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Using Both Hands: Tangibles for Stroke Rehabilitation in the Home

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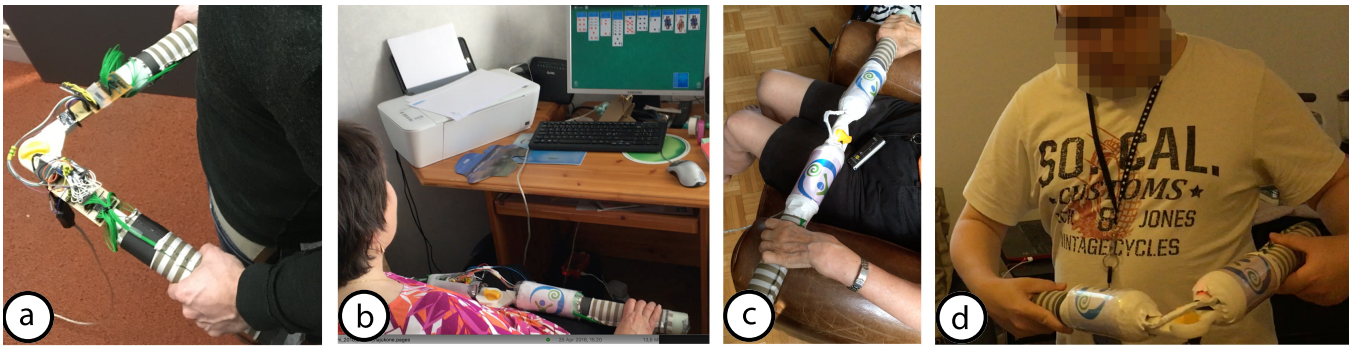


Figure 1: a) ActivSticks and examples of participants doing exercises with ActivSticks in their homes: b) Sally playing Spider solitaire, c) Anna conducting squeezing exercises, and d) Todd doing rotations.

ABSTRACT

Stroke is one of the most common causes of long-term disability in the world, significantly reducing quality of life through impairing motor functions and cognitive abilities. Whilst rehabilitation exercises can help in the recovery of motor function impairments, stroke survivors rarely exercise enough, leading to far from optimal recovery. In this paper, we investigate how upper limb stroke rehabilitation can be supported using interactive tangible bimanual devices in the home. We customise the rehabilitation activities based on individual rehabilitation requirements and motivation of stroke survivors. Through evaluation with five stroke survivors, we uncovered insight into how tangible stroke rehabilitation systems for the home should be designed. These revealed the special importance of tailorable form factors as well as supporting self-awareness and grip exercises in order to increase the independence of stroke survivors to carry out activities of daily living.

CCS CONCEPTS

• **Human-centered computing** → **Field studies**; **Empirical studies in HCI**; • **Applied computing** → *Consumer health.*

KEYWORDS

stroke, rehabilitation, bimanual, bilateral, tangible interaction, home

ACM Reference Format:
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1 INTRODUCTION

There are over 25 million stroke survivors globally, making it one of the leading causes of serious long-term disability in the world [11]. Stroke causes a wide range of physical and

psycho-social impairments, with approximately half of all stroke survivors having to rely on assistance to carry out basic activities of daily living (ADLs), such as dressing, walking and eating [33]. Stroke impacts primarily one side of the body, causing significant motor and cognitive impairments, while leaving the other side of the body unaffected. Whilst hemiparesis is evident in both the lower and upper body, initial rehabilitation is focused on the lower body than upper limbs [35]. Only 17% of stroke survivors discharged from hospitals felt that they received 'good arm and hand therapy' [17] and approximately 80% of stroke survivors never recover fully from motor impairments in their upper limbs [24]. As a result, many ADLs (e.g., dressing and cooking) that would normally be carried out bimanually, are performed mainly one handed by stroke survivors [31, 32]. This is tedious or even dangerous, inhibits independent living and causes anxiety [34]. Incorporating the impaired hand into ADLs can be frustrating or is forgotten, leading to inactivity of the impaired upper limb, and thus limiting the recovery from the stroke [31, 32].

In this study, we aim to support the rehabilitation of the impaired upper limb by designing tangible, bimanual, interactive and tailorable solutions. To achieve this, we customised ActivSticks (see Figure 1a), a dedicated bimanual rehabilitation device resulting from a user-centred design process involving stroke survivors and rehabilitation professionals [25]. Although recent work indicates that bimanual rehabilitation is potentially more effective than one-handed training [28] and bimanual interaction guarantees the use of impaired hand, existing work on interactive stroke rehabilitation has mainly focused on one-handed interaction (e.g., [2, 5, 13, 19, 51, 54]). Moreover, commercial game controllers have been mainly used in previous studies (e.g., [3, 13, 16, 54]) limiting the range of possible movements, such as squeezing.

Supporting at home stroke rehabilitation is extremely important, as only approximately one third of stroke survivors do the exercises as prescribed by physical and occupational therapists [45]. The approach of our research project is to provide tangible and interactive systems for stroke survivors to be used in the home that are small, safe to be used alone, and easy to take into use without the help of therapists. There is a clear need for such systems, as interactive exercise devices have been so far designed primarily to be used at rehabilitation centres and are typically large and expensive [7]. Furthermore, our approach includes tailoring the exercises according to rehabilitation needs and mapping outcomes of the exercises to individual interests of stroke survivors. By doing so we aim to increase the motivation and adherence of daily exercising in the home.

We employed a user centred process, customising tangible rehabilitation systems to the needs and motivations of five stroke survivors. Following an evaluation of the ActivSticks with five stroke survivors and their caregivers, we provide novel insights for designing bimanual tangible devices for home environments. We argue that the results are useful for rehabilitation professionals, especially rehabilitation system designers.

2 RELATED WORK

Bimanual Rehabilitation. . Whilst there has been debate if bimanual exercising provides better rehabilitation results than one-handed rehabilitation [31, 40, 46, 50], a recent study provides evidence that bimanual rehabilitation is more effective [28]. There are reasonable justifications for supporting bimanual training from functional (everyday life involves using both hands), motor control (learning motor control from the healthy hand due to coupling between both hands) and neurophysiological perspectives (bimanual training activates larger brain areas) [31]. Moreover, bimanual rehabilitation is beneficial and effective for recovering from different severities of stroke [9, 47].

