# An Assistive Robotic Table for Older and Post-Stroke Adults: Results from Participatory Design and Evaluation Activities with Clinical Staff

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## ABSTRACT
An inevitable new frontier for the CHI community is the development of complex, larger-scale, cyber-physical artifacts where advancements in design, computing and robotics converge. Presented here is a design exemplar: the *Assistive, Robotic Table* (ART), the key component of our envisioned *home*+ suite of networked, robotic furnishings for hospitals and homes, promoting wellbeing and independent living. We begin with the motivations for ART, and present our iterative, five-phase, participatory design-and-evaluation process involving clinicians at a rehabilitation hospital, focusing here on the final usability study. From our wide-ranging design-research activities, which may be characterized as *research through design*, we found ART to be promising but also challenging. As a design exemplar, ART offers invaluable lessons to the CHI community as it comes to design larger-scale, cyber-physical artifacts cultivating interactions across people and their surroundings that define places of social, cultural and psychological significance.

### Author Keywords
Assistive Robotics; Design Research; Ethnography; Human-Robot Interaction Design; Eldercare; Healthcare

### ACM Classification Keywords
H.5.2 User interfaces: User-centered design, J.5 Arts and Humanities: Architecture, K.4.2 Social Issues: Assistive technologies for persons with disabilities

## INTRODUCTION
In hospitals, technology has become pervasive and indispensable during medical crises. In homes, technology proliferates as computerized health monitoring systems and, perhaps in the future, as assistive, humanoid robots. The physical aspect of these built environments, meanwhile, largely remains ill adaptive to, rather than accommodating dramatic life changes of its inhabitants.

Common architectural and industrial design strategies for accommodating aging and clinical populations suffer numerous shortcomings. While the conventional components of "adaptable" homes (e.g. walls) are organized to anticipate remodeling, they demand of their homeowners the tremendous will and substantial means to remodel them. And while homes and their personal effects informed by "Universal Design" principles accommodate "everyone" from the outset, they tend to suffer from the limitations of a "one-size-fits-all" conception.

Common computing strategies for accommodating aging and clinical populations suffer their own shortcomings. While homes and assistive residences outfitted with "ubiquitous" computing (e.g. sensor networks, camera networks, and RFID tagging) can detect crisis, can support tasks like taking medication, and promise peace-of-mind to caregivers, the "Smart Home" approach has a range of difficulties (as considered in [1]): its technology is distributed most everywhere, whether desired or useful; its inhabitants intervene with the technology; and its systems suffer from accidental mishaps and are not sufficiently sensitive to individual differences – particularly, the need for privacy. As for the possibility of an in-home, humanoid service robot, data suggests that people fundamentally want a service robot to compensate for their reduced capacities; independent of whether the robot looks or acts particularly human [6]. And while KAIST's "Intelligent Sweet Home" shares our vision of embedding robotics in the home, the only robotic component receiving significant attention, to our knowledge, is a hoist for transferring users to/from bed [19]. Moreover, towards realizing an ecosystem responsive to the challenges and opportunities of our increasingly digital society, the domains of architectural design, computing and robotics have not yet been made to function cooperatively.

These shortcoming motivated the *Assistive, Robotic Table* (ART), the key component of our *home*+ suite [22] of networked, distributed, "architectural-robotic" furnishings, envisioned for domestic environments (for aging in place) and healthcare facilities (for clinical care). ART and home+


*CHI 2014,* April 26 - May 01 2014, Toronto, ON, Canada
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http://dx.doi.org/10.1145/2556288.2557333

