Investigating How Smartphone Movement is Affected by Lying Down Body Posture

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In this paper, we investigated how "lying down" body postures affected the use of the smartphone user interface (UI) design. Extending previous research that studied body postures, handgrips, and the movement of the smartphone. We have done this in three steps; (1) An online survey that examined what type of lying down postures, participants, utilized when operating a smartphone; (2) We broke down these lying down postures in terms of body angle (i.e., users facing down, facing up, and on their side) and body support; (3) We conducted an experiment questioning the effects that these body angles and body supports had on the participants' handgrips. What we found was that the smartphone moves the most (is the most unstable) in the "facing up (with support)" condition. Additionally, we discovered that the participants preferred body posture was those that produced the least amount of motion (more stability) with their smartphones.

CCS Concepts: • **Human-centered computing** → *Human computer interaction (HCI).*

Additional Key Words and Phrases: Handgrip; Smartphone; Lying down; Body posture.

ACM Reference Format:
Kaori Ikematsu, Haruna Oshima, Rachel Eardley, and Itiro Siio. 2020. Investigating How Smartphone Movement is Affected by Lying Down Body Posture. *Proc. ACM Hum.-Comput. Interact.* 4, ISS, Article 192 (November 2020), 17 pages. https://doi.org/10.1145/3427320

1 INTRODUCTION

In recent years, smartphones usage has penetrated various sectors of everyday life [33]. Individuals use smartphones while sitting, walking, standing, and lying down [3, 33], and there are increasing demands for browsing information while lying down on a couch or bed [29]. Smartphone interaction often begins as soon as individuals awaken, with smartphone users checking social media or online news shortly after rising in the morning [29]. Users may also check for new messages or browse websites during a short break on a couch. In addition, when lying in bed before going to sleep, users often play games, read e-books, set their alarm, or check their schedule for the following day. Although UIs for smartphones have been extensively investigated in terms of basic postures such as sitting or standing postures, interactions while lying down have not received much attention from either researchers or smartphone manufacturers. However, application developers and designers should take into account that smartphones are "often operated by users in lying down" postures [7, 35].

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2573-0142/2020/11-ART192 $15.00
https://doi.org/10.1145/3427320

Smartphones make it possible to design intuitive interactions, as they combine input and output in a single interface. Indeed, UI design for smartphones is not limited to the creation of onscreen components [13, 14]. Hand usage, including handgrips and directional movements, such as back-of-device interaction [9, 27] and motion-based interaction [20], can either replace or supplement onscreen interactions. Researchers have empirically and theoretically demonstrated how hand usage is affected by various smartphone form factors [14, 28], hand size [25], body postures [14], or encumbrance (e.g., carrying a common object such as a bag) during interactions [31].

Although there is a large body of research on hand usage, only a few studies have investigated interactions in a lying down scenario. Eardley et al. [14] reported the effects of body posture, including a lying down posture, on smartphone movement, but they only examined the posture in which users were lying down on their back. In actual cases, users may have other lying down postures, such as face down or on their side; thus, the experimental conditions were limited. Eardley et al. also reported that different arm usage was observed when the participants were lying down (e.g., resting the arms on the upper torso or raising the arm). The authors mentioned that differences in arm support could impact interactions; however, no study has yet revealed this. Considering that many users operate smartphones on a daily basis while lying down, a follow-up study focusing on the lying down posture is important. For example, in the online survey reported in this paper, more than 97% of users responded that they had experience operating a smartphone while lying down. Furthermore, according to Levitas [29], more than 40% of users reach for their phones as soon as they wake up in the morning.

In this study, focusing on lying down postures, we used similar experimental methods to conduct a follow-up study to the tasks reported by Eardley et al. [14]. Specifically, we included a variety of lying down postures and arm supports as experimental conditions that have not been investigated formally. First, we systematically expanded lying down postures in terms of body angle (i.e., facing down, facing up, and on one's side) and body support. Second, we conducted an online survey to determine the lying down postures that users actually favor when using their smartphones. We then conducted an experiment that extended previous work by exploring how body angle and body support affect hand usage. The results for tilt and rotation deepened our understanding of user behavior for smartphone UIs. Investigating how users interact with technology and avoiding complex heuristics is crucial for improving UI design [14], and understanding the variability of hand usage and support conditions for lying down postures can help designers improve mobile interaction design [13].

2 RELATED WORK

2.1 Smartphone Usage in Lying Down Postures

There has been extensive research on smartphone usage for various postures, and several studies have investigated the lying down posture. For example, the conventional gravity-based automatic rotation is unable to properly support screen rotations in the lying down posture [7]. To improve the viewing experience and usability in the lying down posture, Cheng et al. proposed methods that automatically rotate screens to match the users' viewing orientations based on how the users grasp the devices [7]. They also proposed a computer vision approach [6]. In [37], the authors demonstrated how standard classification algorithms can use labeled smartphone-based accelerometer data to distinguish the physical activities performed by a user (e.g., walking, jogging, sitting, standing, and lying down). While these studies report promising results in terms of developing a suitable UI for a variety of postures (including lying down), they focus only on implementing applications or hardware for posture distinction. In contrast, in this study we focus on clarifying the appropriate smartphone UIs for the lying down posture.

2.2 Hand Usage in Smartphone Interaction

There has been extensive research on hand usage while interacting with a smartphone. In [11], the authors mapped four grips during an observational study with three types of smartphone interaction. In [28], the authors investigated three grips using a smartphone and examined the accuracy of the resulting touch inputs. In [2], the authors investigated the reachable area for the thumb during interaction with a touchscreen. Another study revealed that thumb length significantly correlated with touch error [25]. These approaches explore static grips rather than hand movements during interaction. Studies conducted by Eardley et al. [12–14] were the first to provide empirically derived metrics of factors (such as handgrip, body posture, smartphone size, and target position) that affect hand movements.