However, the majority of the work for supporting stroke rehabilitation with interactive devices has focused on designing one-handed interaction (e.g. [2, 5, 13, 51, 54]) and bimanual interaction has not been the primary design principle. For example, in a study by Balaam et al. [5], whilst the therapist recommended a stroke survivor to do the rehabilitation activity two-handed, the stroke survivor used only one of her upper limbs to perform the movements. Although Balaam et al. [5] designed motivating activities, all of them could be completed using one arm. In order to activate both upper limbs, Kirk et al. [21] developed a drum rehabilitation game where stroke survivors hit pads with objects, however the movements were limited to moving one upper limb at a time. Also, there was no guarantee that stroke survivors actually used their impaired upper limb as much as their healthier upper limb for playing the drums.

Despite the lack of hard evidence that bimanual exercising is more efficient than one-handed training, designing stroke rehabilitation devices that require use of both hands guarantees individuals will use their impaired limb [50]. The closest to our work in terms of bimanual interaction is a study by Hijmans et al. [16]. Their device required simultaneous bimanual interaction attaching a standard games controller to a custom handlebar. They found improved motor performance after conducting 2.5 weeks of clinical trials in a rehabilitation centre. However, it is unknown how bimanual rehabilitation should be designed for homes that guarantees the use of both upper limbs. The home environment, as discussed in the following sections, differs greatly from a clinical environment, especially in terms of available space and lack of rehabilitation experts.

Tangible Interaction and Stroke Survivors. Currently only 20% of stroke survivors fully regain their ability to use their impaired upper limb [24]. The impairments are significant, especially in terms of grip and fine motor control [37]. Due to this, a large body of previous research on interactive stroke rehabilitation systems are implemented using gestural input devices without the need to grip [49]. For example, Alankus et al. [2] suggested removing the need to hold anything in a hand as one design guideline for stroke rehabilitation games.

However, not having a good grip does not mean that it should not be exercised, as many ADLs require grip, and grip strength is an important factor of how well stroke survivors perform ADLs [14, 29]. In order to support grip, tangible rehabilitation devices are needed. Previous studies have explored interactive gloves as one potential approach, but they are tedious to place on the hand of the stroke survivor and require assistance (e.g. [23]). Robotic interfaces have also been widely investigated (see a review in [30]). However, they are typically costly, large and designed not to be used outside a clinical environment [30]. Most of the studies on tangible stroke rehabilitation devices designed for home environments have used fixed size objects, and the impact of form factor has not been discussed [6, 27, 38, 44]. A few studies have acknowledged the importance of the form factor of the hand-held object and have allowed stroke survivors to choose their preferred size [12, 51, 52] or the tangible object itself [21], but no further insight of the impact of the sizes and the materials has been given. Overall, it is unclear how tangibles for home environments should be designed and what properties should be tailored.

Designing Motivating Interactive Systems for Stroke Survivors for the Home. Whilst the benefits of exercising to improve motor function rehabilitation (e.g. [40]) are evident, a lack of motivation and opportunities for stroke survivors to exercise enough are significant issues, leaving many survivors performing only minimal, if any, in-home exercises daily [45]. Although there is no clear limit on what is 'enough' [26], with animals 400-600 repetitions have shown visible changes in the motor cortex area of the brain due to plasticity [22, 39]. Conducting such a large number of repetitions decreases motivation [45], but it can be improved by linking home-exercising to a personally motivating interactive activity [5]. A large body of studies have used games in order to increase stroke survivors' motivation to complete rehabilitation exercises at home (see [48] for a review), and to provide an appropriate level of challenge (e.g., [2, 8]). However, personal interests should be utilised more when designing the outcomes of rehabilitation exercises [5].

In addition to motivation, stroke survivors need more opportunities to exercise [45]. However, opportunities for exercising are very different in homes than they are at hospitals (or other rehabilitation centres) as the "clinical" looking devices with significant dedicated space are infeasible in home environments [4]. Despite the differences between home and rehabilitation centres, most evaluations with stroke survivors have been conducted in lab settings with such [7, 49]. There is a clear need for low-cost and effective stroke rehabilitation devices [7] that "fit-in" to the home and are not abandoned [4]. In addition to exercise space, the home environment differs in terms of time. Whilst typical therapeutic sessions last about an hour in rehabilitation centres, in order to maintain high adherence in-home exercising, therapists prescribe shorter daily exercise sessions for homes, typically 16 - 30 min/day [41]. In-home exercise sessions lasting more than 30 min were found to be burdensome [41]. Moreover, the devices designed for homes need to be safe and easy to use independently without the assistance of therapists.

3 ACTIVSTICKS DESIGN

The Device

In order to explore bimanual stroke rehabilitation at home without the limitations of existing game controllers, we customised a dedicated bimanual device (ActivSticks) that was a result of an iterative user-centred design process involving stroke survivors and stroke rehabilitation professionals [25]. ActivSticks (see Figure 1a) is designed to support both bimanual arm movements as well as bimanual grip. ActivSticks evolved from a ring form to a 'scissors' form in order to support more movements, such as shoulder abduction and adduction.

ActivSticks is built from a pair of large chalkboard compasses as used in school teaching. Each half of the compass tool is covered with polyethylene pipe insulation having a high pressure sensitive fabric ('zebra fabric' [36]) on top. Zebra fabric (see Figure 2f) allows detection of pressure and spatial movements of grip as well as pressure, from the intersections of vertical and horizontal stripes of electrically conductive material forming a pressure sensitive grid (7x10). The arm movements are measured with BN0055 absolute orientation sensors (magnetometer, accelerometer and gyroscope) [1], fixed to both arms. All the sensors are connected to an Arduino Pro micro controller. This both logs exercises completed, and allows the ActivSticks to act as interaction device to control a variety of devices and applications, supporting tailoring to an individuals interests and motivation.

