the surface the watch band is rubbed across. The technique was only recognized if a displacement of > 10 mm occurred within a 300 ms window. In our study, four discrete directions (up, down, left, right) were used and the directions were determined when the displacement from the starting location exceeded 10 mm.

4.3 Using the Head: Blow

The *Blow* technique enables users to bring their watch-wielding hand to their mouth and blow across the surface of the watch. This technique could be used for either discrete or continuous input (e.g., to flip pages of instructions on the watch or to scroll the screen). The duration or intensity of the air passing over the watch could be measured and used as a degree of freedom for the technique.

To detect this gesture, the RMS of 30 ms of audio waveform samples from microphones situated on the bezel of the watch was calculated. If the RMS value was higher than the heuristically determined threshold value for one second, the gesture was detected. The use of four microphones enabled the technique to register directionality.

4.4 Using the Foot: Foot Tapping

Using the shoe sensor module, two foot tapping techniques were implemented. For *Side Foot Tap*, the foot is lifted, tapped to the left or right of the original position, and returned to the original position within 1.5 seconds. *Double Foot Tap* is activated when two consecutive toe taps occur within 500 ms of each other. Such techniques can activate single-bit operations such as selection or cancelation, or flip pages left or right.

Both techniques incorporated a lift and land of the toe, which were recognized by attending to consecutive positive and negative peaks in a pitch velocity curve. Changes in yaw angle during the lift and land indicated whether a toe tap was to the left or right.

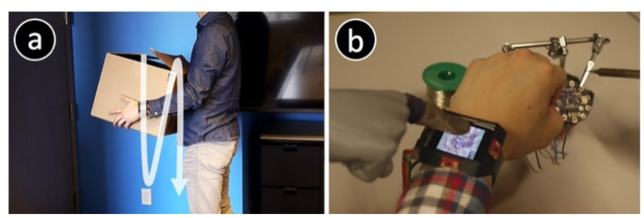

Figure 5: Example interaction techniques using (a) the whole body, and (b) external objects.

4.5 Using the Whole Body: Body Bounce

With the *Body Bounce* technique, the user moves their torso up and down twice in quick succession (e.g., by bending their knees while standing; Figure 5a). This single-bit operation can enable simple interactions such as activating voice command input.

This technique was detected using rotation-independent linear acceleration values, by finding peaks from the velocity curve derived by accumulating the acceleration of the smartwatch and smartphone. The recognizer used a peak detection window that was 330 ms long and triggered a peak event if the largest or smallest acceleration was in the middle of the window and if the difference between the peak value and the values at the edges were larger than a detection threshold. If four direction-alternating peaks were detected from the watch and the phone within a 2-second bounce detection window, and no foot movement occurred, the *Body Bounce* technique was detected.

4.6 Using External Objects: Pseudo Finger

With the *Pseudo Finger*, a 3D model of a hand was printed, and the index finger was wrapped in conductive fabric to mimic the properties of a real finger, and enable "touch" input on a smartwatch screen (Figure 5b). This technique enabled all 2D touch gestures commonly achievable with one finger to be performed.

5 STUDY 1: ONLINE SURVEY

To gain initial feedback on the proposed techniques and to refine the design of the in-laboratory study (described later), an online questionnaire was administered via Amazon Mechanical Turk. Participants viewed animated demonstrations of the techniques in no-handed interaction scenarios, and indicated how likely they would be to use each technique, and factors influencing their decision.

The use of animated demonstrations to evaluate the acceptability of gestures has been used in previous work on touch-screen interactions [73]. For our purposes, the main advantage of this approach is that it yielded quick, low-cost insights into people's reactions to the techniques, which enabled us to select and refine techniques for our second study, in which participants performed the techniques in no-handed interaction scenarios.

Forty participants responded to the questionnaire (M = 30 years, Range = 22–55 years, 20 male, 20 female). Participants were paid $6 and the questionnaire took ~30 minutes to complete.

