HF-MAI: Touchless Mid-Air Interaction for Individuals with Dexterity Impairment

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Abstract. For individuals with Multiple Sclerosis (MS) and dexterity impairments (MS-Dex), touchscreen interaction can be particularly challenging, as symptoms like finger numbness and impaired motion regulation negatively impact smartphone usability. This study investigated the usability and accessibility of a mid-air gesture interaction technique for MS-Dex. Touchscreen technologies are ubiquitous, but these individuals often face challenges with touch-based interaction. Touchless input methods, like mid-air gestures, offer a promising alternative for enhancing interaction and communication with touch-based technology. We developed an interactive tool (HF-MAI) using hand and finger mid-air gestures for common touchscreen tasks, using the Leap Motion Controller (LMC) for gesture recognition. MS-Dex individuals, MS therapists, and a usability and user experience (UX) expert participated in the evaluation. We assessed usability, user satisfaction, and accessibility of the HF-MAI system. Results indicate HF-MAI is highly usable and accessible; participants performed gestures successfully and reported high satisfaction. Notably, pinch, spread, and rotate (two-finger/single-finger) mid-air gestures were performed with faster completion times, contrasting with the difficulty of such gestures on touchscreens. The gesture vocabulary, particularly the adaptation to single/two-finger movements, facilitated easier interaction, reducing difficulty for users with limited dexterity. This study demonstrates the potential of mid-air gestures using co-created vocabularies to enhance accessibility for individuals with MS, offering a promising alternative to traditional touch-based input. This technology can significantly improve their access to touchscreens, enhancing independence and quality of life.

Keywords: Touchless Interaction · Mid-air Gestures · Accessibility · Usability · Dexterity Impairment · Multiple Sclerosis

1 Introduction

The rapid development of novel interaction approaches is shifting away from traditional input devices (e.g., mouse and touch interfaces) toward more natural user interfaces (NUIs) based on modalities such as gesture, speech, and vision [36]. Mid-air interaction, a key component of this evolution, enables users to engage with technology through natural, touchless hand and arm gestures [14]. Mid-air gesture interaction, a form of embodied input, is considered more intuitive, natural, and engaging because it leverages the physical gestures people already use in everyday communication [12]. This shift towards NUIs is particularly relevant for individuals with motor impairments, such as those with Multiple Sclerosis (MS). While MS can affect dexterity, hand and finger movements are crucial for daily tasks and independent living [52]. These individuals often experience difficulties with traditional input methods due to challenges like small touch targets, and pressure sensitivity, which affect their accuracy and timing, hindering overall performance [8]. Our research aims to assist these individuals in using touchscreen technologies by developing a touchless interaction approach that adapts to their hand and finger capabilities, enabling them to interact with digital content as others do.

While touchscreens have become ubiquitous in modern communication, effective interaction with these devices requires precise hand and finger dexterity [58]. Actions like taps, swipes, and pinches, essential for touchscreen use, can be challenging for individuals with MS who often experience limitations in hand function and hand-eye coordination. Traditional touchscreen gesture recognition also presents challenges, as it often requires finger occlusion and precise positioning [33]. Small selection areas lead to missed or incorrect inputs, and pressure sensitivity can be problematic for those with reduced touch force for those who cannot provide strong touch force [13]. Furthermore, finger numbness, a common symptom of MS dexterity impairment, can further hinder touchscreen and keyboard interaction [43]. Furthermore, individuals with dexterity impairments often exhibit significantly longer dwell times and apply significantly more force during simple tapping tasks compared to those without such impairments [39]. Consequently, individuals with MS often require assistive technologies for effective touchscreen interaction [21]. While some research has explored improving touch accuracy for users with dexterity challenges [33, 49, 50], these solutions still rely on touch. Clearly, reliance on touch poses a significant barrier for many individuals with MS. Therefore, exploring alternative interaction methods that minimize or eliminate the need for touch is crucial. Mid-air interaction offers a promising avenue for enhancing accessibility for individuals with MS, addressing the fine motor control challenges associated with the condition.

Although resources like the International Classification of Functioning, Disability and Health (ICF) suggest general HCI approaches for various disabilities—such as those affecting physical ability, eyes and face, voice, or involving brain-computer interaction [51]—the diversity in the causes, types, and severity of MS presents challenges for achieving universal accessibility [30]. This diversity underscores the need for human-centered solutions tailored to the specific motor

challenges of MS, such as the mid-air interaction system explored in this paper. Our work addresses the challenge of designing usable and accessible interaction systems for individuals with Multiple Sclerosis and dexterity impairments (MS-Dex) by investigating a hand and finger mid-air gesture interaction system. This system utilizes a gesture vocabulary, previously co-created with MS-Dex individuals, that translates common touchscreen gestures (tap, swipe, pinch, spread, drag, and rotate) into mid-air gestures.

This study builds upon our prior work, which established a baseline understanding of the challenges faced by MS-Dex individuals with traditional touchscreen interaction through quantitative and qualitative evaluation (under review). Drawing on this baseline, as well as a subsequent gesture elicitation study that gathered extensive qualitative and quantitative data on MS-Dex preferences for mid-air interaction, we developed the current mid-air gesture paradigm. While the detailed data and results from these prior investigations are beyond the scope of this paper, the development of the gesture vocabulary and the focus of this study are directly informed by the needs and challenges identified in these prior evaluations. This study serves as a crucial next step, exploring a novel interaction modality tailored for this user group, building upon our foundational research. This vocabulary was designed through a user-centered methodology (Wobbrock et al. (2009) [54]; Xia et al. (2022) [55]), prioritizing direct user involvement to ensure the resulting gestures are discoverable, intuitive, and preferred by MS-Dex individuals. Specifically, we incorporated qualitative feedback on gesture preferences and usability, considering: (1) situational factors, including context of use and social acceptability; (2) cognitive factors, such as discoverability and intuitiveness; and (3) physical factors, like ergonomics and efficiency.

Our goal is to investigate this touchless interaction approach, utilizing the mid-air gesture vocabulary and design guidelines, for seamless integration into touch-based devices like tablets, smartphones, and self-service kiosks. These devices, commonly used in daily life, often pose challenges for individuals with dexterity impairments. This touch-free approach aims to increase their accessibility by addressing the limitations of traditional touch interfaces, as identified in the prior work, and by leveraging the user-preferred mid-air gestures elicited from our target population.

This study aims to provide empirical evidence on the effectiveness of this touchless approach compared to traditional touch-based interaction, focusing on its impact on usability (measured using the System Usability Scale (SUS) [4, 5] adapted with an adjective rating scale [1]), accessibility (assessed through performance metrics [28, 29]), and overall user experience (evaluated through experience ratings, as detailed in the Methods section) [17, 37]. Ethical approval for this study was granted by the School of Computer Science & Informatics Research Ethics Committee at Cardiff University and the Institutional Review Board at Sultan Bin Abdulaziz Humanitarian City. The primary contributions of this paper include: (1) empirical evidence demonstrating the impact of a mid-air gesture system on usability, accessibility, and user experience for individuals

with MS-Dex; (2) insights into the design considerations for accessible mid-air interaction systems, including gesture vocabulary design, user preferences, and potential challenges for individuals with dexterity impairments.