Supported Movements

We collected feedback from several physical and occupational therapists about the ActivSticks and movements it should support at different stages of design process [25]. The therapists tried out the ActivSticks and provided views about the movements and suggested new ones. In addition, our

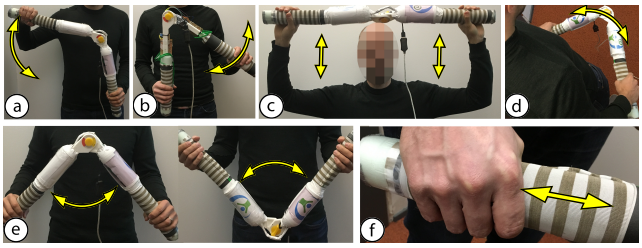


Figure 2: Supported bimanual movements: a) Right hand lift (right shoulder abduction and adduction), b) Left-hand lift (left shoulder abduction and adduction), c) Two-handed lift (both shoulders flexion and and extension), d) Rotation (whole upper-body rotation), e) Scissors up (both shoulders abduction and adduction) and Scissors down (shoulder internal and external rotation, elbow flexion and extension), and f) Grip/Squeeze and Release (finger flexion and extension). The participants were able to choose if they want to do the Scissors movement having the tip upwards or downwards (see e).

project partner, rehabilitation experts from the Faculty of Nursing in University of Iceland, provided feedback about the movements to ensure that the devices supported effective ADL exercises. We chose to support folding, lifting, rotation and squeezing movements shown in Figure 2.

The supported movements cover many versatile movements such as bimanual grip and release, shoulder abduction and adduction, shoulder flexion and extension, elbow flexion and tension, shoulder internal and external rotation and upper body rotation. Whilst there are more possibilities for movements, these movements enable us to explore possible bimanual movements as they include symmetric (both arms move in-phase) and asymmetric (both arms do not move similarly at the same time) movements, as well as grip. In order to also support stroke survivors in gaining strength in upper limbs (one important factor in upper limb stroke rehabilitation [10]), we added a possibility to adjust the resistance of the folding movements with a knob at the tip of the device. By tightening the knob resistance increased, with the angle between the two arms becoming fixed when fully tightened. This allowed the use of ActivSticks as a straight bar in bimanual lifts (see Figure 2c).

4 PARTICIPANTS

We recruited five participants (see Summary in Table 1) through a local stroke organisation. The participants were different to those who took part in initial design process of ActivSticks [25]. We had a variety of participants in terms of gender (3 female, 2 male), age (min 37 years, max 76 years) and severity of stroke (description provided in the following sections). Participants were asked to provide written consent before each visit and were rewarded with one movie ticket after each visit, worth roughly 10 euro. Each participant is represented with a pseudonym. All our work was approved from the ethical committee of Aalto University.

5 CUSTOMISATION

In order to understand how ActivSticks should be tailored to support individual rehabilitation requirements and to map the exercises to personally motivating activities, we conducted an in depth user centred design process, where customised how the technical components embedded in the ActivSticks were used (so not the components themselves) to support the rehabilitation requirements of each stroke survivor. Based on the individual needs, we customised the movements, movement detection thresholds, feedback, and outcomes of the exercises. The customisation consisted of three visits in each stroke survivors' home. Stroke survivors' caregivers participated in each visit based on their availability. Two stroke survivor's (Sally's and Mike's) caregivers participated. The stages of customisation process were.

(1) Home observation and initial interview: At the first stage, we gathered in-depth information with a semi-structured interview about how the stroke impacted the life of the participant and their current rehabilitation routines. We familiarised with rehabilitation requirements and the stroke survivor's home environment. As motivation has been found to be extremely important in stroke rehabilitation [5], we asked the stroke survivors what motivates them and what interests and hobbies they have. We were able to use this information for mapping the exercises to motivating activities. We video and audio recorded the interviews and this visit lasted 1-2 hours. Three of the participants were interviewed in English, while the other two were interviewed in Finnish. In the case of the English interviews, these were transcribed. Finnish interviews were translated and transcribed into English. All interviews were transcribed intelligent verbatim, a process whereby filler words such as "er" are removed during transcription. Two researchers examined independently the parts of the interview that concerned rehabilitation needs and personal interests. After this, the researchers devised together potential rehabilitation requirements and possible motivating activities for each stroke survivors. Following this, they were used to formulate several design concepts, which were presented as video prototypes and non-functional tangible prototypes to the stroke survivors.
(2) Presentation of design concepts: We showed the video prototypes to stroke survivors and allowed them to try out the movements using ActivSticks. We collected feedback with a semi-structured interview. We video

Table 1: Summary of participants including customised rehabilitation solutions and their use. * = The log files were not available from each day as we encountered difficulties implementing them for some participants.

Participant	Age	Gender	Time since stroke (years)	Side most affected	Dominant hand	Targeted upper body rehabilitation requirement	Designed movements	Output	Daily goal (time or repetitions)	Average daily use (% of the goal and time)	Evaluation period
Sally	63	F	23	Left	Left	Grip and fine motor movements	Bimanual squeezing and releasing, moving hands horizontally	Solitaire game on PC, progress on a lamp, progress on a smart watch	60 min	218 % and 131 min	13 days
Mike	65	M	12	Left	Right	Arm	Movements in Figure 2a-2e	Showing progress on a screen and on a lamp	For each movement 3 sets with 15 reps (total 225 reps)	92% and 15 min*	7 days
Anna	76	F	20	Left	Right	Grip	Movement in Figure 2f	Showing progress on a screen and on a lamp, unlocking Spanish lessons on a tablet	3 sets with 5 reps (total 15 reps)	100% and 5 min	6 days
Todd	37	M	3	Left	Right	Arm and grip	Movements in Figure 2a-2f	Showing progress on a screen and on a lamp, unlocking travel documentaries on a tablet	Each movement 3 sets and 5 reps (total 90 reps)	90% and 11 min	8 days
Keila	59	F	3	Right	Right	Arm and grip	Movements in Figure 2a-2f	Showing progress on a screen and on a lamp, giving auditory feedback about the grip	Each movement with 5-16 reps (increased daily)	100 % and 3 min	8 days

and audio recorded the interviews and this visit lasted 1-2 hours. The interviews were transcribed similarly to the home observation and initial interview.
Based on the feedback, two researchers designed and constructed the customised rehabilitation implementations which could be tuned with later consultation with the stroke survivor based on his or her individual motor functionalities (e.g., grip strength) and preferences (e.g., target number of repetitions).

(3) Configuration of working devices: In this session, we tested the technical functionality of the customised rehabilitation implementations with stroke survivors and tuned the parameters, so that we were able to detect the movements successfully. As the individual differences (e.g. in speed of arm movements and pressure of the grips) were large, we needed to use different detection thresholds for each participant. Also due to the lower dexterity and strength of the impaired arm, individual thresholds for each arm had to be determined. This visit lasted 1 - 2 hours.