5.1 Questionnaire Format

The questionnaire consisted of seven scenarios in which a user would not be able to use standard touchscreen interaction techniques on a smartwatch due to physical, temporal, or social constraints. Participants were provided with a task description using text and images, and a short animated demonstration of each technique being applied to complete the task (Figure 6). Participants were asked to rate each technique using a five point Likert scale (*"If the above gesture was available and would [complete the task], how likely would you be to use it?";* 1 - Extremely Unlikely, 5 - Extremely Likely). For each task, participants were also asked to indicate their most and least preferred technique and provide a rationale for their choice.

5.2 Scenarios and Tasks

The scenarios and tasks were drawn from the taxonomy and selected such that they simulated different constraints one could encounter while invoking an action or responding to a notification. The *Cooking* (hands dirty, starting a timer), *Carrying a Box* (arms constrained, accepting a phone call), *Soldering* (hands constrained, flipping pages of a circuit schematic), and *Bus Waiting* (hands covered by mittens, checking bus arrival times) scenarios simulated physical constraints. The *Driving* (attention constrained, answering an incoming call), and *Piano Playing* (duration constrained, flipping pages of virtual sheet music) scenarios simulated temporal constraints. Finally, the *Attending a Meeting* (viewing sports scores) scenario simulated social constraints.

5.3 Results

Overall, participants showed a preference for the two foot-based techniques, which received consistently high median ratings in all but the Driving scenario (Table 1). In contrast, Body Bounce and Pseudo Finger received consistently low ratings for all scenarios. The remainder of the techniques received a range of scores depending on the scenario (e.g., the Swipe technique received high scores for Bus-Waiting and low scores for Cooking). These diverse ratings suggest that no one technique is appropriate for all situations.

While only two techniques were impossible to perform without stopping the main task (Slap and Blow during the Carrying a Box scenario), the rationales provided by participants revealed some interesting implications of body-based no-handed interaction.

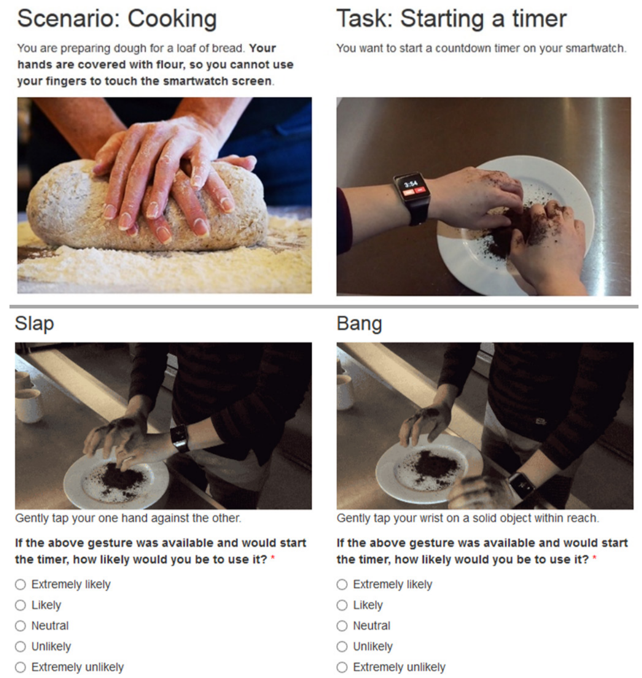

Figure 6: (Top) The Cooking scenario shown to respondents. (Bottom) Animated images demonstrated each gesture within each situation for respondents.