2 Background

To address the challenges of touchscreen interaction for individuals with dexterity impairments, researchers have explored various touchscreen enhancements and personalization techniques. For example, Montague et al. (2012) [32] demonstrated that adapting the interface through a shared user modeling approach can improve performance and reduce errors for individuals with motor and visual impairments. Their approach involved adjusting on-screen elements, such as target size, dwell time, and font size, to match user needs. Other studies have focused on the impact of touch characteristics. Chen et al. (2013) and Sesto et al. (2012) [8, 39] reported that button size significantly affects touch characteristics for individuals with fine and gross motor disabilities during digit entry touchscreen tasks. Their touch interaction approach revealed that button size influenced dwell times, the force needed to activate buttons, and the level of user discomfort. Based on these findings, they recommended increasing button sizes, which demonstrated performance improvements. However, while these studies demonstrate the potential for improving touchscreen accessibility, they sill rely on touch as the primary interaction modality, which may not be suitable for all users.

Given the challenges of touch-based interaction, there is a clear need to investigate alternative approaches. While assistive technologies like voice control and eye tracking offer valuable alternatives, mid-air interaction presents unique advantages, particularly for individuals with limited hand function. This is the focus of our research. Mid-air gestures offer a touchless approach to technology use, relying on intuitive movements performed with various body parts [7, 57]. This can reduce the physical demands and fine motor control required by touch-based interfaces, potentially improving usability for individuals with motor impairments. Body-centered gestures are increasingly recognized as a valuable approach, and research has explored the use of various body parts, including head movements, for interactive tasks [19, 29, 38]. These gestures have also proven useful in controlling assistive technologies, promoting greater user independence [25]. This potential for improved comfort, accuracy, and accessibility motivates our research, which aims to develop and evaluate a mid-air gesture interaction system that can enhance the user experience for individuals with MS and dexterity impairments.

A number of studies have explored hand and finger mid-air gesture interaction for older adults [14] and individuals with motor impairments [28, 56]. Ferron et al. (2019) [14] utilized a tablet with a top-mounted camera to design mid-air gestures for a set of subtasks, including opening the camera app, selecting special effects, zooming, taking a picture, opening the gallery, and scrolling. They reported that these gestures were easy to use and provided a natural and intuitive

way for older adults to interact with mobile devices. For instance, Malu et al. (2018) investigated accessible gestures for smartwatch touchscreens with motor-impaired participants, highlighting how personalized interaction design can significantly enhance usability and user satisfaction for individuals with dexterity limitations [28]. Yamagami et al. (2023) [56] investigated upper-body accessible gestures using on-body sensors for ten defined functions (move, select, rotate, delete, pan, close, zoom-in, zoom-out, open, and duplicate). Some gestures relied primarily on shoulder and upper-arm muscles, while others used only finger muscles. They found that the designed gestures were tailored to individual abilities, engaging a range of upper-body muscles, allowing for greater customization and accessibility. This approach informed the design of the gesture vocabulary and the interaction approach.

In addition to physical and ergonomic considerations, it is also important to consider the cognitive load imposed by mid-air gesture interaction, especially for users with cognitive impairments. Mid-air gesture systems should be designed to minimize cognitive load, aiming to ensure that gestures are easy to learn, remember, and perform. Several factors can influence the cognitive load of mid-air gestures. For example, Ferron et al. (2019) [14] found that gestures that closely resemble existing touch-based interactions are easier to learn and remember. Their study highlighted the positive aspects of mid-air gestures, including comfort and ease of replication. These findings emphasize the importance of designing intuitive and user-friendly gestures. Both Malu et al. (2018) and Yamagami et al. (2023) [28, 45, 56] works underscore the importance of a user-centered approach to gesture design, when considering the diverse abilities and needs of individual users. This highlights an area of investigation: developing hand and finger mid-air gestures that are tailored to the specific abilities and needs of individuals with dexterity impairments. However, the gestures investigated by Ferron et al. (2019) [14] were limited to eight touchscreen tasks (directional swipes, pinch and spread gestures, and a "take photo" task), necessitating an expansion to cover other common touchscreen gestures and develop corresponding mid-air equivalents for a comprehensive vocabulary. While some studies have explored mid-air interaction for accessibility, there is a need for more research on human-centered hand and finger gesture interaction for individuals with dexterity impairments, focusing on comprehensive evaluations of usability, accessibility, and user experience with touch-based technology, which is what our research aims to address.

In the next section, we detail our study design. We employ a user-centered design approach to develop and evaluate a mid-air gesture vocabulary co-created with MS-Dex individuals. This vocabulary covers the most common input actions for touchscreens, including tapping, swiping, pinching, and dragging. This co-creation process prioritizes intuitiveness and ease of recall. Furthermore, the gesture vocabulary was refined through qualitative feedback from Ms-Dex individuals and therapists, gesture agreement calculations and post-benchmark following established procedures for evaluating gesture sets outlined by Nielsen et al. (2004) [35], which focus on assessing learnability and ergonomic aspects. The final gesture vocabulary incorporates 16 relevant gestures corresponding to

tap, swipe, pinch, spread, drag, and rotate actions. It is structured into categories mirroring common touch-based interactions on tablets. Physical/deictic gestures, which have spatial information and a direct relationship to the manipulated object, are preferred as they enhance logical functionality and contribute to easier recall. User-defined gestures also promote memorability [14].

This study provides empirical evidence demonstrating the impact of this mid-air gesture system on usability, accessibility, and user experience for individuals with MS. Additionally, it provides insights into design considerations for accessible mid-air interaction systems, including gesture vocabulary design, user preferences, and potential challenges for individuals with dexterity impairments.

3 Methods

To understand the feasibility and suitability of our touchless hand and finger mid-air interaction system (HF-MAI), we will assess its usability and accessibility through various measures with a diverse team consisting of (1) MS-Dex individuals, (2) MS specialists and therapists, and (3) a UX expert.

Subjective assessments of usability will be collected using the System Usability Scale (SUS) [5, 4], adapted with an adjective rating scale [1]. This will measure the overall usability of interacting with the system using the HF-MAI approach. The SUS, a standardized measure of perceived usability, assesses overall satisfaction and ease of use, enabling comparisons across different systems and contexts [22]. Including an adjective rating scale with the SUS improves the interpretation of individual scores and facilitates communication of findings to a broader audience [1]. The SUS consists of 10 questions used to assess the usability of various products and services, including interactive systems and novel input methods [16, 22, 24]. The questions were adapted to refer to the whole experience of mid-air interaction, with responses on a 5-point Likert scale ranging from "strongly disagree" to "strongly agree". In addition to the SUS, participants will answer the adjective rating question about the user-friendliness of the HF-MAI approach, selecting their response from a seven-point scale ranging from "Worst imaginable" to "Best imaginable".

The effectiveness and efficiency of the HF-MAI approach will be evaluated by examining participants' performance on the intended mid-air gestures. Effectiveness, defined as the ability to achieve the intended purpose of the interaction, will be assessed through task completion rate [37]. This will be measured using LMC log data and confirmed through qualitative analysis of video recordings. Efficiency, represented by improvement in task completion time, will also be measured using LMC log data [34]. This metric provides a quantitative indicator of the approach's usability for individuals with MS-Dex [37].

To understand the interaction experience—a central element of interaction design [17, 37]—participants will rate the usability and effectiveness of the mid-air interaction within each interaction treatment block. Ratings will include acceptance, comfort, ease of use, memorability, and usefulness, measured on 7-point scales.

Accessibility refers to the extent to which users, regardless of their technical skills, cognitive abilities, or physical capabilities, can effectively interact with a system or technology [9]. The accessibility of the HF-MAI approach for individuals with MS and dexterity impairments will be evaluated by analyzing task completion rates [28, 29]. This analysis will aim to determine whether mid-air interaction using the co-created gesture vocabulary could improve accessibility compared to traditional touchscreen interaction, which has been shown to present challenges for this population.