Participant Needs and Customised Implementations

Sally. Sally is able to move her arm and hand reasonably well, and her range of movement is good. Sally's priority is to maintain the strength and improve fine motor control in her left hand. For example, she cannot write, and uses the desktop mouse with her right hand although she is left handed. She likes to play Spider Solitaire[1] with the mouse and sometimes she can spend a couple of hours playing the game, which makes her feel a bit guilty for not doing something more useful. In order to activate her left hand when playing Spider Solitaire, we customised the ActivSticks to control a mouse cursor (see Figure 1b). ActivSticks was in her lap sideways, and Sally used her impaired hand to move the cursor to the left and right by squeezing the left and right parts of the handle. To move the cursor in the up-down direction, she needed to rotate her wrists backward and forward. Squeezing the right hand corresponded a primary button mouse click. This solution guaranteed that Sally had to use both hands to drag cards in the game. Sally determined her daily goal was to play 60 mins Spider Solitaire with ActivSticks. We presented her progress on a smart watch and a lamp. The lamp (see Figure 3b) was placed in her living room and changed colour as she progressed through her exercises.

Mike. Mike is able move his arm, but is not able to grip and release with the impaired hand due to spasticity. He could not hold ActivSticks in his hand and thus he used a separate band to hold it. He used to exercise frequently before his stroke. He did not want his exercises to be mapped to anything particular, as he wants to keep exercising separate from other activities. His goal was to complete all the movements with ActivSticks apart from squeezing, as it was too difficult a task for him. Mike decided that his daily goal was to do three sets with 15 repetitions each. Mike was able to follow his progress in completing his exercise on a small screen display (screen size 155 mm x 86 mm) shown in Figure 3a. Additionally, a lamp was placed in his living room that lit up gradually as his exercises completed. Mike wanted to do the exercises in front of a mirror, which helped him to follow movements of his impaired hand.

Anna. Anna is able to move her impaired hand well but needs more strength in her grip. For example, she wants to have more confidence in driving her electric mobility scooter, which requires her to grip handles with both of her

[1] A Solitaire card game where one needs to order cards from King to Ace in the same suit. Available at: https://www.microsoft.com/en-us/p/free-spider-solitaire/9wzdncrdnc5h#activetab=pivot:overviewtab

hands in order to control acceleration and brakes. For her, we designed an exercise where she had to squeeze the ActivSticks for three seconds with both of her hands and then release the grip (see Figure 1c). Anna decided to set her daily goal to three sets with five repetitions each and she was able to see the repetitions on a small screen (shown in Figure 3a). Anna is interested in Spain and Spanish; therefore, we implemented a system that unlocked videos on a tablet each time she completed a percentage of her daily exercises.

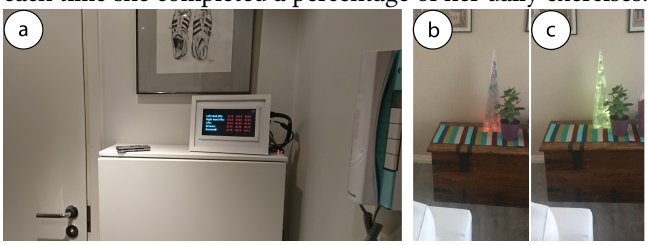


Figure 3: a) The small screen placed in Mike's home and b) the lamp placed in Keila's home, lighting up an example colour when only few exercises are conducted, and c) showing an example colour when the exercises are completed.

Todd. Todd has challenges in gripping or applying force using his left hand; this has an impact on his day to day activities. He often neglects his upper limb and does not integrate it in his everyday activities. As such, he did all the exercises that were available with ActivSticks, both arm movements and squeezing, in order to improve his grip. He decided to do the movements with five repetitions (see an example in Figure 1d). His primary interest is travelling the world, so we mapped successful completion of exercises to unlocking short travel documentaries. After doing 20% of exercises he unlocked a new documentary. Todd was able to follow his progress in completing exercises on the small screen (see Figure 3a) and with colour changes on a bespoke feedback lamp.

Keila. Keila's rehabilitation has focused mainly towards her walking and balance, so she has exercised her upper limbs very little after her stroke. Keila stated that she needed to increase strength and movement range in her impaired hand. Sometimes she forgets to concentrate on gripping in her impaired hand, causing it to start slipping gradually. To help her to maintain grip, we provided a sound notification that signalled if her grip loosened. By doing so we aimed to increase her awareness of her grip.

For Keila, we implemented all the movements supported by the ActivSticks, excluding the squeezing as it was too challenging for her. She did not want the exercises to be mapped to anything, but in order to motivate her she wanted to have periodical notifications that reminded her to complete her rehabilitation exercises. We implemented this by showing her a blinking light on a feedback lamp (shown in shown in Figure 3b) and alarm sound every half an hour from midday until she had completed all of her exercises. Additionally, she wanted to be able to increase her challenge daily. Keila decided to start with five repetitions, adding another repetition of each movement daily. Keila was able to follow her progress in completing exercises on the small screen (shown in Figure 3a) and also on a lamp (the same lamp we used for the blinking light), which changed colour as she completed her exercises (shown in Figure 3b and 3c).

6 EVALUATION

Method

After our three visits to develop bespoke customisations for the participants, we investigated how stroke survivors used and perceived the customised rehabilitation implementations. The stroke survivors used the devices in their homes for 6-13 days, depending on availability of the stroke survivor.

We gathered both quantitative and qualitative data during the evaluation period. We logged the number of exercise repetitions, when and how long they were carried out to understand how ActivSticks were used. Data collection was implemented by reading serial data from the Arduino and storing it on a memory card using a Raspberry PI. Interaction time was logged from when movement was detected with the ActivSticks and stopped if no movements were detected in the preceding 10 seconds. In order to measure perceived task load we asked participants to fill out NASA-TLX questionnaire [15] after finishing the daily exercises (applying it similarly to stroke rehabilitation as [55]), and we collected subjective feedback about how participants found the exercises with a diary.

Analysis

Following the evaluation, we conducted semi-structured interviews with each participant (and in the case of two participants, their caregivers) to gather feedback on their experience using the ActivSticks. The diary entries and responses to NASA TLX-questionnaires were used to provide discussion points in the interviews. We audio and video recorded the interviews, which lasted 1-2 hours. In this time frame, we allowed for breaks if the stroke survivor needed it.

Interviews were transcribed similar to the customisation process (see Customisation Section) and were analysed thematically using a framework approach [42], having bimanual movements, grip, body awareness, form factor, and future use as initial codes. Log files were used to determine when and what exercises the stroke survivors had completed. We then triangulated between these data sources to understand how the customised bimanual rehabilitation implementations were used daily.