	Forearm			Head	Full Body	External Object	Foot	
	Slap	Bang	Swipe	Blow	Bounce	Pseudo Finger	Side Foot Tap	Double Foot Tap
Cooking	3	3	2	3.5	2	1	4	4
Carrying a Box	1	3	2	1	2	2	4	4
Soldering	2	3	4	2.5	1	2	4	4
Bus Waiting	4	2	4	2	1.5	1	3	4
Driving	3	3	3	3	1	1	2	2
Piano Playing	2	2	2	2	2	1.5	4	4
Attending a Meeting	2	2	4	1	1	2	4	4

Table 1: Median preference scores for the statement, "*If the above gesture was available and would [complete the task], how likely would you be to use it?*"

5.3.1 Limitations Mediate Interaction Preferences

The physical, temporal, and social limitations imposed by a given scenario were at the forefront of participants' minds. Many participants expressed a desire to maintain the pace and flow of the task in the face of physical constraints. For example, one participant noted that, "*I would tap my toe because it wouldn't involve hand movement [while soldering]*", whereas another stated "*[Bounce] would let me keep my hands on the box without risk of dropping it.*" For these participants, being able to continue their primary task considering the limitations imposed by the situation, dictated the technique they preferred and should be a paramount concern for those designing no-handed input techniques.

Speed and temporal challenges were mentioned as reasons why some techniques were preferred over others. In situations where attention is diverted, such as while playing the piano, quick techniques were desired, "*Blowing on your watch might be the most* *practical way to [play piano] while keeping all your hands on the keyboard"*, *"(Blowing) seems to be the quickest most convenient gesture to use."*

Respondents also highlighted the importance of hygiene and cleanliness. When discussing the cooking scenario, one respondent stated *"Banging seems the easiest and quickest option [while cooking]. Swiping and slapping could make things more messy."* Although this scenario did not impose physical limitations, (i.e., one can still move their arms or hands), the desire to keep clean imposed something akin to a physical constraint.

5.3.2 Safety

Many participants focused on the safety of various interaction techniques. In scenarios where attention cannot be diverted from the main task, respondents emphasized the importance of *safe* and *quick* techniques. One respondent mentioned that *"[The blow gesture] can be done really quickly and shouldn't be too much of a distraction from driving."*, whereas another highlighted the challenges associated with using one's feet for quick input while driving, *"[The double foot tap gesture] may have you accidentally press a pedal and cause and accident"*. Another thought of how the items one may hold could cause injury, *"Bouncing with a hot instrument in your hands [while soldering] isn't a good idea – you could burn yourself"*. These comments indicate that it is important to be mindful of how no-handed techniques and usage scenarios could potentially interact to cause dangerous situations.

5.3.3 Social Acceptability

In situations where multiple people could view smartwatch input, respondents recognized the value of techniques that mimic natural movements, and thus would be difficult for others to detect as input (e.g., *"[The swipe gesture is the] least obtrusive and noticeable to others, would also not disturb anyone [in a meeting]."*)

Respondents were also concerned about other people's perceptions of them performing the techniques. For the Bounce technique and the meeting scenario, one participant commented *"people would think you're a weirdo"*. The desire for social acceptance was also reflected in the consistently low preference ratings of Body Bounce across all scenarios. Such comments highlight the importance of considering not only the opportunities and additional modalities that could be used for interaction, but also how such input will enhance or diminish one's comfort and likelihood of performing such techniques.

5.3.4 The Use of External Objects

The Pseudo Finger, which employed an external object for interaction, received many negative comments. Most comments centered around practicality, as the finger would need to be portable or preinstalled to be useful, e.g., "*this may work well in your own kitchen, but I do not think that fake fingers will be available everywhere."* Although other types of external objects, such as a magnet or an RFID tag could be used to create more portable external objects, it is understandable that unpredictable availability is a concern.

5.4 Discussion and Implications

Overall, no single technique was perceived as appropriate for all scenarios, which suggests that it is worthwhile to provide a range of techniques for smartwatch input in no-handed scenarios. Conversely, the Pseudo Finger technique was almost universally disliked, and is unlikely to be a practical solution in practice.