3.1 Participants

Ten individuals with Multiple Sclerosis experiencing dexterity (MS-Dex) impairments affecting one or both hands were recruited from SBAHC. This sample size aligns with recommendations from Koutsabasis et al. (2019), who suggest that a relatively small sample size is of ten sufficient for laboratory-based usability tests to identify key usability issues and conduct meaningful statistical analysis [24]. Participant demographics were as follows: six female and four male, with a median age of 43 and a median MS diagnosis duration of 15.5 years. The majority of participants had secondary progressive (SPMS) or primary progressive (PPMS) MS, characterized by gradual progression of symptoms with (SPMS) or without (PPMS) initial relapses and remissions. None had prior experience using touchless (mid-air) technologies. Dexterity impairment severity was assessed by physiotherapists and occupational therapists using the Neuromusculoskeletal and Movement Related Functions Assessment. Participants exhibited a range of impairment severity, from mild difficulties with fine motor tasks to more substantial limitations in hand and arm movements. Eight were right-hand dominant, with three experiencing impairments in their dominant hand. Overall, five had limitations in their left hand, two in their right, and three in both. Many experienced challenges with fine motor skills, such as grasping small objects or using touchscreens. Beyond dexterity, some participants also reported mild to moderate difficulties with vision (3 with monocular diplopia) and speech (1 with minor fluency issues). All had prior experience with touchscreens. To aid mobile device interaction, some used assistive tools, including screen magnifiers (4), audio commands (2), hand grips (2), and mobile stands (4). Additionally, one usability and user experience (UX) expert and three healthcare professionals specializing in MS care (a physiotherapist and two occupational therapists) participated in the study. Their expertise informed the design and evaluation of the mid-air interaction approach, ensuring its feasibility and suitability for individuals with MS.

3.2 Procedures

This controlled study investigated the usability of a novel mid-air gesture interaction technique for touchscreen-based technologies. Usability was evaluated using the SUS and user ratings. Feedback was gathered from UX expert, physiotherapist, occupational therapists, and individuals with MS-Dex. The study

focused on user-centered mid-air gesture vocabularies for interacting with on-screen content, aiming to obtain usability evaluations from both expert and user perspectives. The study took place in a dedicated hospital room adapted for research purposes. Each participant completed a 60-minute session, during which their hand and finger movements were recorded as they interacted with on-screen tasks using a Leap Motion Controller 2 (LMC). The LMC was selected due to its simple setup, cross-compatibility [41], ability to capture fine hand and finger movements [23], and greater accuracy for hand tracking compared to other technologies like Microsoft Kinect [48]. This accuracy is crucial, as the tracking technology directly affects system performance and user interaction in terms of usability, accuracy, satisfaction, and more [20]. A laptop connected to the LMC was positioned on a table in front of the participant. The laptop screen provided visual feedback during the session, and the LMC tracked hand and finger movements to capture the gestures. For technical reasons, a laptop was used instead of a touchscreen or tablet, as the laptop's compatibility with the LMC was crucial for accurate gesture tracking.

Upon arrival, each participant received information about the study's activities and goals, completed a demographic questionnaire, and participated in a brief five-minute introductory session. This session familiarized them with the technology and allowed them to configure the setup to their preference, including choosing their preferred location (e.g., sitting at a table, sitting on a bed with a table) and positioning the LMC for comfortable gesture execution. To ensure optimal tracking, the researcher helped participants position the LMC within the device's tracking range. Participants were encouraged to experiment and inform the researcher if adjustments were needed throughout the study (see Fig. 1).

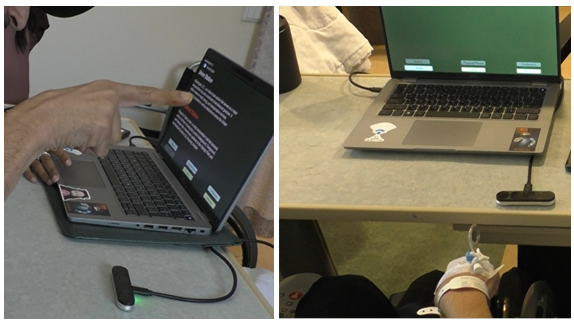

Fig. 1: Capturing MS-Dex Participants During Gesture Elicitation Activities.

During the introductory session, participants also received a comprehensive overview of the LMC and how to interact using mid-air gestures. They then had a practice session to minimize learning effects for the subsequent tasks. They were explicitly instructed to disregard any concerns about the technol-

ogy's performance, enabling them to concentrate on evaluating the usability and intuitiveness of the interaction approach.

To investigate the usability of the new mid-air gestures (Fig. 2), participants used a custom app on the laptop with the LMC. They completed 16 tasks mimicking common touchscreen interactions organized into six treatment blocks (Block 1: Tap (single-finger), Block 2: Swipe (single-finger), Block 3: Pinch (two-finger), Block 4: Spread (two-finger), Block 5: Drag (two-finger), Block 6: Rotate (single-finger)). Tasks were presented in random order to avoid bias and performed once to assess initial learnability and ease of use, mitigating potential learning effects [11]. Each task was presented with an animated image of the corresponding gesture, following research by Theil et al. (2019) [42], which found that this approach led to faster learning, higher accuracy, and greater perceived ease of use. After each gesture was performed, the corresponding action was executed on the screen, a completion message appeared, and participants rated the gesture's acceptance, comfort, ease-of-use, memorability, and usefulness on a 7-point Likert scale. Upon completion of all tasks, participants completed the SUS to assess the overall user experience.

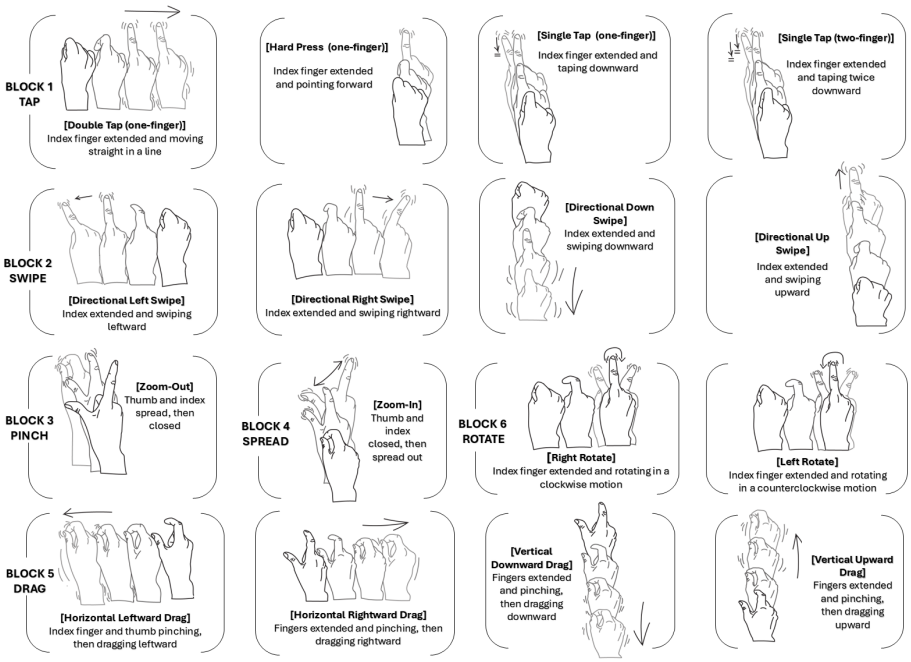

Fig. 2: Mid-air Gesture Vocabulary Design for Common Touchscreen Interactions, Organized by Treatment Block (Touchscreen Equivalents in [ ] Brackets).