7 RESULTS FROM EVALUATION

Rehabilitative Support

Body Awareness in Bimanual Movements. We identified that different feedback needed to be applied for each stroke survivor to guide their body awareness in performing bimanual movements. Bimanual exercising increased the challenge of concentration on exercising as both hands need to be controlled instead of one. Participants raised awareness of their impaired upper limb as a fundamental issue when conducting bimanual exercises. Especially with symmetrical movements, the challenge is to match the movement with both hands and some stroke survivors voiced concerns on whether the quality of movement of the impaired hand was good enough (Keila: *"My focus is 100 per cent on the movement of the arm in question. But when I'm doing that with both arms, I'm maybe focusing more on the symmetry than on actually performing the exercise itself."*). As such, the differences between movements with impaired and healthy are inevitable (Mike's caregiver: *"But maybe it was also the device that it didn't record it because...the arms were not in the balance."*). This emphasises the need to provide feedback about the movements of the impaired hand, especially in symmetric movements where both hands move simultaneously.

Improving body awareness might also be discouraging, as it may lead to some stroke survivors having concerns about their own performance (Keila: *"...when you're doing the symmetrical exercises, your performance on your healthy side would help you do the exercise. It might help with the rhythm, indeed, but because the performance on the other side is left incomplete, it's also annoying."*). Thus, providing feedback should be made honestly but positively. Mike acquired body awareness through a mirror (Mike: *"If you don't have a mirror, you don't necessarily know you're doing the movements correctly. In the mirror, you can see you're not lifting your arm high enough. You can correct it, so in that sense the mirror is good'."*). However, not all participants had such a place in their homes where they could train in front of a large mirror. Additionally, a mirror cannot provide feedback about the strength and fine posture of the grip.

Body Awareness in Bimanual Grip. We found that supporting awareness of bimanual grip turned out to be an important feature for the design of devices supporting two-handed movements and that each stroke survivor needed different supports to trigger awareness in bimanual grip. Participants discussed bimanual grip extensively, and it played an important role in the daily lives of participants. Grip performance and ability varied amongst the stroke survivors. While some could not grip at all using their impaired hand, others needed to improve fine motor control. Three participants (Mike, Todd, and Keila) discussed how it took a lot of attention to ensure that their grip was good (Mike: *"I have power in that hand, but I must look, otherwise it will drop."*). When Todd was concentrating on his bimanual grip, he was able to squeeze well and he also highlighted the importance of releasing a grip (Todd: *"...when I take a really good grip, I really have to concentrate in letting it go."*). However when he did other exercises than squeezing, he felt that his grip was not in control (Todd: *"They [symmetrical movements] are also a little bit more difficult, because there I have to follow both sides and when I lose concentration I will lose the grip. Or at least there is a danger that something like that would happen. But I think that is very important."*). Keila heard a repeating sound notification when her grip with her impaired hand was loosening below a threshold level, and she had to focus a lot to maintain it (Keila: *"I think that almost 80 per cent of the exercise was focused on the tightness of my grip."*). Sally focused more on fine control rehabilitation, but she also found that her awareness of grip strength has decreased due to stroke. The speed of the cursor in the Solitaire game helped her to be aware of the strength of her grip (Sally: *"Maybe sometimes it felt that I had to push harder, or correct grip. Because my left hand is numb. So sometimes when I tried to push it, the cursor didn't move that easily, while sometimes it went really fast."*).

Perceived Challenge and Effectiveness. Finding the appropriate level of challenge for exercises is a fundamental issue in stroke rehabilitation. Through our customisation process, we were able to offer appropriately challenging exercises from the opinions of every stroke survivor. Nonetheless, it appeared that stroke survivors sometimes needed to find a way to deal with unanticipated challenges during use. For example, the required effort to complete the daily exercises was between 45 and 75 (see Table 2) in a scale from 0 (no effort at all) to 100 (maximum effort). The appropriate level of perceived challenge was determined by adjusting the speed, movement range and pressure thresholds according to individual needs.

Whilst participants were able to do all the other movements, for Mike the scissors were too challenging (Mike: *"I wasn't able to lift my left arm high enough, so it had an effect on the counter")*. The scissor movement was challenging also to Keila who found a way to do them, but the quality of the movement suffered (Keila: *"I wonder if I cheated a lot, because I used to pull backwards like this. And I was able to perform the movement [Scissors] so that it was logged on there, but had I done it here, it would've been totally different. This is more strenuous. So perhaps I cheated a little bit."*). Also the squeezing task was challenging. However, through design explorations with the stroke survivor before the evaluation study we found squeezing thresholds that were testing, yet

Task load	Sally	Mike*	Anna*	Todd	Keila	**Mean**
Mental	59	35	75	47	15	46
Physical	57	40	75	59	39	54
Temporal	61	30	25	50	11	35
Performance	58	85	75	75	65	72
Effort	60	45	75	59	57	59
Frustration	60	5	25	50	16	31

Table 2: Responses to NASA TLX-questionnaire. *=participant responded to the questionnaire once after the evaluation period.

where the challenge was at an appropriate level for the participants (Anna: *"I thought it was sufficient for me at least. I really had to put effort into it."*).

In contrast to other participants' activities, Sally's task to control the Spider Solitaire game required simultaneously concentrating on using the ActivSticks as well as the game which made exercises with the ActivSticks more challenging. However, it was not too difficult for her (Sally: *"Yeah, I feel like I learnt to control it. And moving the card with my left hand and I learnt to hold down the right handle when moving the card, so. At first, I made mistakes there, because it was quite difficult to use both hands."*). Sally rated overall task load (as measured with NASA task-load index (TLX), see Table 2) higher than other participants on average, but still pretty far from maximum load. Sometimes she had to use a mouse if the movements with ActivSticks were too challenging (Sally: *"I did use it [the mouse] a few times. For example, when you deal new cards, it easily happens that, because you only have to push the button once to deal just one set of new cards, and then it dealt two sets of cards."*). For this reason, having an aid to play a game is useful in order to avoid frustration and support adherence to game play. Her playing durations were significantly longer (average 2h 11 min) than the other participants, who completed repetitions in sets (average across participants 9 min). Sally found playing rewarding as she was able to concentrate in controlling the game (Sally: *"My left-hand fine motor skills are pretty poor, however, when I concentrated and was patient, I succeeded. I was even able to win Solitaire."*).