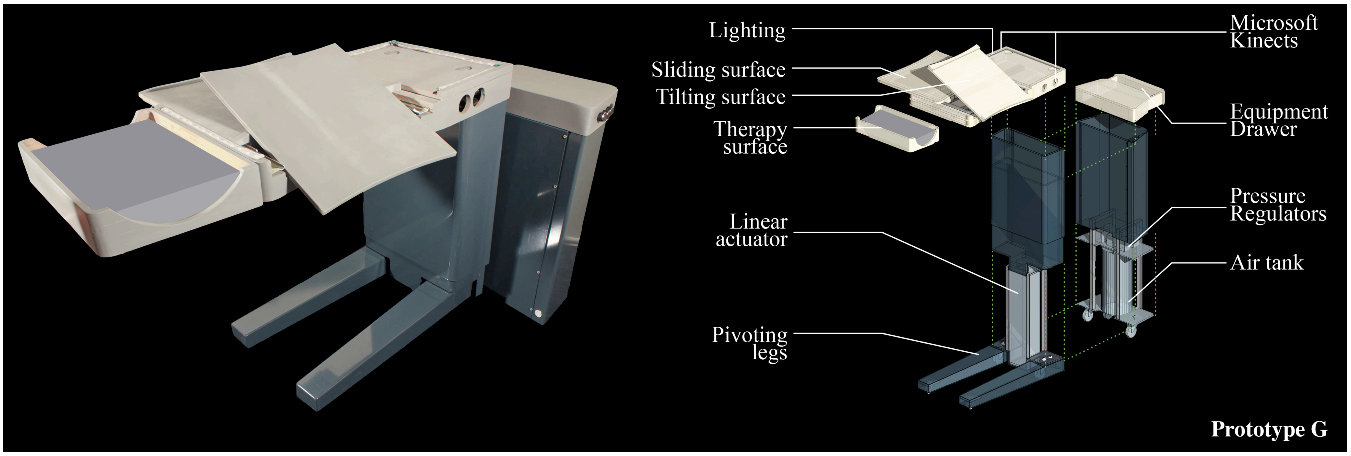



**Figure 1: The Assistive Robotic Table (Prototype G) and an architectural drawing of its components.**

benefit from the convergence of advanced architectural design, computing and robotics largely absent from prior efforts. In particular, this enabling technology is not distributed everywhere in the physical environment but *where it's needed*; is not intended to be invisible but *visible* by design *and, moreover, attractive and integral* to the home; and is not employed for surveillance but rather as *environmental support* that recognizes and dignifies what people can do for themselves.

These attributes of ART and home+ are of a kind identified by Donald A. Norman as "the next UI breakthrough," defined as "physicality," and accomplished with "microprocessors, motors, actuators, and a rich assortment of sensors, transducers, and communication devices" [18]. In broad theoretical terms, ART and the home+ project were anticipated in the 1970s by Nicholas Negroponte in his vision of "intelligent environments" and, in particular, a responsive "domestic ecosystem" which regulates aspects of "communications, … environmental comfort and medical care" [17]. Recent inspirations for ART include William Mitchell's vision that "our buildings will become…robots for living in" [12], and Malcolm McCullough's plea for "architecturally situated interaction," which "permit the elderly to 'age in place' in their own homes" [10].

## ART AND ITS KEY COMPONENTS

We envision ART integrated into the domestic routines of its users, even as users transition from home to clinic and hopefully home again. Our research team, drawn from Architecture, Robotics, Human Factors Psychology and Medicine, hypothesizes that users employing ART as part of their domestic landscape will live independently, longer. Moreover, ART frees familial caregivers from performing certain arduous tasks for ART's target populations, allowing caregivers to devote more energies to meaningful, human interaction with ART's users. In the clinic, ART aims to augment the rehabilitation environment by improving patient well-being, rehabilitation, and staff productivity (in this trying moment of limited resources).

Physically, ART is a significant development of the over-the-bed table (OBT) universally found in hospital patient rooms. What distinguishes ART from the conventional OBT is its novel integration of physical design and functioning, coupled with a smart, human-object interface (as we present in [25]). Integral to ART is a novel, plug-in, continuum-robotic therapy surface (figures 1 and 3) that helps patients perform upper-extremity therapy exercises of the wrist and hand, with or without the presence of the clinician. Moreover, the components comprising ART, like ART and its companion components of home+, recognize and communicate with each other in interaction with human users as an ecosystem, we envision, of *bits, bytes and biology*.