Recently, an emerging stream of research has investigated adaptive UIs focusing on hand or finger usage during mobile interaction. Buschek and Alt introduced ProbUI [4], a graphical user interface (GUI) framework for smartphones that makes it possible to define probabilistic gestures instead of static bounding boxes. Its probabilistic model enables gestures to be detected and onscreen components to be adapted. Zhang et al. [39] proposed posture-aware interfaces that sense and transition between body-, arm-, grip-, and hand-centric frames of reference, for pen or touch interaction on tablet PCs. Interaction techniques based on built-in inertial sensors of smartphones that detect grips [17], finger proximity [19], differentiate between finger and palm touches [26], finger and objects such as a touch pen [22], fingertip and fingernail [23], and estimate finger pitch and yaw [38] can also be utilized in terms of adaptive interfaces. Although these studies introduce promising ways to interact with smartphone UIs, their focus is limited to specific applications or hardware implementations.

2.3 Body Posture

Researchers have investigated the influence of body posture [18] and the muscles used when interacting with a smartphone using single and asymmetric bimanual grips in the sitting posture [1]. In [16, 32], the authors investigated how pointing or text entry is affected by walking. Researchers have also focused on various contexts of smartphone use. In [31], the authors investigated how encumbrance (e.g., carrying a common object such as a shopping bag) affects the accuracy of touch input. The authors of [6] investigated how smartphone movement varies depending on different physical positions during activities such as sitting, standing, walking, and sitting on a moving bus. In [14], the authors demonstrated how smartphone movement is affected by body posture, including the lying down posture. However, they only examined “the posture of lying down on one’s back”. Our work extends that study [14] to include various lying down postures.

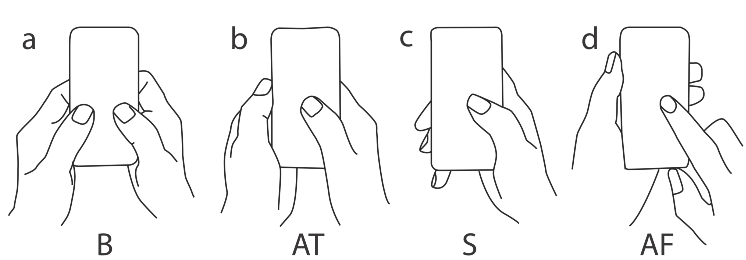

Fig. 1. Four handgrips: a) symmetric bimanual (B), b) asymmetric bimanual thumb (AT), c) single-handed (S), and d) asymmetric bimanual finger (AF). (From [14])

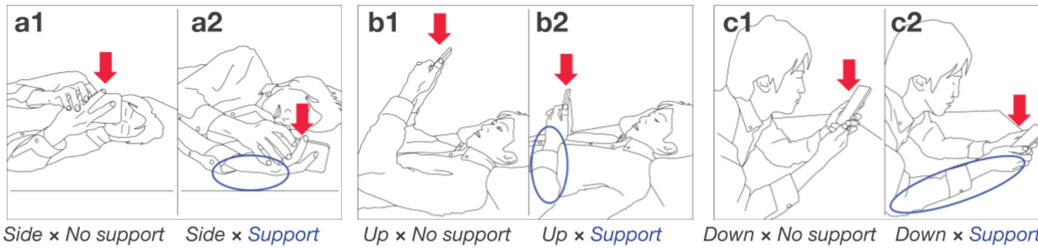

Fig. 2. Three lying down postures with/without support conditions: a) lying down with one's back to the floor, b) lying down on one's side, and c) lying down face down. The arrows represent gravity and the circles represent physical supports for the arm.

3 THEORETICAL EFFECTS

In this study, we examined factors affecting hand usage for different lying down postures. In addition, we constructed hypotheses to be tested in a subsequent controlled experiment. We refer to *X*, *Y*, and *Z* as the rotational axes of a smartphone (see Fig. 4 (a)), where the overall movement of the smartphone is defined as the spatial rotation computed from rotation quaternions. Note that previous studies [11, 12, 14] have defined the overall movement as the sum of the individual rotations for each axis, which is different from the definition in this paper. Eardley et al. [11] reported that the form factor type (i.e., touchscreen, stylus, or keyboard) affects the way smartphones are gripped in a sitting position. Focusing on touchscreen interaction, they investigated the effects of handgrip and smartphone size on hand usage [12]. They also investigated the effect of body posture, such as sitting at a table while resting one's arms, standing, and lying down with one's back to the floor (here in after called *typical postures*), and handgrip [14]. These studies [11, 12, 14] produced the following insights.

- When a range of four hand grips (Fig. 1) was used, with the grips dependent on the application and interaction type, it was found that the smaller the size of the smartphone, the smaller the movements were.
- The overall movements of the smartphone were dependent on the position of the target. Less movement occurred when the targets were in the functional area [2] (Fig. 4 (c)).
- Differences in axis movements were noted, such as an overall smaller Z but larger Y. The authors provided a table of movement metrics for each condition.
- The overall movements of the smartphone were dependent on posture. Less movement was observed for standing, followed by sitting and lying down.
- The orders of overall movements for the grips was consistent for all body postures.
- Rotation of a smartphone was dependent on body posture.

Focusing on lying down postures, we extrapolated two main factors affecting hand usage: body angle and body support. We then formed hypotheses regarding objective measurements (quantity of movement performed by the hand in the different axes) and subjective measurements (users' perceptions of security and comfort).

3.1 Body Angle

Eardley et al. demonstrated that smartphone movement trends vary depending on users' typical postures [14]. Because distinct body postures involve distinct sets of muscles when interacting with touch surfaces [1], the authors conjectured that the trend was due to differences in muscle use. Based on the above findings, we supposed that different lying down postures affect smartphone movements. There are several lying down postures: lying on either side, lying on one's back face up, or lying on one's chest face down. In general, the angle around the longitudinal axis of one's body does not affect hand movements while sitting or standing; however, it may be crucial when lying down. The position of one's hand and a smartphone relative to the ground differs for each lying down posture. For example, in the face-down posture, the hand supports a smartphone from the ground side (Fig. 2 (c)). Due to the direction of gravity, this is considered stable gripping. In contrast, the hand and smartphone positions are reversed in the face-up posture (Fig. 2 (b)). In this posture, the smartphone is grasped from above, which is considered a relatively unstable gripping style.