For most of the stroke survivors, the type and amount of movements to be completed remained consistent throughout the study. However, for Keila, the challenge was increased by adding one repetition each day (Keila: *"I think I was doing better and better all the time...and I was always expecting to have one more, because it was nice. But in the end, you couldn't keep adding them forever...doing one hundred exercises could be a bit too much."*). This emphasises the need for more sophisticated mechanisms to increase challenge beyond just adding more repetitions. In the context of rehabilitation games, the adaptivity of challenges has been suggested to be important in order to keep motivation [2] and it is typically achieved by modifying speed and size of moving game objects [54]. Whilst this could help stroke survivors to make the same movements faster and with a higher precision, also the order of which the different movements are conducted should be adjustable as well.

Whilst the amount of movements to be completed each day remained constant for most participants, the perceived challenge of those exercises was not constant. For example for Todd, the performance in conducting the exercises varied between 77 and 52 between two consequent days. Todd could not explain what caused the change (Todd: *"Trying to operate with this body is pretty close to some kind of witchcraft...you never know how you are going to operate...some days my left side is just locked and then doing these movements is...much more difficult."*). The changes in performance indicates that there should be an option to choose easier or fewer exercise target for the 'bad' days, and vice versa; when feeling better than normal or ambitious, stroke survivors should be able to conduct exercises at higher level of difficulty or with more repetitions than usual.

The challenge of the movements had an impact on the order participants wanted to conduct them in, as participants preferred doing first the easy movements and then moving on to more challenging ones (Mike: *"It [the impaired arm] was tired after the left lifts since those were the first exercises. So I wasn't able to do that so well...So changing the order of the exercises could be an idea for development."*).

The perceived effectiveness of the movements did not always increase with perceived effort. For example, all participants perceived the rotation movement (see Figure 2d) as effective, although it was rather easy to do (Todd: *"The rotation moves I liked and enjoyed the most. They felt the most athletic of those actually, because it is a kind of, far greater area of the body. So, it felt like, really, doing something."* and Keila: *"I thought the rotation movement was really good. It was really relaxing, because it was easy to do, and it also felt like it was beneficial, because it's not a movement you do all that much."*). Therefore, the bimanual device can help the stroke survivor to activate a large part of the body in the exercises, that can be perceived easy to conduct and effective at the same time.

Perceived Progression. Providing the appropriate level of challenge provoked the participants in perceiving that they were progressing. This had a motivating impact on some stroke survivors to continue with bimanual rehabilitation. Although Mike could not hold the ActivSticks without a band, he perceived that his grip improved during training (Mike: *"I had the supporting band there, which worked well, and the thickness [of the handle] was good, and we progressed every day... So it improved my grip."*) and similar observation was noted

by Mike's caregiver (Mike's caregiver: *"...now at the end of the week or even after three or four days, that I could see, he could concentrate on the left hand properly so that he could do the right-hand lifts much better than in the beginning."*). As such the possible improvement in grip in Mike's impaired hand resulted as a byproduct of exercising his healthy arm. The effects were not limited only to the exercises, but were also reflected in performing ADLs (Anna: *"I'm extremely insecure about and afraid of carrying stuff with both hands. But now that I noticed that I could squeeze with both hands, I thought it encouraged me to try that in the future, too."*).

Requirements for Form Factor of ActivSticks

The form factor of ActivSticks was liked by participants due to it's simplicity and familiar shape (Mike: *"It makes me think of stick exercises that I used to do...In sports, they use sticks a lot, so this is comparable to that. There's a bit of added activity, but basically, it's the same thing."*). Also ActivSticks was perceived to be light (mass was 0.54 kg) enough for lifting exercises. Preference on the form factor of the handles of ActivSticks was individual for each participant. Here, we illustrate how participants voiced their preferences toward handle design and resistance.

Tactile Design of the ActivSticks. Preference for tactile design (materials used and handle thickness) differed between stroke survivors. However, all commented on how tactile design could impact their rehabilitation performance. Most of the participants shared their opinions on the material used to design the handle. Mike wanted to have nodules (i.e., small bumps) (Mike: *"Nodules. That could be a development idea...It activates especially when you have no deep sensation."*), Todd preferred stickier fabric (Todd: *"I think a little bit stiff here or stickier fabric would make it easier, maybe made of some kind of gum"*). We provided stickier fabric for Keila, but after trying out the material she preferred the cotton fabric (Keila: *"It [cotton fabric] does not feel as disgusting as the foam, normal fabric feels nicer...I do not like the foam if my hands start to sweat or something."*).

Additionally, participants shared their views on the thickness of the handles (currently 5 cm). For Sally, Mike, and Anna the thicker handle than typically used in gym bars was good (Anna: *"I thought it was pleasant. I have no complaints about that"* and Mike:*"And this thick one is good. And the softness, not bad.")*. However Keila wanted the thickness to be adjustable (Keila: *"In the beginning, it [the handle] could be a bit thinner...it could be extendible in accordance to how well my grip improves."*). There can also be variation between the impaired and healthy hand (Keila: *"The thickness is really good for my healthy hand, but not for the other hand."* and Todd: *" I didn't like or enjoy the fabric of the left side. For the right side, it was okay, because I have a normal functionality in my right hand. But for the left hand it was maybe a little bit difficult to use.*). Thus, the handles should be easily changeable in order to support a variety of different fabrics and thickness.

Adjustable Resistance. Participants who carried out folding movements (Mike, Todd and Keila) were able to adjust the resistance. In these instances, we revealed the lack of body awareness in the resistance level during use. We aimed at possibility that stroke survivors can adjust the difficulty of the movements depending on which arm they are exercising (healthy or impaired) and how they progress in increasing strength. However, although Mike acknowledged this opportunity (Mike: *"So the tightening [increasing resistance] is good. If it's too easy, you notice that you have to add resistance. Or if it's your weaker arm, it's the other way around, so you have to decrease resistance. That's how you can adjust the quality."*). In Todd's case, he did not remember that the resistance could be changed during the evaluation. Keila did not adjust the resistance as her main goal was just to move the impaired hand (Keila: *"I feel like adjusting the resistance is kind of useless to me right now...since I cannot precisely tell how much resistance there is because of the stiffness of my hand, in that I cannot really feel the difference."*). Both Mike and Keila said that there should be clear steps for adjusting resistance (Keila: *"...there would be steps like click, click, click, or something, so that I could see that it's at four...and tomorrow I'll readjust it to three or five, whatever's better."*). Although we had marked numbers on the resistance knob, so that users were able to see the resistance level, its adjustment should have clear steps instead of continuous adjustment. Additionally, providing auditory feedback (e.g. through a clicking sound) may aid stroke survivors in selecting resistance values.