With respect to robotics, ART, on one hand, offers two degrees of freedom, raising and lowering from its base, and tilting its work surface; on the other hand, the novel therapy surface at the extreme tip of ART offers theoretically infinite degrees of freedom, given its continuum (compliant) surface, actuated by twelve pneumatic muscles. The material composition of the therapy surface was fabricated to our performance specifications as a "spacer fabric," engineered from woven polyester fibers to induce maximum surface curvature while providing stability for the rehabilitating arm of its users, while also decreasing lateral compression (as elaborated in our technical paper [11]).

While our research team envisions ART working productively for those aging in place at home, the team felt strongly that developing ART within a clinical environment would subject this assistive, cyber-physical artifact to the urgent demands of critical care, providing the research team a wealth of insights toward making the most promising prototype. In consultation with our partners at the *Greenville Health System*, we designed and evaluated ART for post-stroke patients and their clinical caregivers within the *Roger C. Peace Rehabilitation Hospital* ("RCP"), as post-stroke patients, in many instances, present physical and cognitive deficits that are apt and challenging to our design pursuit.

More specifically, the objective of our iterative design-and-evaluation activities for ART was to develop an assistive table that, when evaluated by clinicians and post-stroke patients, was an improvement (by subjective scales) over the current OBT typically used in rehabilitation hospitals. This objective follows from numerous preparatory research activities we conducted within RCP aimed at understanding the contents of patient room furniture [4], understanding clinicians' preferences for current OBTs [7], designing and evaluating a new, smart nightstand as part of home+ [5, 20], understanding how healthcare practitioners use OBTs [8], and validating healthcare practitioner's requirements for an interactive, assistive-robotic table [9].

## A SCENARIO IN BRIEF

Amy had a stroke and has right hemiplegia (paralysis of the right extremities) and aphasia (speech and language problems). After treatment in the hospital, Amy returned home, fitted with home+, the same suite of robotic-embedded furnishings that supported her in her patient room. Home+ has uploaded Amy's preferences learned from her hospital stay, and modifies these preferences and those of her caregivers over time to best support Amy's recovery. Amy depends on home+'s Assistive Robotic Table every day: the continuum surface of ART helps Amy rehabilitate her arm, ART tilts and changes height to best accommodate Amy's activities, ART's non-verbal lighting cues remind Amy to take her medications, ART learns and adapts to Amy's gesturing as she gains more movement in her arm (as we elaborate in [25]), ART logs Amy's reading time as a wellness metric, and ART initiates storage of Amy's reading glasses when she's finished reading. These functions and others help Amy improve more quickly. ART's components recognize and partly remember, communicate with, and cooperate with human users and the other components of home+, empowering Amy to remain in her home for as long as possible, even as her physical capabilities alter over time; and, in more grave circumstances, affording Amy some semblance of feeling "at home" as she moves to an assisted facility with home+.

## POST-STROKE PATIENTS

"In the United States, stroke is the fourth leading cause of death, killing over 133,000 people each year, and a leading cause of serious, long-term adult disability" [13]. In the southeastern United States (where our field evaluations were conducted), the percentage of people affected by stroke is increasingly higher than in other regions due to tendencies for higher blood pressure, smoking, and poor diet [16]. After a patient suffers a stroke, the rehabilitation that follows is critical to the future wellbeing of the stroke patient, often requiring intense and direct interaction between patient and therapist. Stroke survivors often suffer from cognitive deficits (short-term memory loss, dementia, or aphasia) and/or impairments (visual field cuts or hemiparesis) that sometimes require lifelong medical intervention. Due to the escalating cost of healthcare and shortage of healthcare providers, post-stroke patients are often resigned to performing rehabilitation exercises at home, alone [14, 16].

Cognitively, aphasic patients (i.e. those with brain damage in areas controlling language) may lose their "ability to communicate orally, through signs, or in writing" [21]. Physically, hemiplegic (i.e. paralyzed) patients may be inattentive to their upper extremities as they have "weakness or the inability to move one side of the body" [15]. Rehabilitating the affected limb of the hemiplegic patient often requires the retraining of fine motor skills demanded of daily routines, which is more nuanced than the gait-training rehabilitation of gross motor movement. To further complicate the rehabilitation of some post-stroke patients, a narrowing of the visual field reduces peripheral vision. Rehabilitation methods include exterior sensory stimulation or other visual or auditory feedback strategies with increased intensity and difficulty in an attempt to increase the patient's awareness for the neglect in vision and limb [13].