Finally, the UX expert and three therapists with expertise in working with individuals with MS participated in the evaluation of the mid-air gesture in-

teraction approach. The UX expert focused on usability and user experience considerations, while the therapists provided a clinical perspective. All experts interacted with the developed system using the gesture vocabulary and completed the SUS.

3.3 Data Analysis

This study employed a mixed-methods approach, combining qualitative and quantitative analyzes to provide a comprehensive understanding of the impact of the HF-MAI on individuals with MS-Dex, compared to traditional touch-based interaction.

Quantitative data, including mid-air task completion time and completion rates, were analyzed using descriptive statistics (e.g., mean, median). To analyze differences between the interaction blocks in this study, a Linear Mixed-Effects Model (LMM) was utilized. This model was particularly applied for comparisons involving more than two blocks, and significant effects were followed up with post-hoc pairwise comparisons using Tukey adjustment. Descriptive statistics were used to further assess differences between interaction blocks in this study and to compare these results to those from a previously conducted study on touchscreen interaction. Furthermore, the SUS questionnaire, comprising 10 statements rated on a 5-point Likert scale, was used to measure perceived usability. SUS scores were calculated using Brooke's scoring method [4], yielding a final score between 0 and 100. A correlational analysis was performed to assess the relationship between SUS scores and the 7-point Likert scale adjective rating question, which was included to improve the interpretation of individual scores [1].

To assess the mid-air gestures experience, Ms-Dex participants rated their acceptance, comfort, ease of use, memorability, and usefulness on 7-point Likert scales. The cumulative link mixed model (CLMM) was employed to assess differences in ratings across these aspects within each interaction treatment block.

Qualitative data also included insights gathered from the UX expert and three therapists with expertise in working with individuals with MS. The experts' feedback focused on potential benefits and challenges of the HF-MAI approach from both usability and clinical perspectives. We analyzed the qualitative data to identify key usability challenges, potential benefits for individuals with MS-Dex, and areas for improvement in the HF-MAI system. We reviewed the experts' feedback and summarized their key observations, focusing on recurring themes and suggestions.

We compared the qualitative insights with the quantitative findings to gain a holistic understanding of the HF-MAI system's impact. The analysis, across different gesture treatment blocks, aimed to identify areas for usability and accessibility improvements and quantify the benefits of the HF-MAI system. This provides evidence for its effectiveness and potential for widespread adoption. By examining how performance and experience vary across tasks and gesture types, the study provides insights into the impact of the new interaction system on individuals with MS-Dex.

4 Results

4.1 Task Completion and Timing

The system is designed to facilitate successful interactions (task completion) by accurately interpreting mid-air gestures and executing the corresponding tasks. A successful interaction is characterized by the completion of the intended task, regardless of the number of attempts required. The results show that the MS-Dex participants achieved a 100% completion rate across all mid-air gesture tasks, with no participants skipping or withdrawing from any task. To analyze task completion times, we first conducted a Linear Mixed-Effects Model (LMM) analysis, which revealed a statistically significant overall effect of treatment blocks ($F(5, 176.19) = 2.7916$, $p = 0.0188$). This suggests that some types of gestures were completed more efficiently than others. To identify which specific blocks differed, we performed a Tukey-adjusted pairwise comparisons (refer to Table 1).

Table 1: Completion Time Statistics in Seconds for Mid-Air Interaction Tasks Across Treatment Blocks, Including Pairwise Comparisons.

Block	Pairwise Comparisons (p-values)					Statistics			
	Block 2	Block 3	Block 4	Block 5	Block 6	Mean	SD	Min Time	Max Time
Block 1	0.494	0.558	0.999	0.289	0.694	8.48	7.39	1.00	27.00
Block 2	-	0.062	0.752	0.994	1.000	9.47	5.79	1.00	23.00
Block 3	-	-	0.907	0.034*	0.113	5.00	4.20	1.00	14.00
Block 4	-	-	-	0.590	0.783	7.20	4.80	1.00	15.00
Block 5	-	-	-	-	0.999	10.70	6.29	1.00	24.00
Block 6	-	-	-	-	-	9.19	4.80	1.00	21.00

Post-hoc pairwise comparisons using the Tukey method revealed a statistically significant difference in completion times between Block 3 (Pinch) and Block 5 (Drag) (estimate = -0.865, SE = 0.287, $t(176) = -3.018$, $p = 0.034$). The negative estimate means that the mean completion time for Block 3 is significantly lower than for Block 5. This indicates that participants were significantly faster at completing pinch gestures compared to drag gestures. There was a trend suggesting that completion times for Block 2 (Swipe) were higher than for Block 3 (Pinch), although this difference did not reach statistical significance (estimate = 0.776, SE = 0.278, $t(176) = 2.797$, $p = 0.063$). No other significant differences were found between the remaining blocks.

To further understand the performance across blocks, we examined descriptive statistics. The mean completion time ranged from 5.00 (SD = 4.20, Min = 1.00, Max = 14.00) in Treatment Block 3 (Pinch), indicating a tendency for faster task completion in this block, to 10.70 (SD = 6.29, Min = 1.00, Max = 24.00) in Treatment Block 5 (Drag), suggesting longer task durations. Notably,

Treatment Block 1 (Tap) exhibited the greatest variability in completion times (SD = 7.39, Min = 1.00, Max = 27.00), while Treatment Block 3 (Pinch) showed the least (SD = 4.20, Min = 1.00, Max = 14.00). All treatment blocks shared a minimum completion time of 1.00, with maximum completion times varying from 14.00 to 27.00. These descriptive differences offer valuable context for understanding the observed patterns in task completion times across the treatment conditions (refer to Table 1).

4.2 SUS

The SUS questionnaire involved 10 statements, each rated on a scale from 1 to 5. To calculate the final SUS score, we used Brooke's scoring method [5], adjusting responses to positive statements by subtracting one point and subtracting responses to negative statements from 5. These adjusted scores were summed and multiplied by 2.5 to yield a final score between 0 and 100. In this study, both average SUS scores and adjective ratings were used to evaluate the HF-MAI approach (refer to Table 2). The average SUS score was 95.50,

Table 2: MS-Dex Participant Usability Scores Measured by the System Usability Scale (SUS) and Subjective Adjective Ratings.

Participant ID	SUS	Adjective Rating (HF-MAI User-Friendliness)
P1	65	Good (5)
P2	80	Best imaginable (7)
P3	85	Best imaginable (7)
P4	85	Best imaginable (7)
P5	82.5	Excellent (6)
P6	100	Best imaginable (7)
P8	100	Best imaginable (7)
P7	100	Best imaginable (7)
P9	90	Best imaginable (7)
P10	42.5	OK (4)

which falls within the "Excellent" range on the SUS rating scale, indicating that participants perceived the HF-MAI approach to be highly usable. The average adjective rating was 6.4 on a 7-point scale ranging from "Worst Imaginable" to "Best Imaginable," further supporting the positive usability assessment. To assess the relationship between these two measures, we performed a correlational analysis. The analysis revealed a strong positive correlation between participant ratings on the adjective scale and their corresponding SUS scores ($r = 0.91$, $p < .001$, 95% CI). This finding indicates that participants who rated the HF-MAI approach higher on the adjective scale also tended to give it higher SUS scores. This result aligns with previous research by Bangor et al. (2009) [1]. This strong correlation suggests that both the SUS and the adjective rating scale are effective measures of usability in the context of our study.