Balancing Attention on Movements and Activities

Providing Simple Visual Real-Time Feedback. Increased cognitive and motor demand caused by bimanual and grip highlighted the importance of mapping movement to simple outcomes. Participants needed to pay a lot of visual attention during bimanual training towards their impaired hand. Especially when doing symmetric movements, Mike, Todd, and Keila focused at their impaired hand while they were exercising. This result indicates that the visualisation of outcomes should be simple in order not to distract from the rehabilitative movements being carried out (Keila: *"I also have trouble concentrating, so it would help a great deal, if you didn't need to focus on several things at the same time."*). Thus, there is a risk in losing the awareness of the impaired hand, if the concentration is focused too much on the interaction, such as playing a game. This is especially important in tangible interaction where grip of the impaired hand is easily loosened

if concentration is towards something else than the impaired hand (see section Body Awareness in Bimanual Grip).
For most of the participants (Mike, Todd, Anna and Keila) we showed the number of completed repetitions on a small screen. This simple method to display the progress in repetitions provoked Keila to exercise properly (Keila: *"Actually, I was looking at it [screen] all the time...I was trying to perform well enough to change the number on the screen."*). The focus on screen was enabled by providing auditory feedback about her grip, which helped Keila to divide her attention (Keila: *"...when it quieted down, that made me happy, because that meant my grip was good."*).

Games Are Not for Everyone. Playing games with a bimanual tangible device was found to be very challenging, or not motivating, for four out of the five participants. Visualising progress in terms of numbers on the screen was found to be motivating for two out of the four stroke survivors who had the screen, and two stroke survivors did not need even that. Mike and Anna did not feel that visualising the completion of exercises would have had an impact on their exercising (Mike: *"But basically, you have to count it manually, too, so it's a back-up thing. You can compare it. But it doesn't matter. The main thing is that your exercising is of good quality."*). Due to difficulties in concentrating on other things than the bimanual exercise itself, having the reward after the exercise was found to be a good approach. Both stroke survivors who had this opportunity found it very motivating to 'unlock' short video clips on a topic they were interested (Anna: *"...we're going to Spain in January, so I think it's wonderful that I learn to hear it in a whole new way."*).
For Sally, we mapped the exercises to her favourite computer game, namely Spider Solitaire. Games have shown to support a large number of exercise repetitions. For example, Hijmans et al. [16] estimated repetitions to be around 500 - 800 (no actual log data was provided) in their bimanual game. Indeed, having the exercises mapped to a game provided a lot of repetitions in our study as well. For Sally, we measured the daily number of repetitions to be 1172 on average for her impaired hand. This was much greater than other participants, whose movements were not mapped to a game. Their number of repetitions was between 15 and 270 (mean = 89 repetitions), higher than the mean number of upper limb repetitions (N = 54) in rehabilitation therapy sessions [26], but less than number of repetitions shown to provide visually perceived changes in motor cortex of animals [22, 39].

Designing Bimanual Devices for Home Environments

Supporting Portability. The home environment imposed both spatial and temporal requirements for stroke rehabilitation in terms of exercise space. None of stroke survivors wanted to do exercises in front of the main TV, although there was typically enough space to do this. Most of the participants commented that the room where the main TV exists is meant for relaxation and is not feasible for doing exercises. Also other spaces were not fully dedicated to exercising and the rather small size of ActivSticks (length of one half was 45 cm and total length was 90 cm) and the possibility to fold the ActivSticks and put it to the closet was pointed out to be a nice feature (Mike's caregiver: *"I like this thing, it's, you can place it in the closet and it doesn't need so much space and it's light and easy and not too complicated."*).
Whilst we targeted the device to be used in the home, participants suggested the use also in other contexts, for example for group exercises (Mike: *"I could very well use a device like this along with other exercises. So I recommend this to others, too, for home use, but also for group exercises. So everyone should have a device of their own. But it could work well, because I also attend group exercises and arm exercises."*). Thus, having a portable device enables use in wider contexts and also more social use, which has been suggested to be an important factor in stroke rehabilitation [34].

Enabling Exercising in Short Periods of Time. Existing daily routines could have an impact on how and when new rehabilitation activities are performed at home. In addition to exercise space, participants discussed time. From the interviews and data logs we found out that participants did all the exercises at once if they had time. However, if participants were in a hurry, they tended to complete them in parts throughout the day (Todd: *"I have pretty clear routines and there is no space for almost anything else. So, for example, these couple of minutes that I'm doing these movements I had to schedule that in my morning."*). This highlights that exercises should be able to complete in shorter parts, retaining the history of previous exercises completed within same day. The importance of enabling short exercise sessions is in line with findings by [41], that exercises should be less than 30 minutes in order to keep adherence to exercising high. In addition to supporting short exercises periods, setting up the devices should be made easy and fast by the stroke survivors. In our case, users needed to plug-in an USB cable in to start using ActivSticks, but once also this was demanding as one of the participants did not find the end connector from the USB-cable.

8 IMPLICATIONS FOR DESIGN

From our work we have identified a number of considerations that should be taken into account when supporting effective daily rehabilitation for stroke survivors.

Support Customisation of Exercises and Activities. The rehabilitation needs of stroke survivors are individual, and thus rehabilitation devices must be customised for each person.

Through our customisation process, we were able to provide exercises that were perceived to be at an appropriate level in terms of challenge. Our results agree with Alankus et al. [2], who found that customisation is highly important when designing rehabilitation games for stroke survivors. However in their approach, as well as in many other studies, the games were developed first, and only customised following these developments, depending on the stroke survivors' rehabilitation requirements (see a review in [49]). Having determined what games to implement beforehand does not take into account that stroke survivors may have diverse interests for games that ought to be considered when customising them to home environments [18]. Instead of defining what games to implement beforehand, we took another approach by first finding out what motivates stroke survivors, and then customised the activity accordingly. For example, Sally liked to play a Spider Solitaire game, so we mapped her exercises to controlling a Spider Solitaire game with the help of dedicated input device (ActivSticks) in order to support rehabilitation. The key benefit in using this approach is that the stroke survivors are given an opportunity to articulate what motivates them on a broader level (whether that is a game, reminder system, or feedback), which can be expected to be more motivating in a long-term use.