3.2 Body Support

This factor was also partially investigated in a previous study [14]. The authors assumed that body support conditions were dependent on body postures [14]; however, they reported that different types of arm or hand support were observed when participants were lying down, such as raising an arm (without support, Fig. 2 (b1)) or resting the arms on the upper torso (with support, Fig. 2 (b2)). It is thus likely that the physical body support significantly contributes to hand stability. In another example, when users operate a smartphone while lying down and facing down, they can naturally rest an arm on the bed or couch. However, in addition to hand stability, the comfort or screen visibility may vary depending on whether individuals rest an entire arm (Fig. 2 (c2)) or only an elbow (Fig. 2 (c1)). We conclude that body support and body angle may thus affect hand usage differently and should be evaluated as separate conditions.

3.3 Hypotheses

From the above, we present the following hypotheses.

- H1: Overall smartphone movement is greater for the *no support* condition than the *with support* condition owing to the arm muscles being used to lift the smartphone upward. In addition, because less physical effort is required in the *with support* condition, the *with support* condition should be rated more "secure", "comfortable", and "preferable" than the *no support* condition.
- H2: Considering the position of the hand and a smartphone relative to the ground, the overall smartphone movement is greater for the *lying down face up* posture.
- H3: The *directional movement* for each body angle varies due to different directions of gravity.
- H4: Similar to previous results, for grips in lying down postures, *S* has the most movement, followed by *AT* and *B*, then by *AF*.
- H5: Similar to previous results, the total movements of the smartphone differ according to the target position for all body postures (i.e., targets farther away require more movement, while those in the functional area of the thumb, require less).
- H6: When less movement is required, the rating for the "secure" and "comfortable" conditions is higher, which is preferable. For example, *S* is estimated to involve the most movement, and should thus have the lowest rating.

4 ONLINE SURVEY

We conducted an online survey to investigate whether the postures in our listed combinations of factors are commonly used ones. The survey was created in Google Forms and we sent the link to the respondents. First, we asked whether they had experience operating a smartphone while lying down. Those who selected "No" finished the survey, while those who selected "Yes" proceeded to the following questions. We instructed the participants to answer the questions while recalling how they operate their smartphones while lying down on a bed or couch.

- Q1: Which posture do you usually take while laying down? (Select from 1: lying down on his/her side; 2: facing up; 3: facing down, or 4: other (free answer).)
- Q2: With which grip do you hold your smartphone while you are in the Q1 posture? (Select from Fig. 1 (a)–(d), or free answer.)
- Q3: How do you support your arm while you are in the Q1 posture and using the Q2 grip? (Select from 1: supporting your hand that holds the smartphone with your body or part of a bed or couch, 2: without support, or 3: free answer.)

Respondents were permitted to answer these questions up to three times (i.e., respondents could select a maximum of three preferred lying down posture combinations of Q1–3). On average, we collected 1.3 responses per respondent. A total of 438 respondents aged between 8 and 70 (average age: 28 years, SD = 10.4) participated in the survey; 64.3% were females and 35.7% were males; and 88.1% were right-handed, 8.2% were left-handed, and 3.7% were ambidextrous. Most of the respondents had experience operating their smartphones in a lying down posture (429 of 438).

4.1 Results

Regarding posture preference, a total of 60.2% of responses were *lying down on side*, 25.2% were *facing up*, and 14.5% were *facing down*. These results indicate that the majority of respondents preferred to use their smartphones in the *lying down on side* posture. Regarding grip preference, as shown in Fig. 3 (a), the majority of responses were *S*, followed by *AF*, *AT*, and *B* in all postures. Regarding support preference, as shown in Fig. 3 (b), for the *lying down on his/her side* and *facing down* postures, the majority of responses were with support, followed by without support. In contrast, for the *facing up* posture, most responses were without support, followed by with support.

For the *facing down* posture, four respondents reported that they propped the smartphone against the wall or placed it on the bed or pillow to operate it (i.e., they operated the smartphone without holding it in their hand). However, most respondents selected the lying down postures from the provided options. These results indicate that the postures in the combinations of body angle and support conditions are typical postures for users in the lying down position. We therefore used these postures in the following experiment.

5 CONTROLLED EXPERIMENT

The goal of this experiment was to explore whether a user's lying down posture affects a smartphone's tilt and rotation, particularly how the body angle and support empirically affect the smartphone's movement. We replicated the setup from [14] to ensure study validity and used the same user interfaces and graphics (Fig. 4 (c)) .

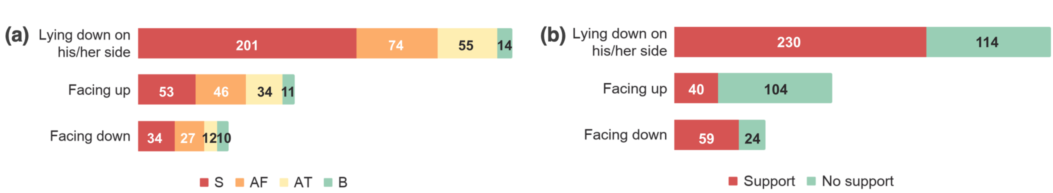

Fig. 3. Survey responses: (a) users' preferred grip for each posture. (b) users' preferred arm support (elbow to hand) while holding a smartphone for each posture.

5.1 Participants

A total of 12 individuals with no known disabilities (2 males and 10 females) aged between 22 and 56 years (average age: 26 years, SD = 9.1) participated in the experiment. In accordance with [5, 15], we first performed a power analysis. The number of participants satisfied the necessary sample size with a medium effect size of 0.25, power of 0.8, and α level of 0.05 (these parameters were suggested by Cohen [8, 36]). To prevent distortion of the sensor values due to difference in handedness, we limited the experiment to right-handed participants. All participants either studied at or worked for a local university. Their hand characteristics were as follows: length 82–107 mm, width 69–95 mm, thumb length 50–65 mm, and finger length 72–90 mm. All participants had daily experience with smartphone usage while lying down.