4.3 Rating Scale

Participants rated five categories (acceptance, comfort, ease of use, memorability, and usefulness) of the gestures on 7-point Likert scales. The median rating was consistently 7 (the highest point on the scale) for all categories within every treatment block, indicating a strong overall positive perception across all tested gestures and attributes. However, variability in participant agreement, as measured by the interquartile range (IQR), differed across these conditions.

For instance, Treatment Blocks 3 (N=10 per category) and 4 (N=10 per category) demonstrated very high consensus, with an IQR of 0 for all five rating categories, meaning at least 75% of ratings were '7'. In contrast, Treatment Block 6 ('Rotate', N=20 per category) and Treatment Block 2 ('Swipe', N=60 per category) displayed more diverse opinions for several categories. Block 6 ('Rotate') showed notable variability for 'Comfort' (median 7, IQR 1.00), 'Ease-of-Use' (median 7, IQR 1.00), and also for 'Acceptance', 'Goodness', and 'Usefulness' (all median 7, IQR 0.25). Similarly, Treatment Block 2 ('Swipe') had IQRs of 1.00 for 'Acceptance', 'Goodness', and 'Usefulness' (all median 7), indicating a wider spread of ratings for these specific gesture-attribute combinations. Other blocks, like Block 1 (N=40) and Block 5 (N=40), showed intermediate levels of variability, with IQRs of 0.25 for some categories (e.g., Block 1 'Memorability' and 'Usefulness'; Block 5 'Acceptance' and 'Comfort').

While all medians were 7, mean ratings (which are more sensitive to lower scores in a skewed distribution) highlighted some differences between the blocks. For instance, Treatment Block 6 ('Rotate') tended to have the lowest mean ratings across most categories (e.g., 'Goodness' M=6.05, SD=1.90; 'Ease-of-Use' M=6.15, SD=1.73), suggesting a greater presence of lower scores in this block compared to others. The only exception was 'Usefulness,' where Treatment Block 2 ('Swipe') recorded a slightly lower mean rating (M=6.38, SD=1.15) than Block 6 (M=6.45, SD=1.05).

To understand the effect of the treatment blocks, rating categories, and their interaction, we used a cumulative link mixed model (CLMM). CLMM is a statistical method suitable for analyzing ordinal data (like Likert scale ratings) with repeated measurements, as in this study. While descriptive statistics highlighted some numerical variations, the CLMM analysis revealed no significant main effects of treatment blocks or rating categories, nor a significant interaction effect on the participants' ratings (all p-values > 0.05). This suggests that neither the specific treatment block (gesture type) nor the category being rated had a statistically significant impact on how participants rated the gestures. In other words, participants' perceptions of acceptance, comfort, ease of use, memorability, and usefulness were found to be generally consistent across the different types of gestures when subjected to this statistical model.

4.4 Expert Evaluation

To gain further insights into the HF-MAI approach, we gathered feedback from three therapists with expertise in working with individuals with MS and one UX

expert. The therapists had an average of 2.5 years of experience (ranging from 1.5 to 4 years). The therapists provided a clinical perspective on the mid-air gestures and interaction approach, while the UX expert focused on usability and user experience considerations.

All experts evaluated the effectiveness of the HF-MAI approach by interacting with the developed system and using the gesture vocabulary. This evaluation included completing the SUS to assess overall usability. The average SUS score was 95.6, which falls within the "Excellent" range on the SUS rating scale. This suggests that the experts perceived the HF-MAI approach to be highly usable and effective for individuals with MS-Dex.

The therapists also provided separate ratings for physical comfort, ease of use, and memorability of the gestures. The average ratings for these categories were 6.67 for physical comfort, 6.68 for ease of use, and 6.65 for memorability, all on a 7-point scale. The range of ratings for each category was 6.14-7 for physical comfort, 6.25-7 for ease of use, and 6.06-7 for memorability. Beyond these quantitative ratings, the experts offered detailed qualitative feedback, particularly on the system's ease of use, comfort, potential benefits, and areas for consideration.

Regarding ease of use and intuitiveness, therapists generally found the gestures easy to perform and remember, aligning with their high average rating scores (6.68 for ease of use and 6.65 for memorability, respectively). One occupational therapist (T1) noted, "As I performed the gestures, I saw that the majority were easy, and I believe they would be easy for the patients." Another occupational therapist (T3) added, "Everything is easy, even though when I see the gesture video visualization, I think this might be difficult, but when I perform the gesture, I see how easy it is." However, concerns were raised about gestures requiring two-finger coordination. One occupational therapist (T1) explained, "Gestures that have two-finger coordination, I believe, would be difficult for the patients to coordinate (e.g., pinch using index and thumb and then directional drag and then drop)." They also mentioned that eye-hand coordination might affect the performance of these gestures. The UX expert, while agreeing that the approach was generally easy to use, cautioned against introducing new mid-air gestures that are not similar to existing touch-based interactions, as this could add complexity.

The comfort and ergonomic benefits of the HF-MAI approach were also prominent in the therapists' feedback, consistent with the high average comfort rating of 6.67. One occupational therapist (T1) commented, "Most of the gestures are beneficial for their hand and finger therapy." Another (T3) noted, "This is an easy way of interaction, and comfortable as their hand won't be fixed in one position for a long time to perform the gesture."

In terms of potential benefits and broader impact, therapists expressed enthusiasm about the HF-MAI approach, particularly for communication and rehabilitation. One occupational therapist (T1) stated, "This kind of interaction is fascinating, and I feel this would help the patient either to communicate and would contribute to their rehabilitation as well. And it's a more comfortable interaction approach than the touchscreen." A physiotherapist (T2) shared this

view, highlighting the potential for the system to support greater user independence.

Finally, the experts also pointed out potential challenges and considerations for the system. One occupational therapist (T1) suggested avoiding similar gestures to minimize cognitive load and confusion. They also observed that for the "rotate" gesture, individuals with severe dexterity impairments might perform wider or imperfect circles due to coordination issues. The physiotherapist (T2) emphasized the importance of considering patients' inability to fully extend their fingers and suggested incorporating a degree of curl in gestures requiring finger extension due to finger flexion difficulties. The occupational therapist (T1) suggested that for swipe gestures, it might be easier for patients to use all fingers as it's a single movement that does not require individual finger extension. The UX expert agreed that inconsistency in the gestures could be a challenge, particularly the introduction of new gestures that differ from touch-based interactions, which could lead to confusion. They also noted that additional training might be required to effectively use the approach, particularly for remembering new gestures. However, they acknowledged that most users would likely learn quickly.

5 Findings and Discussion

This study investigated the usability and accessibility of a mid-air gesture interaction approach for individuals with MS and dexterity impairments (MS-Dex). Individuals with MS-Dex often experience challenges using touchscreens on common devices like tablets and smartphones. Therefore, a key goal of this research was to develop a touchless-based interaction approach using a mid-air gesture vocabulary and design guidelines, readily integrated into these devices as a substitute for touchscreen input, thereby increasing accessibility. We designed and evaluated a touchless system (HF-MAI) incorporating the co-created gesture vocabulary created with MS-Dex individuals. To ensure that the interaction approach was tailored to their specific needs and abilities, we grounded our study in both human-centered design (HCD) (according to ISO 13407:1999 [40]) [27] and ability-based design principles [53]. Our evaluation included usability metrics, user satisfaction, effectiveness, efficiency, and accessibility through user testing, SUS scores, questionnaires, and therapist and expert feedback. Through this mixed-methods approach, we combined the quantitative data with the qualitative feedback from users, the UX expert, and MS specialists, enabling a human-centered evaluation of the mid-air gesture interaction approach.