Nevertheless, the use of games is useful for achieving a lot of repetitions. Our results supports that with games the number of repetitions (1172 on average) can reach the repetition limit (400 - 600) of causing visible changes in motor cortex in animal models [22, 39] and conducting exercises in repetitions do not (89 on average). However, despite the less number of repetitions there are still reasons to conduct exercise in more controlled way in repetitions and sets, as the some participants liked to control the order of the different movements (easier movements first) and the ability to concentrate fully on exercising as discussed above. The importance of order in conducting the exercises have not yet been incorporated into game design, but should be taken into account in the future.

Provide Simple Real-Time Feedback for Increasing Body Awareness. Stroke survivors discussed how they needed to pay full attention towards their affected upper limb during the bimanual exercises to maintain body awareness. Thus, bimanual, unfamiliar and real time games would have been very demanding for many of the participants. This finding emphasises the importance of providing reward after completing the exercises, such as 'unlocking' videos of interest.

Support Bimanual Grip. We supported exercising of bimanual grip, which have not been explored for in-home stroke rehabilitation, despite the importance of grip in ADLs [14, 29]. Whilst it is true that many stroke survivors have difficulties in gripping, it does not mean that is should be neglected and we suggest developing rehabilitation systems where the bimanual grip is a required. In the context of games for supporting stroke rehabilitation, one good approach would be attaching a motion controller to an object (e.g., a bar) which can be held bimanually, similar to the device used by [16]. However, that device [16] should be extended allowing squeezing as nearly one third of the stroke survivors in their study were not able to press keys of the game controller with their impaired hand, thus limiting the training of the strength of the grip.

Support Customization of the Physical Device. Based on the interviews, to support individual stroke survivors in gripping and using the bimanual device, it should provide different thicknesses and fabrics. Thus, properties of the tangible device (such as thickness and fabric) should be customisable depending on participant's needs and preferences. Customisation of tangibles for stroke rehabilitation has received little attention in previous research, as for example in the very recent review by [49] only 10% of the studies used tangibles at first place, and none of those studies [6, 27, 38, 44] discussed tailoring form factor of the used tangible.

Support Portability for Home Use. The home environment imposed requirements and constraints on exercising and devices. Participants did not want to exercise in front of the main TV because the living room where the TV was placed was primarily meant for relaxation. Therefore, rehabilitation games played in front of the main TV screen may not the most feasible approach (TVs have been used in multiple studies utilising game controllers, e.g. [6, 43]), especially because in our case where bimanual interaction required full concentration without distractors. In addition, whilst the majority of studies providing bimanual and tangible interaction require a fixed exercise space [7, 21, 50], the portability and possibility to hide the ActivSticks was found to be important in order to 'fit-in' to the home.

Enable Flexible Daily Exercise Times. We found the importance of enabling exercise over short periods to complement the routine of participants, as some completed their exercises in short periods throughout the day rather than at once. Additionally, 'bad' days also impacted participants' motivation to complete their exercises. This requires an easy way to start exercising (plugging in an USB-cable in our case) and supporting flexible exercise times so that participants can continue effortlessly where they left.

9 LIMITATIONS AND FUTURE WORK

Whilst participants found the movements simple and effective, having the movements designed together which each person's personal physiotherapist would have enabled more

optimal rehabilitation. However, as stroke rehabilitation professionals tend to be available only during the acute phase, but rehabilitation exercises may need to be conducted for the rest of the stroke survivor's life, not all individuals will have a physiotherapist available. This was the case for three of our patients. All of our participants had at least three years since their stroke, and all except one participant have had experience about the upper-limb rehabilitation before. Thus, they had a working knowledge of what kind of movements would be beneficial for them, and what kind of exercises they should do.

The large differences in stroke survivors' capabilities in their impaired upper-limb imposed challenges to detecting the movements, and counting them was not fully accurate in our study. The differences in motion speed and motion range were so large that it was difficult to count the repetitions without errors using constant threshold values for each participant. In order to improve this and involve therapists in the tailoring process, a machine learning approach could be used for detecting the movements. This could be implemented by using therapists' movements as a training set, which stroke survivors would need to match their movements to. This approach would help to ensure the technical correctness of the movements. However, back tracing the problems and differences between therapists' and stroke survivors' movements into user understandable parameters such as motion speed and direction would be difficult. Most likely the use of use machine learning approach would be feasible for detecting more complex movements than used in this study.

Whilst the movements with ActivSticks can be expected to be clinically useful as they are similar to those used in a previous study where improvement in motor function was evident [16], conducting clinical evaluations would be important. Moreover, three participants reported improvement in their grip and one participant reported increase in her confidence to bimanual grip. Even the self-perception of improvement can increase self-efficacy and independence in ADLs [20]. Nevertheless, clinical evaluations are needed to evaluate the rehabilitative impact of ActivSticks with longer intervention periods. Longer periods would also provide new knowledge about how the exercising could become daily habit, not only for stroke survivors who can increase their performance, but also for stroke survivors who may not improve their performance but just help maintain current levels of mobility. Our goal in this work was to ensure the potential of customisable tangible activities to support stroke rehabilitation, before the cost and time of a clinical evaluation. Within the project we are currently undertaking a 6 month clinically driven study to understand the effectiveness over a longer period.

Finally, as visual attention was occupied by following the impaired upper limb during the exercise, the use of auditory cueing could be investigated more for facilitating and giving feedback about the exercises. Whilst we used auditory cueing to improve awareness of a grip for one participant, the auditory cues could also be used to give rhythm for conducting repetitions, as rhythmic auditory cueing has been found to provide good rehabilitation results for bimanual rehabilitation [53].

10 CONCLUSION

This paper provided previously unexplored insight into bimanual stroke rehabilitation beyond the game-based solutions, typically used in HCI. Evaluations with stroke survivors showed that it is possible to configure the tangible devices to facilitate the stroke rehabilitation in homes. Compared to previous studies on upper-limb rehabilitation, the results emphasised the importance of body awareness and grip in the training in order to support activities of daily living and customising the outcome beyond games designed by researchers. The study provided insight to the design of bimanual tangibles in order to increase stroke survivors' independence in their daily lives.

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