6 Study 2: Situational Usage

The feedback gathered in the first study provided valuable insights into no-handed interaction and the developed techniques, but was limited in that participants did not actually use the techniques or experience the scenarios first hand. Thus, a second study was conducted with a subset of the techniques from the first study to understand how successful the techniques were when performed in no-handed scenarios, and to gain further insights into how the techniques and no-handed interaction would be perceived.

As the Body Bounce and Pseudo Finger techniques were strongly disliked in the first study, they were not included in this study. Because the two foot gestures received similar preference ratings and comments in the previous study, only the side foot tap gesture was included in this study.

6.1 Participants

Fourteen participants were recruited (M = 29 years, Range = 20–48 years, 10 male, 4 female, 2 left handed). Three participants had experience using a smartwatch and two wore a smartwatch every day. The study lasted one hour and participants received a $25 gift card.

6.2 Study Design and Procedure

The study followed a mixed design, with technique as the within-subject factor and scenario as the between-subject factor. Each participant used all five techniques, but was only exposed to two of the seven scenarios. The order of scenarios was counterbalanced across participants. Technique order in each scenario was randomized.

At the beginning of the study, each technique was demonstrated to participants and they were given a few minutes to practice performing them. Participants then completed two scenarios. For each scenario, the participant was asked to perform an action (e.g., dismiss an incoming phone call) in response to a stimulus that occurred (e.g., the watch screen would turn green, vibrate, and emit a 'ding' sound) a total of 15 times for each technique. There was an inter-trial interval of approximately eight seconds. Participants were instructed to perform the techniques as quickly and accurately as possible.

During idle time between actions, participants were asked to think aloud, to capture their reactions to performing each technique. After each scenario, participants rated each technique using a 7-point Likert scale ("*I would want to use this gesture in the given scenario*"; 1– Strongly Disagree, 7 – Strongly Agree). At the end of the study, a survey elicited additional comments on each technique. Since only four participants experienced each scenario, we decided it would not be appropriate to perform statistical analysis on the preference ratings. Rather, we confine our analysis to preference rating trends, participant feedback, and experimenter observations.

6.3 Scenarios and Tasks

A realistic simulation of seven scenarios drawn from the taxonomy (Figure 7a-h) was set up in a lab environment, while taking care to ensure participant safety and minimize fatigue.

Cooking: Participants manipulated pizza dough into a variety of shapes, based on instructions provided by a notification on the watch. This situation replicates the real-world physical constraints one would encounter while viewing a recipe and handling food materials that they would not want to get on the watch.

Carrying a Box: In this scenario, participants lifted a large cardboard box (51 cm × 37 cm × 32 cm) and were asked to imagine that each notification was a phone call they needed to answer. This simulated the physical constraints imposed by carrying large, awkward, or heavy items. The box was left empty to reduce fatigue.

Soldering: Participants held a soldering iron in one hand and solder in the other. They were asked to simulate soldering at a location specified in the notification they received. This scenario mimicked situations where a user is following a tutorial on their watch, but the tools needed to perform the steps keep their hands busy. For participant safety, the soldering iron was not plugged in.

Bus Waiting: In this scenario, participants were asked to wear mittens and imagine they were waiting for a bus in the cold. Notifications appeared on the watch with different bus arrival times. When a notification was received, they were asked to speak the arrival time aloud. This scenario evaluated physical constraints that enable hand movement but prevent touch.