Usability and Accessibility

The HF-MAI system proved to be an effective interaction approach. All 10 MS-Dex users successfully completed all 16 mid-air gesture tasks across 6 treatment blocks, resulting in a 100% successful completion rate. This high success rate, along with the excellent average SUS score of 95.50, indicates the high perceived accessibility and usability of the system. This success can be attributed to the user-centered design approach, ensuring that the system was designed with

the needs and preferences of MS-Dex individuals in mind. The co-created nature of the gesture vocabulary played a crucial role, as it ensured alignment with users' abilities and preferences. The relevance of the chosen tasks to typical interactions with the target application also contributed to the positive outcomes. These tasks focused on common touchscreen functionalities that were translated to mid-air gestures, building upon the findings from the prior study, in which the target user group, along with experts, adapted these common gestures to the mid-air interaction context. This approach allowed us to investigate the usability of this translation and how well these established touchscreen interactions could be effectively performed using mid-air gestures. For example, the "rotate" gesture, commonly used for rotating objects on touchscreens using two fingers, was refined based on user feedback to accommodate limited finger dexterity and translated to a single-finger mid-air gesture that was both comfortable and effective.

The high task completion rate and positive SUS scores also align with the core principles of ability-based design [53]. By using a co-created gesture vocabulary and grounding the design in ability-based principles, we ensured that the HF-MAI system was adapted to the specific needs and capabilities of this user group. This aligns with the therapists' general consensus that the gestures were easy to learn and perform, which is further supported by our user testing results, where all participants successfully completed all tasks. These findings resonate with previous research exploring different touchless interaction approaches for individuals with motor impairments, and in some cases, show even more promising results. For example, [42] found that older adults preferred hand and fingers mid-air interaction over mouse interaction, suggesting that the benefits of touchless input extend beyond individuals with diagnosed motor impairments. Similarly, [29, 38] reported excellent SUS scores (87.1) for head-tracking as an alternative to touch input on iPads for both able-bodied and motor-impaired users. [46, 47] demonstrated the feasibility of mid-air gesture interaction with various devices in smart environments, achieving very satisfactory usability with a SUS score of 79.0. While these studies highlight the potential of touchless interaction, our study achieved an even higher SUS score of 95.50 for the HF-MAI system, suggesting superior usability compared to previous approaches. Furthermore, this score compares favorably to SUS scores reported for touch-based interactions in similar populations. For example, [2] reported an SUS score of 85.0 for a home-based dexterity training tablet app, and [31] reported a score of 80.1 for a touchpad video game. These comparisons suggest that mid-air gesture interaction may offer usability advantages over both traditional touch-based input and other touchless methods, particularly for individuals with MS-Dex.

User Experience and Acceptance

User experience ratings support the high completion rate and perceived usability. While our CLMM analysis did not reveal statistically significant differences in user experience ratings across gesture types, the qualitative and descriptive data suggest positive trends, contributing to their successful task

completion. These positive experiences were echoed by the therapists, who also observed the comfort and ergonomic benefits of mid-air interaction, particularly for individuals with dexterity impairments. Furthermore, qualitative feedback from the prior gesture elicitation study reinforces this, as participants frequently described the created gestures as 'natural' and 'easy to understand', and felt 'very comfortable' to perform. This consistent positive feedback resonates with the Technology Acceptance Model (TAM) [10], which emphasizes the importance of perceived usefulness and perceived ease of use as fundamental determinants of system use. The participants' feedback on the comfort, ease of use, and perceived usefulness of the gestures aligns with these TAM constructs. This connection to TAM suggests that the positive user experiences reported in our study could lead to greater acceptance and adoption of the HF-MAI system. The perceived efficiency of the HF-MAI system is further supported by task completion times. When compared to the prior investigation of touchscreen accessibility assessment with MS-Dex participants—a study that involved the same treatment block tasks representing basic tablet touchscreen interactions (such as tapping an icon or swiping through a calendar)—the completion times for most mid-air gesture tasks in this study were shorter. Specifically, Block 1 (Tap), Block 2 (Swipe), Block 3 (Pinch), and Block 6 (Rotate) all showed faster completion times compared to their touchscreen counterparts. However, Block 5 (Spread) showed longer completion times for mid-air gestures compared to the same task using touchscreen gestures.

Design Implications

While overall SUS scores were positive, individual variability suggests that the system's usability is not uniform. Two participants (P1 and P10) had notably lower SUS scores, despite P1's generally high ratings on other measures. This discrepancy for P1 may indicate that overall satisfaction is not solely determined by individual task experiences, with the "rotate" gesture (Block 6) potentially posing a specific challenge. P10's lower SUS score aligns with generally lower ratings across other measures, suggesting a more pervasive issue. Their difficulties with "rotate" (Block 6), "swipe" (Block 2), and "drag" (Block 5) highlight these gestures as potentially challenging, which underscores the importance of considering individual user experiences.

Furthermore, challenges were observed, particularly with longer completion times for some treatment blocks. Pinch (Block 3) gestures had the shortest mean completion time (5 seconds), while drag gestures (Block 5) had the longest (10.7 seconds) (refer to Table 1). This contrasts with touchscreen-based studies, which often report rotate gestures as most challenging [6, 15, 26]. These studies, including Caliz et al. (2021) [6] who specifically examined single and two-finger rotations, suggest that this gesture is difficult for various user groups, aligning with therapists' concerns about the two-finger coordination and eye-hand coordination required for touchscreen rotate gestures.

However, our findings show the opposite: rotate (single-finger), pinch (two-fingers), and spread (two-fingers) gestures had shorter completion times than

drag (two-fingers). This suggests that mid-air interaction may mitigate the challenges associated with these gestures on touchscreens. The "rotate" gesture in our study was adapted to a single-finger clockwise/counter-clockwise motion, while pinch and spread adopted similar motions to their touchscreen counterparts. The longer completion time for the two-finger "drag" gesture (drag-directional move-drop) could be due to its more complex, combined movement. This single/two-finger adaptation in mid-air reduces the difficulty for users with limited dexterity by eliminating precise two-finger manipulation required on touchscreens. Our findings also contradict Trewin et al. (2013), who highlighted the difficulty individuals with dexterity impairments face with precise multi-touch input [44]. Our results demonstrate that, with mid-air interaction, even pinch, spread, and rotate (two-finger/single-finger) gestures were performed efficiently. Therapists' feedback further supports this. They emphasized the difficulty some patients have extending their fingers due to flexion limitations, suggesting that gestures requiring finger extension (like the "tap" gesture in Block 1) could be modified to accommodate a slight finger curl. This highlights the importance of personalized gesture design for individuals with varying degrees of dexterity impairment.

Future iterations of the HF-MAI system should incorporate alternative gesture options or adjustable parameters that allow users to customize the gestures to their specific needs and abilities. These results suggest that mid-air gesture interaction may offer advantages over touchscreen input for certain gestures, particularly those that require complex or precise movements. This has important implications for the design of accessible technologies for individuals with dexterity impairments, as it suggests that mid-air gestures can provide a more usable and effective alternative to touch-based input for certain tasks.

Considerations and Future Research

While the findings of this study provide valuable insights into the potential of mid-air gestures as an alternative interaction method for individuals with MS-Dex, it is important to acknowledge the study's scope. Conducted in a controlled laboratory setting, this study focused on a specific set of tasks designed to be representative of common interactions. Future research should explore a wider range of tasks (including more complex or open-ended interactions) and participant perspectives to evaluate the system's usability and accessibility in diverse real-world scenarios, such as homes or workplaces, considering their inherent complexities, distractions, and social interactions. Expanding to larger, more diverse participant groups, encompassing a broader range of dexterity impairments, is also crucial for assessing generalizability, broader applicability, potential for customization, and gathering qualitative insights.