5.2 Task

At the beginning of the experiment, the participants were instructed to place their hands on a piece of A4 7-mm graph paper and we traced the outline of their hands. Each participant was instructed to adopt one posture at a time from the required postures randomized using a Latin square. The phone screen presented an illustration of the handgrip that the participants were supposed to assume. When ready, the participants clicked on the center of the screen to launch the trial. They began a pointing task in which they first selected Target 1 and then Target 2. The targets were 14 mm in diameter as recommended by Holz et al. [21], and appropriate sounds were played to denote error or success. The participants were instructed to be as accurate as possible, and they took an optional break between tasks to avoid fatigue. After completing a task, a "next" button was displayed, allowing the participants to start the subsequent trial. Once a task was completed, the screen presented a new grip to assume. Whenever a trial ended, the participants were instructed to complete a 7-pt. Likert questionnaire for each combined condition with the following questions (where 1 was negative and 7 was positive): "How comfortable was the grip", "How comfortably could you see the screen", "How secure was the grip (risk of device being dropped)", and "How much did you prefer this grip (user preference for a particular condition of the study)". Note that since neck flexibility could be limited depending on the head support, we inserted an additional

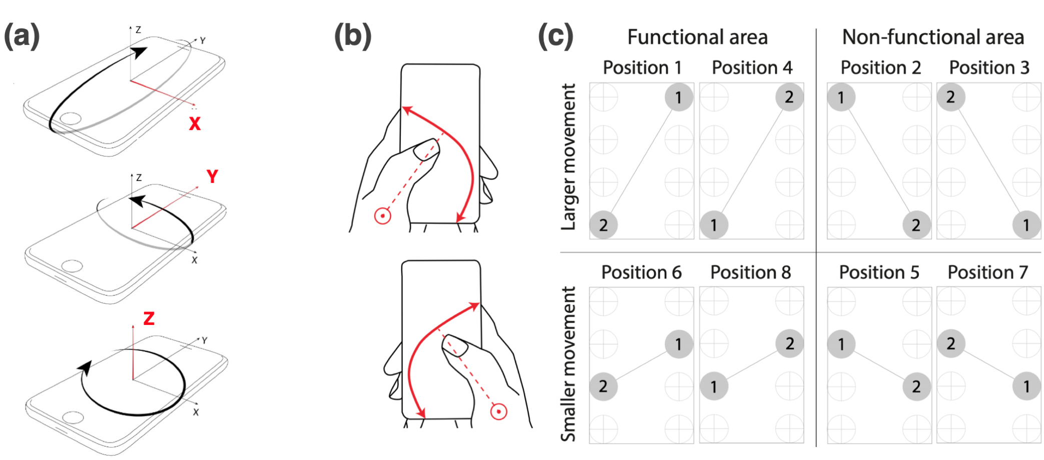

Fig. 4. (a) Smartphone orientation, (b) Fnctional area of the thumb depicting the thumb's natural area of reach [2] and (c) target positions used in the experiment as a reproduction of the study conducted in [14]. (From [14])

question into the questionnaire from the previous work (namely, "How comfortably could you see the screen").

5.3 Apparatus

Similar to [14], we used an iPhone 6 (H: 138.1 mm, W: 67 mm, D: 6.9 mm), as this model demonstrates the most movement variation in [12]. A web application was used to track phone movements (built-in accelerometer and gyroscope) and the participants' touch inputs. During the tasks, we recorded the participants using two iPhone X cameras. For the lying down scenario, we used a single airbed. During the experiment, the participants were allowed to use a pillow for the *side* and *up* postures.

5.4 Experimental Design

We conducted a within-subject experiment with four independent variables: body posture (*side* (Fig. 2 (a)), *up* (Fig. 2 (b)), and *down* (Fig. 2 (c))), body support (no support (Fig. 2 (1)), and *support* (Fig. 2 (2))), hand grip (Fig. 1), and target position (eight different combinations of target positions presented in Fig. 4 (c)). In non-symmetrical postures (i.e., *side*), we fixed the side (right or left) on which participants lay down to simplify the comparison between participants. Specifically, the dominant hand was on the lower side in *B*, *AT*, and *S*, while the non-dominant hand was on the lower side in *AF*. The grips and posture were randomized using a Latin square. For support, six participants performed the tasks with the support condition first, then without the support condition. The other six participants performed the tasks in the reverse order. The target positions were randomized within each block. As a result, 3 *postures* × 2 *supports* × 4 *grips* × 8 *target positions* = 192 double-tapping tasks for a total of 40 minutes.

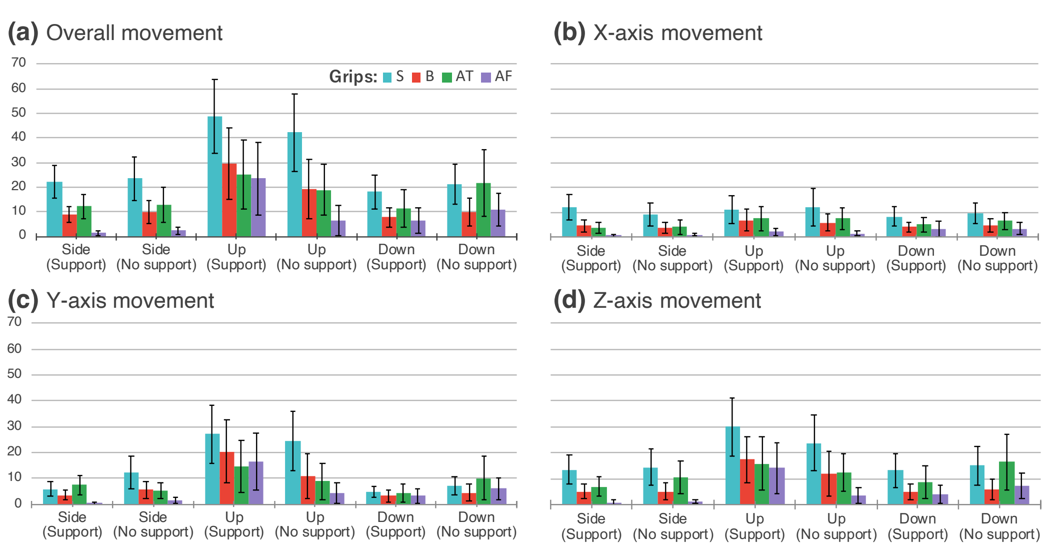

Fig. 5. Estimated level of phone movement with 95% confidence interval demonstrating the interaction between different postures, supports, and grips.