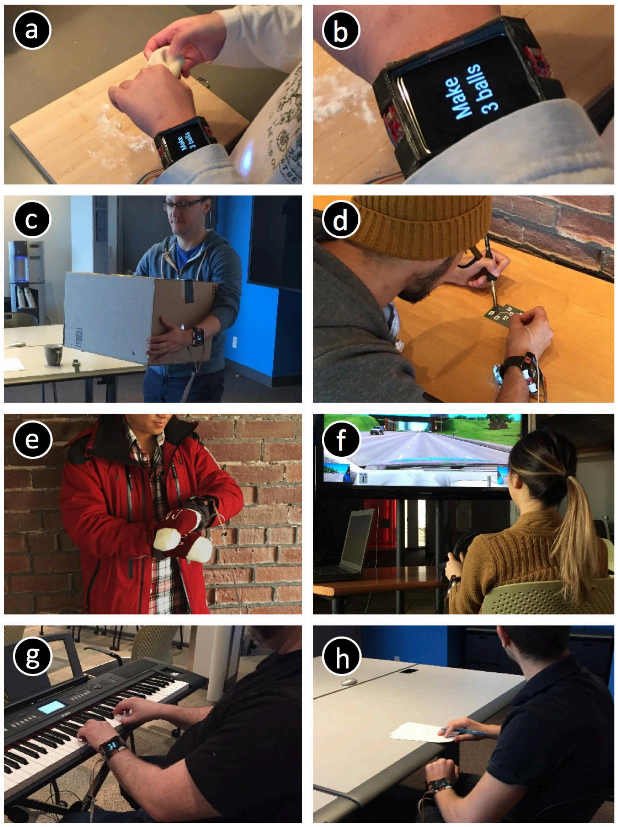

Figure 7: The seven study situations: (a, b) Cooking, (c) Carrying a Box, (d) Soldering, (e) Bus Waiting, (f) Driving, (g) Piano Playing, and (h) Attending a Meeting.

Driving: Using a driving simulator [27] displayed on a 60” display and a Thrustmaster T80 steering wheel with pedal attachment, users drove through a simulated urban area. They were asked to imagine that the notifications they were receiving were incoming phone calls and the technique they performed would answer the phone call. This scenario exemplified the physical and temporal constraints imposed by driving.

Playing Piano: Participants were asked to play a simple pattern of keys on an electric piano. As they did, they received notifications on the watch instructing them to switch to a different area of the piano to continue playing (e.g., left, right, or centre). This task was designed to simulate the temporally-constrained challenge of changing pages of a music score.

Attending a Meeting: As a meeting presents a social situation where a user may want to divert attention in an unobtrusive manner, participants were asked to sit at a meeting room table and pay attention to a video of a person giving a presentation. Participants were asked to covertly read, and then write down sports scores, that appeared on the smartwatch screen.

6.4 Results and Discussion

Participants were generally successful at performing the techniques to complete each task. A notable exception was using the Slap and Blow techniques in the Carrying a Box scenario, where participants had trouble due to an inability to bring their arms together or move their face close enough to the watch face. We did observe a few clever workarounds, including using the legs to support the box, or rotating the box in the arms, which further demonstrated people’s natural tendency to compensate for situational constraints using other parts of the body.

	Forearm			Head	Foot
	Slap	Bang	Swipe	Blow	Side foot tap
Cooking	**3.5** (1.75–5)	**5** (3.75–6.25)	**3.5** (1.75–5.25)	**2** (1–3.5)	**5.5** (4-6)
Driving	**3.25** (2.75–3.5)	**6** (5.5–7)	**4** (1.75–6.25)	**4.75** (4.25–6)	**3.75** (1.75–5.5)
Carrying a Box	**1.75** (1–2.25)	**4** (3–5)	**4.5** (4–5.5)	**2.75** (1.75–3)	6 (5.75–6.25)
Soldering	**1** (1–1)	**2.5** (2–3)	**5** (4.5–5.5)	**5.5** (4.25–6.25)	**7** (6.5–7)
Attending a Meeting	**2.5** (1.75–3.25)	**2.25** (1 – 2.75)	**6.25** (5.75–7)	**2.5** (1.75–3.25)	**6.5** (6–7)
Piano Playing	**2** (1.75–2.25)	**2.75** (1.75–3.5)	**4** (4–4.5)	**5.5** (5–6)	**7** (6.5–7)
Bus Waiting	**7** (6.5–7)	**6** (5–6.25)	**5.5** (4.25–6)	**3** (1–5)	**6** (5–6.25)