This study's findings highlight the potential of HF-MAI as an assistive input method for individuals with MS-Dex, offering advantages over existing accessibility options and complementing other assistive technologies. While smartphones offer accessibility features like text-to-speech and screen magnification, these often require significant dexterity and visual effort [44], limiting their effectiveness

for this population. Although this study focused on mid-air gestures, integrating other modalities like eye-tracking [3] or speech-based interfaces could enhance accessibility for a wider range of user. For example, voice input might be more efficient for selection tasks, as demonstrated in previous work [18]. Multi-modal combinations, as explored in research with participants with hand impairments [18], hold promise for reducing fatigue and improving the interaction experience. Understanding the considerations and obstacles associated with accessible multi-modality is crucial for creating inclusive input experiences that cater to diverse user needs.

While our study focused primarily on usability and accessibility, it is important to acknowledge the potential impact of cognitive load and fatigue on mid-air gesture interaction. However, the positive feedback from users and experts on the physical comfort of the gestures suggests that the HF-MAI approach may be less fatiguing than traditional touch-based interaction. This aligns with Ferron et al.'s findings that mid-air interaction was valuable for older adults as it does not require fine motor movements [14], which could potentially reduce fatigue. This is supported by the positive ratings received from both users and experts in terms of gesture physical comfort. Future research should investigate these factors in more detail, considering the complexity and duration of mid-air gesture interactions.

To further enhance our understanding of gesture efficiency, future studies should incorporate the collection of error and retry rates during task completion. This would provide valuable insights into user performance and allow for analysis of potential correlations between gesture types, participant abilities, and LMC performance.

6 Conclusion

This research addresses a critical gap in accessible HCI by investigating the usability and accessibility of a hand and finger mid-air gesture interaction system designed in collaboration with individuals with MS-Dex. A key component of this system is a co-created gesture vocabulary, developed through a user-centered, factor-centric approach. This study provides empirical evidence demonstrating that the HF-MAI system is usable, accessible, and provides a positive user experience. Our findings highlight the high usability and user satisfaction achieved. While challenges remain, our findings suggest that mid-air gestures can be effectively tailored to the specific needs and capabilities of individuals with dexterity impairments, potentially improving their access to and interaction with touchscreen technologies. Future research should focus on further refining gesture design and evaluating the long-term impact of mid-air gesture interaction on MS-Dex and individuals with dexterity impairments generally. This includes investigating individual differences in usability, addressing specific challenges, and exploring the potential for combining mid-air gestures with other assistive input methods.

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References

1. Bangor, A., Kortum, P., Miller, J.: Determining what individual sus scores mean: Adding an adjective rating scale. Journal of usability studies **4**(3), 114–123 (2009)
2. van Beek, J.J.W., van Wegen, E.E.H., Rietberg, M.B., Nyffeler, T., Bohlhalter, S., Kamm, C.P., Nef, T., Vanbellingen, T.: Feasibility of a home-based tablet app for dexterity training in multiple sclerosis: usability study. JMIR mHealth and uHealth **8**(6), e18204 (2020)
3. Blignaut, P.: Development of a gaze-controlled support system for a person in an advanced stage of multiple sclerosis: a case study. Universal Access in the Information Society **16**(4), 1003–1016 (2017)
4. Brooke, J.: Sus: a retrospective. Journal of usability studies **8**(2) (2013)
5. Brooke, J., et al.: Sus-a quick and dirty usability scale. Usability evaluation in industry **189**(194), 4–7 (1996)
6. Cáliz, D., Ravivanpong, P., Schankin, A., Jadán-Guerrero, J., Caraguay, W., Arellano, L.: Examining the usability of touchscreen gestures for adults with ds. Journal of Reliable Intelligent Environments pp. 1–26 (2021)
7. Chandra, N.S., Venu, T., Srikanth, P.: A real-time static & dynamic hand gesture recognition system. International Journal of Engineering Inventions **4**(12) (2015)
8. Chen, K.B., Savage, A.B., Chourasia, A.O., Wiegmann, D.A., Sesto, M.E.: Touch screen performance by individuals with and without motor control disabilities. Applied ergonomics **44**(2), 297–302 (2013)
9. Cofre, J.P., Moraga, G., Rusu, C., Mercado, I., Inostroza, R., Jimenez, C.: Developing a touchscreen-based domotic tool for users with motor disabilities. In: 2012 Ninth International Conference on Information Technology-New Generations. pp. 696–701. IEEE (2012)
10. Davis, F.D.: Perceived usefulness, perceived ease of use, and user acceptance of information technology. MIS quarterly pp. 319–340 (1989)
11. Dix, A.: Statistics for HCI (2020)
12. Dourish, P.: Where the action is: The foundations of embodied interaction, vol. 210. MIT Press (2001)
13. Duff, S.N., Irwin, C.B., Skye, J.L., Sesto, M.E., Wiegmann, D.A.: The effect of disability and approach on touch screen performance during a number entry task. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting. vol. 54, pp. 566–570. SAGE Publications Sage CA: Los Angeles, CA (2010)
14. Ferron, M., Mana, N., Mich, O.: Designing mid-air gesture interaction with mobile devices for older adults. Perspectives on human-computer interaction research with older people pp. 81–100 (2019)

15. Gao, Q., Sun, Q.: Examining the usability of touch screen gestures for older and younger adults. Human factors **57**(5), 835–863 (2015)
16. Gao, Y., Zhai, Y., Hao, M., Wang, L., Hao, A.: Research on the usability of hand motor function training based on vr system. In: 2021 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct). pp. 354–358. IEEE (2021)
17. Garrett, J.J.: The elements of user experience: User-centered design for the Web and beyond (2011)
18. Guinness, D., Poor, G.M., Jude, A.: Gestures with speech for hand-impaired persons. In: Proceedings of the 16th international ACM SIGACCESS conference on Computers & accessibility. pp. 259–260 (2014)
19. Hassan, M., Magee, J., MacKenzie, I.S.: Evaluating hands-on and hands-free input methods for a simple game. In: Universal Access in Human-Computer Interaction. Design Approaches and Supporting Technologies: 14th International Conference, UAHCI 2020, Held as Part of the 22nd HCI International Conference, HCII 2020, Copenhagen, Denmark, July 19–24, 2020, Proceedings, Part I 22. pp. 124–142. Springer (2020)
20. Hurst, A., Tobias, J.: Empowering individuals with do-it-yourself assistive technology. In: The proceedings of the 13th international ACM SIGACCESS conference on Computers and accessibility. pp. 11–18 (2011)
21. Jones, S.: Why am i loosing the ability to use devices with touch screens?. (Feb 2014), https://www.healthcarejourney.com/q–a-for-virtual-ms-center/november-02nd-2014, accessed on 29.10.2022
22. Kaya, A., Ozturk, R., Altin Gumussoy, C.: Usability measurement of mobile applications with system usability scale (sus). In: Industrial Engineering in the Big Data Era: Selected Papers from the Global Joint Conference on Industrial Engineering and Its Application Areas, GJCIE 2018, June 21–22, 2018, Nevsehir, Turkey. pp. 389–400. Springer (2019)
23. Khademi, M., Hondori, H.M., McKenzie, A., Dodakian, L., Lopes, C.V., Cramer, S.C.: Free-hand interaction with leap motion controller for stroke rehabilitation. In: Proceedings of the extended abstracts of the 32nd annual ACM conference on Human factors in computing systems. pp. 1663–1668. ACM (2014)
24. Koutsabasis, P., Vogiatzidakis, P.: Empirical research in mid-air interaction: A systematic review. International Journal of Human–Computer Interaction **35**(18), 1747–1768 (2019)
25. Kyrarini, M., Zheng, Q., Haseeb, M.A., Gräser, A.: Robot learning of assistive manipulation tasks by demonstration via head gesture-based interface. In: 2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR). pp. 1139–1146. IEEE (2019)
26. Luna-Garcia, H., Mendoza-González, A., Mendoza-Gonzalez, R., Gamboa-Rosales, H., Galván-Tejada, J.I., Celaya-Padilla, J.M., Galvan-Tejada, C.E., Arceo-Olague, J., Moreno-Báez, A., Alonso-González, O., et al.: Analyzing typical mobile gestures in mhealth applications for users with down syndrome. Mobile Information Systems **2018**(1), 2830851 (2018)
27. Maguire, M.: Methods to support human-centred design. International journal of human-computer studies **55**(4), 587–634 (2001)
28. Malu, M., Chundury, P., Findlater, L.: Exploring accessible smartwatch interactions for people with upper body motor impairments. In: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems. pp. 1–12 (2018)