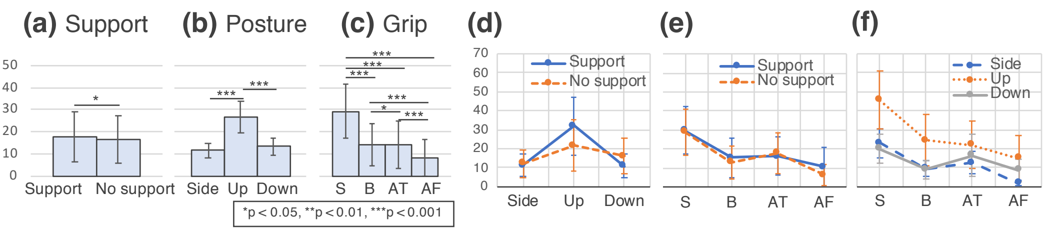

Fig. 6. Main effect of (a) support, (b) posture, and (c) grip on overall movement. Interaction of (d) support × posture, (e) support × grip, and (f) posture × grip on overall movement.

5.5 Quantitative Results

A Shapiro-Wilk test confirmed that our data met the assumption of normality. First, we analyzed the overall movement (spatial rotation computed by converting a 3-axis movement, see Fig. 4 (a)) obtained by the device's built-in sensors into a single quaternion. Second, we detail the directional movement. In addition, we analyze the post questionnaire using analysis of covariance (ANCOVA). ANCOVA extends the analysis of variance by including additional variables (covariates), such as the size of the participants' hands, that influence the dependent variables. To generate a unique covariate using our four hand measurements (palm width, palm length, thumb length, and middle finger length), we used principal component analysis to reduce the number of dimensions, as in [14]. This created a hand size score, which is an effective indicator of general hand size. The variances did not significantly differ from each other, indicating that the assumption of homogeneity of covariance was met. In the remainder of the analysis, we use a p-value below 0.05. We do not report data comparatively uninteresting data that do not affect our main findings (e.g., significant interactions related to the target position).

5.5.1 Overall Movements. Figure 5 (a) presents the estimated values, that is, the hypothetical values unbiased by the hand size scores after correction by ANCOVA. We found significant main effects for support ($F_{1,11} = 4.161$, $p < 0.05$), posture ($F_{2,22} = 192.239$, $p < 0.001$), grip ($F_{3,33} = 163.982$, $p < 0.001$), and target position ($F_{7,77} = 74.189$, $p < 0.001$). We also found significant interactions for support × posture ($F_{5,55} = 43.134$, $p < 0.001$), support × grip ($F_{7,77} = 2.915$, $p < 0.05$), and posture × grip ($F_{11,121} = 16.351$, $p < 0.001$). Figure 6 shows the main effects and the interactions, respectively.

5.5.2 Directional Movements. Next, we examine the movements for each axis (Figure 5 (b, c ,d)). For X, we found significant main effects for posture ($F_{2,22} = 19.2967$, $p < 0.001$), grip ($F_{3,33} = 176.1376$, $p < 0.001$), and target position ($F_{7,77} = 59.5664$, $p < 0.001$). We also found significant interactions for support × posture ($F_{5,55} = 3.7009$, $p < 0.05$) and posture × grip ($F_{11,121} = 297.89$, $p < 0.001$). For Y, we found significant main effects for posture ($F_{2,22} = 110.675$, $p < 0.001$), grip ($F_{3,33} = 116.619$, $p < 0.001$), and target position ($F_{7,77} = 59.395$, $p < 0.001$). We also found significant interactions for support × posture ($F_{5,55} = 33.698$, $p < 0.001$) and support × grip ($F_{7,77} = 4.593$, $p < 0.01$). For Z, we found significant main effects for posture ($F_{2,22} = 204.582$, $p < 0.001$), grip ($F_{3,33} = 50.305$, $p < 0.001$), support ($F_{1,11} = 5.047$, $p < 0.05$), and target position ($F_{7,77} = 33.297$, $p < 0.001$). We also found significant interactions for support × posture ($F_{5,55} = 44.279$, $p < 0.001$) and posture × grip ($F_{11,121} = 20.593$, $p < 0.001$). Figure 7 shows the main effects for the movements of each axis.

5.5.3 Post Questionnaire. The results of the post questionnaire are shown in Fig.8.

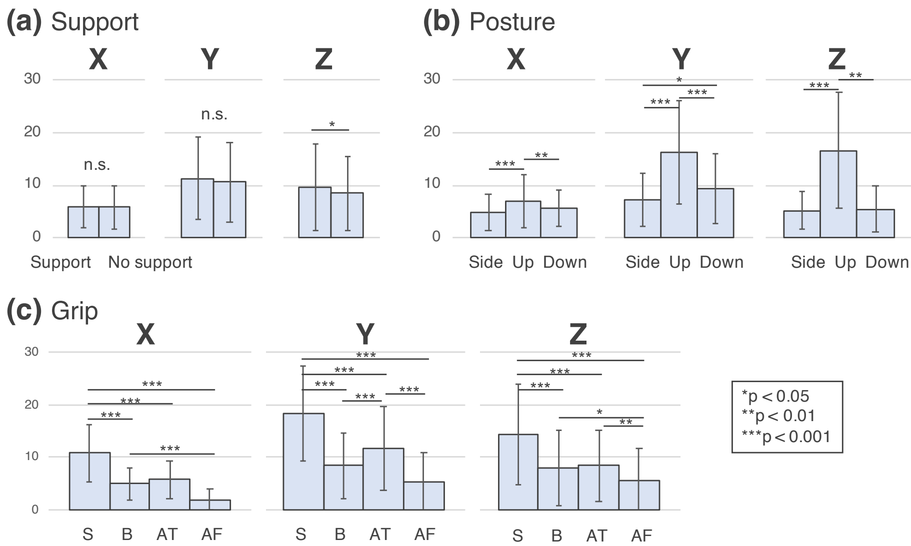

Fig. 7. Main effects of (a) support, (b) posture, and (c) grip on each axis movement.