Table 2: Median ratings and interquartile ranges for the statement “*I would want to use this gesture in the given scenario.*”

6.4.1 Preference for the Least Constrained Technique

Overall, the foot tap technique was the most preferred (Table 2), aligning with the results of the first study. Ten participants mentioned they liked this technique because it allowed them to continue their current task (e.g., “*Kept doing the task without having to stop it”*, “*leaves your arms / hands free to do other things.*”) The only scenario for where there was not a strong preference for foot tapping was Driving, which demanded use of the feet for the primary task. This suggests that part of the preference for foot tap is due to the feet being unconstrained in these other scenarios.

For scenarios with temporal and social constraints, participants’ preferences were also similar to the first study. For the Driving scenario, Bang was the most preferred technique, not only because it could be performed quickly, but also because there were several readily available surfaces to hit the arm against, which may have reduced the cognitive load required to perform the technique. For the Attending a Meeting scenario, both the Swipe and Foot tap techniques were highly preferred, due to their ability to avoid detection by others by mimicking natural movements (e.g. *“(Side Foot Tap) was quiet, invisible, responsive, and hands-free”*, *“(Swipe) feels natural, like scratching”*).

The above results suggest that participants’ preference for a technique is influenced by the constraints of the given scenario, with preferences to techniques that are less constrained.

6.4.2 Context is Important

As compared to the online study, we observed that contextual issues, such as safety and cleanliness, were more prominent in this study. For example, for the Soldering scenario, the Slap and Bang techniques were less preferred than in the online study, because participants recognized that these techniques could be dangerous, e.g. *“the soldering iron would hit my hand a lot”* and *“This one is dangerous; it moves the soldering iron.”* As another example, there was less enthusiasm for the Blow technique in the Cooking scenario, because participants were concerned about the cleanliness of blowing on the flour used in the dough, e.g., *“[Blow] will blow all the flour everywhere”*. This suggests the added value of evaluating the techniques in a simulation of the real-world scenarios to reveal problematic situations that may not be obvious otherwise.

Many comments also related to the environmental context where the techniques would be performed. Participants cited concerns with looking silly, angry (e.g., “*banging would make me look angry.*”), or strange (e.g., “*I don’t like swipe, it will make me look like* *someone itching.*") Participant comments also suggest that these concerns will be increased during interactions with other people (e.g., "*It'd be strange to bang a table if I'm with someone.*"). This suggests that the social context in which techniques are performed is a particularly important consideration.

6.4.3 Supporting Subtlety via Natural Movements

We observed that some participants attempted to perform the techniques in a subtle manner. In the Meeting scenario, participants tried to make a Swipe movement that mimicked natural behaviors, such as bringing their watch-wielding arm close to their body or crossing their arms while adjusting their wrist position. In the Bus Waiting scenario, one participant crossed her arms and then struck them against each other (Bang technique), similar to how one would try to keep warm outside. These behaviors suggest that no-handed interaction techniques that mimic natural movements may have particular value to users, at least in certain situations.

6.4.4 Persistence of Display

Finally, a desire for the display to be visible was mentioned by multiple participants (e.g., "*When I bang, I had to turn the watch away from my eyes*" and "*I can see the screen while blowing*"). In the case of the Slap technique, this advantage appeared to override the perceived disadvantages of the technique, (i.e., its use of both hands and an increased range of motion). While in this work we have focused mainly on input techniques for no-handed interaction, this suggests the value in developing additional feedback mechanisms as well.

7 THE FUTURE OF NO-HANDED INPUT

The studies presented in this paper demonstrate that a range of no-handed smartwatch interactions can be enabled by considering parts of the body other than the hands. We now consider the implications of our findings for the future of no-handed input.