29. Manresa-Yee, C., Roig-Maimó, M.F., Varona, J.: Mobile accessibility: natural user interface for motion-impaired users. Universal Access in the Information Society **18**, 63–75 (2019)
30. Matos, A., Adão, T., Magalhães, L., Peres, E.: A myographic-based hci solution proposal for upper limb amputees. Procedia Computer Science **100**, 2–13 (2016)
31. Mendonca, C.J., Malone, L.A., Mohanraj, S., Thirumalai, M.: The usability of a touchpad active video game controller for individuals with impaired mobility: Observational study. JMIR Rehabilitation and Assistive Technologies **10**, e41993 (2023)
32. Montague, K., Hanson, V.L., Cobley, A.: Designing for individuals: usable touch-screen interaction through shared user models. In: Proceedings of the 14th international ACM SIGACCESS conference on Computers and accessibility. pp. 151–158 (2012)
33. Mott, M.E., Vatavu, R.D., Kane, S.K., Wobbrock, J.O.: Smart touch: Improving touch accuracy for people with motor impairments with template matching. In: Proceedings of the 2016 CHI conference on human factors in computing systems. pp. 1934–1946 (2016)
34. Nielsen, J.: Ten usability heuristics (2005)
35. Nielsen, M., Störring, M., Moeslund, T.B., Granum, E.: A procedure for developing intuitive and ergonomic gesture interfaces for hci. In: Gesture-Based Communication in Human-Computer Interaction: 5th International Gesture Workshop, GW 2003, Genova, Italy, April 15-17, 2003, Selected Revised Papers 5. pp. 409–420. Springer (2004)
36. Norman, D.A.: Natural user interfaces are not natural. interactions **17**(3), 6–10 (2010)
37. Preece, J., Sharp, H., Rogers, Y.: Interaction Design: Beyond Human-Computer Interaction. John Wiley Sons, Nashville, TN, 4 edn. (2015)
38. Roig-Maimó, M.F., Manresa-Yee, C., Varona, J., MacKenzie, I.S.: Evaluation of a mobile head-tracker interface for accessibility. In: International Conference on Computers Helping People with Special Needs. pp. 449–456. Springer (2016)
39. Sesto, M.E., Irwin, C.B., Chen, K.B., Chourasia, A.O., Wiegmann, D.A.: Effect of touch screen button size and spacing on touch characteristics of users with and without disabilities. Human Factors **54**(3), 425–436 (2012)
40. for Standardization, I.O.: Human-centred design processes for interactive systems. International Organization for Standardization (1997)
41. Taylor, J., Curran, K.: Using leap motion and gamification to facilitate and encourage rehabilitation for hand injuries: leap motion for rehabilitation. In: Handbook of research on holistic perspectives in gamification for clinical practice, pp. 183–192. IGI Global (2016)
42. Theil Cabreira, A.: An investigation of mid-air gesture interaction for older adults. Ph.D. thesis, University of Reading (2019)
43. Trewin, S.: Physical impairment. Web accessibility: a foundation for research pp. 37–46 (2008)
44. Trewin, S., Swart, C., Pettick, D.: Physical accessibility of touchscreen smartphones. In: Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility. pp. 1–8 (2013)
45. Vatavu, R.D., Ungurean, O.C.: Understanding gesture input articulation with upper-body wearables for users with upper-body motor impairments. In: CHI Conference on Human Factors in Computing Systems. pp. 1–16 (2022)

46. Vogiatzidakis, P., Koutsabasis, P.: Mid-air gesture control of multiple home devices in spatial augmented reality prototype. Multimodal Technologies and Interaction **4**(3), 61 (2020)
47. Vogiatzidakis, P., Koutsabasis, P.: Mid-air gestures for manipulation of multiple targets in the physical space: comparing the usability of two interaction models. In: CHI Greece 2021: 1st International Conference of the ACM Greek SIGCHI Chapter. pp. 1–9 (2021)
48. Webster, A., Poyade, M., Rea, P., Paul, L.: The co-design of hand rehabilitation exercises for multiple sclerosis using hand tracking system. Biomedical Visualisation: Volume 1 pp. 83–96 (2019)
49. Weir, D.: Machine learning models for uncertain interaction. In: Adjunct proceedings of the 25th annual ACM symposium on User interface software and technology. pp. 31–34 (2012)
50. Weir, D., Rogers, S., Murray-Smith, R., Löchtefeld, M.: A user-specific machine learning approach for improving touch accuracy on mobile devices. In: Proceedings of the 25th annual ACM symposium on User interface software and technology. pp. 465–476 (2012)
51. WHO: International classification of functioning, disability and health (icf) (May 2001), https://www.who.int/standards/classifications/international-classification-of-functioning-disability-and-health
52. Wiesendanger, M., Serrien, D.J.: Neurological problems affecting hand dexterity. Brain research reviews **36**(2-3), 161–168 (2001)
53. Wobbrock, J.O., Kane, S.K., Gajos, K.Z., Harada, S., Froehlich, J.: Ability-based design: Concept, principles and examples. ACM Transactions on Accessible Computing (TACCESS) **3**(3), 1–27 (2011)
54. Wobbrock, J.O., Morris, M.R., Wilson, A.D.: User-defined gestures for surface computing. In: Proceedings of the SIGCHI conference on human factors in computing systems. pp. 1083–1092 (2009)
55. Xia, H., Glueck, M., Annett, M., Wang, M., Wigdor, D.: Iteratively designing gesture vocabularies: A survey and analysis of best practices in the hci literature. ACM Transactions on Computer-Human Interaction (TOCHI) **29**(4), 1–54 (2022)
56. Yamagami, M., Portnova-Fahreeva, A.A., Kong, J., Wobbrock, J.O., Mankoff, J.: How do people with limited movement personalize upper-body gestures? considerations for the design of personalized and accessible gesture interfaces. In: Proceedings of the 25th International ACM SIGACCESS Conference on Computers and Accessibility. pp. 1–15 (2023)
57. Yang, L., Huang, J., Feng, T., Hong-An, W., Guo-Zhong, D.: Gesture interaction in virtual reality. Virtual Reality & Intelligent Hardware **1**(1), 84–112 (2019)
58. Yeo, J.C., Lim, C.T.: Chapter 6 - Wearable Sensors for Upper Limb Monitoring, p. 113–134. Academic Press (Jan 2018). https://doi.org/10.1016/B978-0-12-811810-8.00006-3, https://www.sciencedirect.com/science/article/pii/B9780128118108000063