Q1: Secure. We found significant main effects for posture ($F_{2,22} = 289.74, p < 0.001$), support ($F_{1,11} = 44.73, p < 0.001$), and grip ($F_{3,33} = 1109.21, p < 0.001$). We also found a significant interaction for support × posture ($F_{5,55} = 22.49, p < 0.001$), support × grip ($F_{7,77} = 24.51, p < 0.001$), and posture × grip ($F_{11,121} = 44.90, p < 0.001$). For body postures, participants reported that the *up* posture was significantly less secure, followed by the *side* and *down* postures, which were being the most secure. For body support, *no support* was less secure than *support* for the *side* and *down* postures. For the grips, we also observed that *S* was significantly less secure, followed by *B*, *AT*, and *AF* (Fig. 8 (i)).

Q2: Preference. We found significant main effects for posture ($F_{2,22} = 228.16, p < 0.001$), support ($F_{1,11} = 12.26, p < 0.001$), and grip ($F_{3,33} = 255.19, p < 0.001$). We also found significant interactions for support × posture ($F_{5,55} = 58.18, p < 0.001$), and support × grip ($F_{7,77} = 25.80, p < 0.001$). For body postures, participants reported that the *up* posture was significantly less preferred, followed by the *side* and *down* postures. For body support, *no support* was less preferred than *support* in the *side* posture; however, in the *up* posture, *support* was less preferred. For the grips, we also found that *S* was significantly less preferred, followed by *B*, *AT*, and *AF* (Fig. 8 (ii)).

Q3: Comfort (grip). We found significant main effects for posture ($F_{2,22} = 196.99, p < 0.001$), support ($F_{1,11} = 8.62, p < 0.01$), grip ($F_{3,33} = 265.39, p < 0.001$). We also found significant interactions for support × posture ($F_{5,55} = 62.94, p < 0.001, p < 0.001$), support × grip ($F_{7,77} = 26.27$, $p < 0.001$), and posture × grip ($F_{11,121} = 41.35, p < 0.001$). For body postures, participants reported that the *up* posture was significantly less comfortable, followed by the *side* and *down* postures. For body support, *no support* was less comfortable than *support* in the *side* posture; however, in the *up* posture, *support* was less comfortable. For the grips, we also found that *S* was significantly less comfortable, followed by *B*, *AT*, and *AF* (Fig. 8 (iii)).

Q4: Comfort (visibility). We found significant main effects for posture ($F_{2,22} = 431.20, p < 0.001$), support ($F_{1,11} = 36.21, p < 0.001$), and grip ($F_{3,33} = 479.53, p < 0.001$). We also found significant interactions for support × posture ($F_{5,55} = 98.41, p < 0.001$), body support × grip ($F_{7,77} = 31.88, p < 0.001$), and body posture × grip ($F_{11,121} = 29.63, p < 0.001$). For body postures,

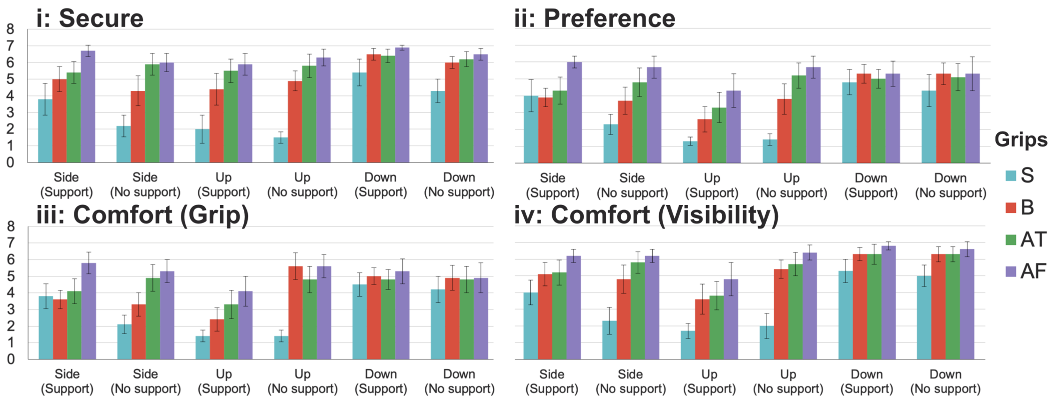

Fig. 8. Questionnaire results: (i) secure, (ii) popular, (iii) comfort (grip), and (iv) comfort (visibility).

participants reported that the *up* posture was significantly less comfortable, followed by the *side* and *down* postures. For body support, *no support* was less comfortable than *support* in the *side* posture; however, in the *up* posture, *support* was less comfortable. For the grips, we found that *S* was significantly less comfortable, followed by *B*, *AT*, and *AF* (Fig. 8 (iv)).

In all four questionnaire items, grip *S* was rated low for all postures except *down* and *side (support)*. From our observation along with feedback from the participants, we conclude that the reason the participants supported grip *S* in the *down* and *side (support)* conditions is as follows. In the *side (support)* condition, there was a large contact area between the holding hand and the bed; thus, the smartphone was stably supported. In the *down (no support)* condition, although the hand that held the smartphone was not supported, it could be placed on the back of the smartphone to stop the smartphone from falling. In addition, the *up (support)* condition was rated low for all grips in all four questionnaire items. The participants could not comfortably operate the smartphones when resting their arms on their upper torso because they had to bend their necks to see the smartphone screen.