7.1 One Technique Does Not Fit All

The main takeaway from the study was that the best technique for a given scenario depends on *context* and the *physical*, *temporal*, and *social* constraints imposed by that scenario. Moreover, constraints from different categories of the taxonomy have different characteristics that must be attended to when designing a technique. Physical constraints prevent interaction unless the primary task is stopped, and thus require the use of body parts not implicated in the primary task. For temporal constraints, one can perform input with the hands, but it must be done quickly. Finally, social constraints can limit the acceptability of actions, making them much harder to define than the strictly physical or temporal. This said, techniques that mimic natural actions appear to have a benefit in these situations.

7.2 Combining Input Modalities

Our evaluation focused on techniques that use a single body part for interaction, however, we see potential in gestures that chain or create combinations of techniques that make use of the feet and wrist, or feet and nose. For example, users already employ their noses to interact with smartwatch screens [69,88], but targeting and precise selection is difficult with the nose. A heel-lift gesture could activate a nose-friendly user interface consisting of one large button displayed at a time, enabling easier activation. When combined with wrist movement, foot-based gestures could be used to provide richer input as well. A toe-lift gesture could initiate a "wrist-scrolling mode", in which a small rectangular cursor is shown on the right side of the smartwatch display and moved up or down depending on how the wrist was tilted, thus enabling continuous scrolling. Exploring the full range of possibilities for combining techniques is an interesting area for future work.

7.3 Sensing and Recognition

This work focused on understanding the appropriateness of our proposed gestures in a range of situational contexts, but robust techniques for sensing and recognition of no-handed gestures will be critical to enabling effective no-handed interaction in practice. It will be important to develop recognition algorithms that can accommodate the range of natural movement variations that users employ in performing these techniques. It will also be important to develop recognition techniques with low rates of false activation, which may be a challenge given our finding that users will sometimes mask no-handed techniques as natural movements. One avenue for future work to address these challenges is through additional sensing, including combinational sensing as additional intelligent devices are worn on the body (e.g., glasses, rings, pendants, and so on). Another approach would be to develop no-handed delimiter gestures, which could be performed subtly to mark the start of a no-handed gesture.

The above having been said, it is promising that the recognition techniques we developed for our prototypes worked well for participants in the lab study, and did so without requiring user-specific calibration.

7.4 Input Bandwidth

While some of our techniques have the potential to provide multi-dimensional or continuous input (e.g. directional blow, 2D swipe), our studies evaluated techniques that essentially emulate a button click. While this is sufficient for many common smartwatch tasks, understanding the potential for the techniques to provide higher-bandwidth input is an important area for future work.

7.5 Perception versus Performance

The online survey enabled us to efficiently determine the acceptability of the various interaction techniques in a range of scenarios. With only a brief description of the situation and a short video of the techniques, respondents revealed many factors that they consider when evaluating the suitability of a technique for a given situation. The survey also revealed a broad dislike for the Body Bounce and Pseudo Finger techniques, enabling us to focus our efforts on other techniques.

While the preference ratings for many of the techniques in the situational study were similar to the survey, the situational study underscored that context becomes more important as immersion increases. That is, additional concerns around safety, cleanliness, and the importance of display visibility became more prevalent when participants had a chance to try out the techniques. The situational study also allowed the research team to observe the natural movement variations employed when performing the techniques. However, the situational study only involved individual participants in a simulated environment in a lab. We believe that future studies conducted "in-the-wild" can yield further insights into no-handed interaction, such as those created by environmental noise and social considerations that arise in real-world situations.

8 CONCLUSION

This work presented *no-handed smartwatch interaction*, i.e., techniques that enable one to interact with a smartwatch when one or both hands are busy. We identified constraints that limit interaction capabilities during no-handed interaction scenarios gathered from the literature, then implemented several techniques that made use of other parts of the body to provide input to a smartwatch. Two user studies evaluated these techniques and found a preference for foot-based input, in addition to concerns about situational safety and social acceptability. We hope that the results of this work will encourage reflection and ideation on constrained input scenarios, and guide future efforts on no-handed smartwatch interaction.

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