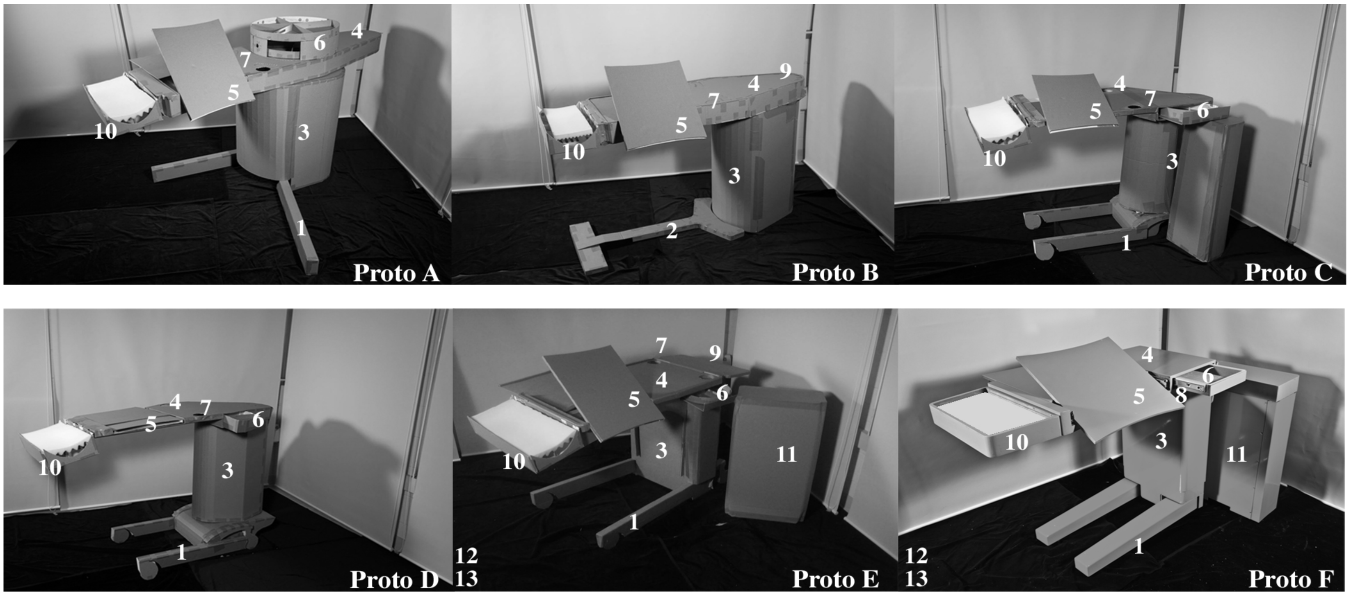
We envision ART providing the stroke patient a companionable and therapeutic aid beginning in those early rehabilitation hours following the stroke event. As effective post-stroke rehabilitation must occur following the stroke, and must continue during the weeks and years that follow, stroke patients require technologies that are adaptable to patient needs, increasing and decreasing assistance to patients as required. Because the design and evaluation of a cyber-physical system like ART is complex, medical staff regularly treating post-stroke patients, rather than the patients themselves, are more apt participants in the early phases of development. To ensure the overall success of ART, future studies must seek input from post-stroke patients. As will be elaborated in this paper, the variety of personas and the subjective scales used to evaluate the features of ART, including its therapy surface, helped to demonstrate ART's versatility with post-stroke patients of various capabilities.