6 DESIGN IMPLICATIONS

We now revisit our hypotheses in light of the statistical analysis results. In this study, we examined the interaction between handgrip and smartphones, investigating how body posture (body angle) and body support affect the tilt and rotation of a smartphone.

Regarding H1, although participants rated the *support* condition significantly higher than the *no support* condition, the overall smartphone movement was greater in the *support* condition. Thus, the results partially agree with our hypothesis. For the interaction between *posture* × *support* (Fig.5 (b)), the *up* posture tended to exhibit grater movement in the *support* condition. We believe this was an uncomfortable angle and that it was difficult to see the smartphone's screen even with a pillow under one's head.

Regarding H2, we found that the posture with the most movement was the *up* posture, which applied to all grip types in the *support* condition. However, in the *no support* condition, we found no evidence that the most movement was in the *up* posture in *AT* or *AF*. Thus, the results partially agree with our hypothesis.

Regarding H3, for the smartphone's movement, we observed that each posture had different directional movements (Fig. 9), thus validating H3. The *up* posture had the most movement of Y, followed by Z and X. The *down* posture had the most movement of Y, followed by X and Z. We estimate that participants tilted the device from side-to-side along the Y-axis to gain better access to the targets while maintaining the specified grip and posture conditions. For the *side (support)* condition, each handgrip had different directional movements (e.g., *S* had the least movement of Z, but *AT* had the most movement of Z and *B* had the most movement of X).

Regarding H4, we found that the movement of the overall grip was consistent with the findings of [14] (*S* had the most movement, followed by *AT*, *B*, and *AF*). Regarding the interaction between *posture* × *grip* (Fig. 5 (d)), the *down* and *side* postures had different movement tendencies from *up* posture (*S* and *AT* had the most movement, followed by *AF* and *B*). This partially validates H4.

Regarding H5, the non-functional targets with the largest distance had the most movement, while the functional targets with the least distance had the least movement, thus validating H5. Note that although no significant differences were found for the target positions in previous work, in this study we observed a significant effect for target positions in the "lying down" postures. We believe that compared to standing or sitting postures, the lying down posture makes it difficult for users to shift handgrips to touch non-functional areas (particularly positions 2 and 3 in Fig. 4, which require large movements).

Regarding H6, AF - the grip with the least movement for all body postures – was considered the most secure, preferable, comfortable, and visible. In addition, *S* with the largest movement received the lowest rating. These results partially validate H6. However, the subjective rating of *S* was not extremely low in the *side (support)* and *down* conditions compared to other postures. We should point out that the online survey also revealed that many users preferred to use the *S* grip in the *side* posture. This handgrip is thus considered sufficient for performing lightweight operations such as using only the functional area in ordinary browsing tasks on a bed or couch.

7 CONCEPTUAL INTERFACE DESIGN

Our study showed that the hand flexibly adapts to the posture and support conditions by dealing with interactions (i.e., target selection) through a combination of grips and movements. In this section, we utilize the findings from the experiment to generate several concepts that suggest appropriate designs for the user interface for lying down postures. We aim to explore important factors in smartphone operation in the lying down posture, rather than to propose a novel interface. We believe our concept and findings can be helpful in examining the suitability of existing input methods (e.g., one-handed input techniques or context-aware interfaces) or menu layout designs for use in a lying down posture.

7.1 Adaptive Menu Bar

Overall, the movement toward the X-axis was small even when the target was outside the functional area (Fig. 9). This is a different trend from the same task when seated [12]. Since the head cannot move flexibly in the side or up posture, the visibility of the screen is greatly affected by the angle of the smartphone. In order to maintain good visibility, we had assumed that the participants would intentionally suppress the X-axis motion of the smartphone. Instead, we found that the Y-directional movement was generally larger than the other directions. As discussed in H3, this would indicate that participants tilted the device from side-to-side along the Y-axis to gain better access to the targets while lying down.

The adaptive menu bar concept (Fig. 10 (a)) has some similarities with sensor synaesthesia [20]. In this concept, the menu bar shifts or appears closer to the dominant hand when the user tilts along with the Y-axis while tap-and-holding at the edge of the screen. This reduces the amount of reach a participant needs to use in order to interact with the smartphone.

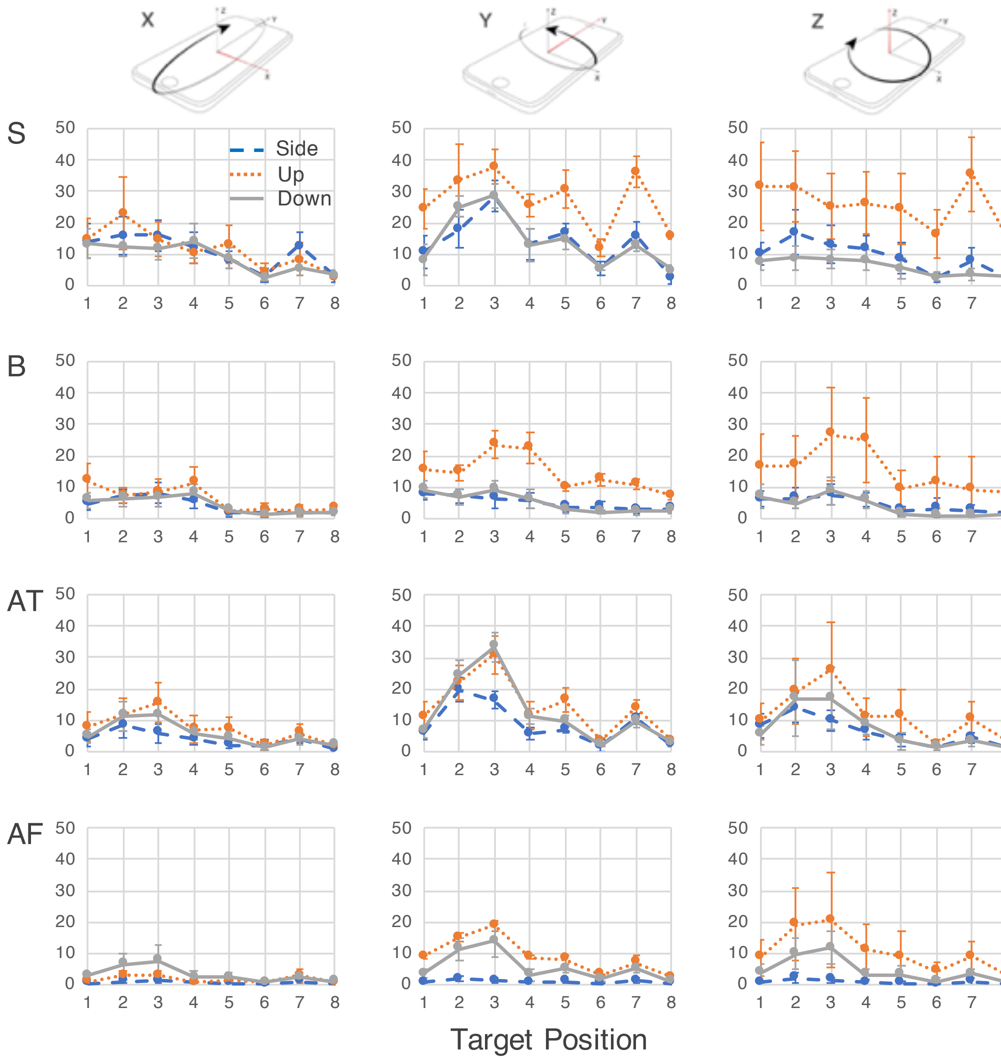

Fig. 9. Estimated extent of phone movement in each axis.

7.2 Virtual Joystick

In the face-up posture during the experiment, the overall movement was large, especially in the S grip, which was the largest among all conditions. Notably, as shown in Fig.9, even when the targets were in the center of the functional area (positions 6 and 8), the movement in the Z and Y directions was large. In addition, the participants mentioned that since the grip was unstable, they were careful not to drop the smartphone. Therefore, an interface that can be operated by fine finger movements will be suitable.

In the concept shown in Fig.10 (b), a user can activate a virtual joystick close to the thumb's contact point by using a trigger action (e.g., tap-and-hold) and operate a cursor pointer on the screen. Similar to the traditional joystick or software-based one-handed pointing techniques such

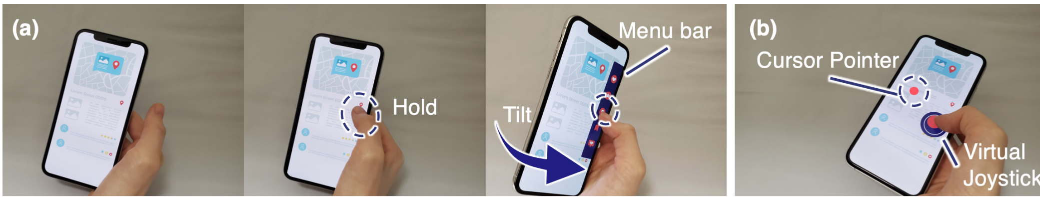

Fig. 10. (a) Concept of the adaptive menu bar. (right) No shifting of the menu bar occurs while the device is held as usual. (Center) Touching the edge of the screen enters the mode for shifting. (Left) The menu bar shifts when tilting the smartphone along with the Y-axis. (b) Virtual joystick.

as MagStick [34], this operation does not require large finger or hand movements from the user. The contents can be scrolled by means of a circular gesture at the edge of the virtual joystick. This interface will increase grip stability while lying on one's back facing up.

8 LIMITATIONS AND FUTURE WORK

Our discussions are somewhat limited by some of the experimental conditions. First, in actual smartphone usage, lying down postures are not limited to our selected conditions, i.e., lying on either side or with the body straight or bent/curled forward or backward. In our experiment, to reduce the number of postures, we selected ones that were most affected by our considered factors. Generally, the weight of an individual's upper body is equivalent to 75% of the individual's body weight [24]. Thus, we did not consider lower-body postures crucial for posture stability or hand usage and instead focused on upper-body postures. Further empirical investigation is necessary to examine this assumption, which will lead to improved design implications for the future. Second, in order to prevent distortion of the sensor values due to difference in handedness, we only used right-handed participants in the experiment. When left-handed users are considered in the application design process, it will be necessary to handle the positive and negative reversal of acceleration in the x-axis and gyroscope in the y- and z-axis directions of the results [10, 30].

Another limitation is that the study was conducted with just one smartphone. Previous research [12] has shown that the size and weight of a smartphone affect the stability of the hand grip. In the lying down posture, the negative effects of using a big and heavy smartphone may be greater than in the seated or standing postures.

In our controlled experiment, the *down* posture was the most preferred by participants, while in the online survey, this posture was the least preferred. We assume this is because the *down* posture was stable enough for our experiment's short tasks (around 40 minutes); however, it is not suitable for long-time smartphone operation. Some participants in the experiment mentioned that "the (*down* posture) operation was the easiest, but was difficult for long-time usage". They also mentioned "Since the physical load is low, I think the *side* posture is the most comfortable for long-time smartphone use". In the future, we will conduct a comparison between short- and long-time tasks that will yield more insights.

9 CONCLUSION

In this paper, we focused on lying down postures during smartphone usage and conducted a follow-up study to Eardley's tasks [14]. The results deepened our understanding of user behavior for mobile UIs. We found that the overall movements of a smartphone depend on posture, with less movement in the *side* posture, followed by the *down* and *up* postures. The participants found the support condition most secure, comfortable, and preferable in the *side* and *down* postures. Understanding the variability of hand usage and support conditions in lying down postures will enable designers to improve mobile interaction design. Our future work will include running a design workshop in which we provide designers and developers with the findings of this study and have them produce examples of mobile UIs for lying down postures to optimize stability and comfort.

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Received June 2020; revised August 2020; accepted September 2020