## PROCESS: FIVE ITERATIVE PHASES OF RESEARCH

In developing the full-scale, fully functioning ART, the research team conducted five iterative phases of research:

PHASE-1: *Needs Assessment*
PHASE-2: *Confirmation of Clinician Needs*
PHASE-3: *Iterative Design/ Prototyping* [Prototypes A-D]
PHASE-4: *Formative Evaluation with Medium- and High Fidelity Prototypes* [Prototypes E and F]
PHASE-5: *Summative Analysis* [Prototype G]

This paper presents the full arc of our participatory design process, briefly presenting Phases 1-4 as context for focusing on results from the summative analysis of Phase 5. All research activities, unless otherwise noted, occurred at our purpose-built *home+ lab* within RCP.




1. Adjustable Legs
2. Static Legs
3. Column/Base
4. Tabletop
5. Flip-up Surface
6. Storage Component
7. Cup Holders
8. Table Controls
9. Lip on Tabletop Surface
10. Therapy Surface
11. Mechanical Column
12. Level Tabletop
13. Shape of Tabletop Surface

**Figure 2: The Assistive Robotic Table design and cardboard prototypes and its components.**

#### PHASE-1: Needs Assessment

During PHASE-1, the research team observed how occupational, speech, and physical therapists work with patients, and how the clinicians used the current over-the-bed table (OBT) in the acute care setting at RCP. The research team learned that OBTs are not used by all clinical disciplines; but occupational therapists typically use OBTs when conducting "activities of daily living" therapy (ADLs) with patients. As the patient population at RCP typically has a high number of post-stroke patients, and as such patients partake in therapies employing OBTs, the post-stroke population was an apt target for our research. It should be noted, from the outset, that the ART research has yet to involve direct participation by post-stroke patients but has involved, instead, their clinical caregivers, assuming their roles as clinical caregiver as well as the roles of their patients as defined by "personas." Post-stroke patient are suffering too many deficits and recovery challenges to interact with ART, a complex cyber-physical machine of considerable size and weight, in its relatively early stages of development in the long course to full implementation. Following our observation task, the research team consequently conducted structured interviews with role-playing clinicians in a mock-up hospital room to determine "how and why" OBTs are used in clinical caregiving tasks primarily by occupational and speech therapists.

Generally in the clinical setting, conventional OBTs in patient rooms are an issue for patients and clinicians alike because they are difficult to maneuver and prone to break. (We quickly learned these shortcomings of the OBT by using one in our university lab). Nevertheless, the OBT serves an essential role for patients during mealtimes and when patients, alone in their rooms, need to access and store items close to their beds [8].

#### PHASE-2: Confirmation of clinician needs

During PHASE-2, clinicians and the research team completed a card sorting activity: to understand the clinician's view on issues related to OBTs; to understand the research team's view on what constitutes a better designed, interactive OBT (e.g. an assistive-robotic table); and to identify areas of compatibility between the view of the clinicians and the view of the research team [9].

Both the clinicians and the research team rated three items "high research aims": Item 1 – *ART must be capable of bracing a patient's weak arm during therapy-strengthening of the strong arm and core*; Item 2 – *The therapy surface for ART must provide programmable visual cues to stimulate awareness on the neglected side of patients suffering hemiplegia*; and Item 3 – *All unit controls of ART must be easy to use for one person, using one hand of limited dexterity* [9].

Additionally in PHASE-2, the research team observed occupational therapists in the inpatient and outpatient rehabilitation settings. The team observed how occupational therapists interact with patients, identified the therapy tools used primarily for fine motor control by therapists, and determined measurements for patient improvement such as the Fugel-Meyer scale [11, 22]. Combined with the card-sorting activity, the research team was able to narrow the focus of ART research to areas deemed most successful by both clinicians and team.

**PHASE-3: Iterative design/prototyping [Prototypes A-D]**
During PHASE-3, clinicians completed a Modified Delphi with conceptual sketches of ART's key components [9]. The clinicians rated as their top requirements for ART: a tilting surface, a therapy surface that maintains an optimal position during therapy; a table that is stable and locks during patient use; and a more stable and reliable raising-and- lowering mechanism.

In the same phase, clinicians rated what they judged to be the most favorable design concept for ART and its therapy surface from a range of further, alternative design concepts towards focusing further the design of ART. Given the prospect of a new assistive technology that might impinge on clinical practice, clinicians not-surprisingly reported a preference for the therapy surface being used exclusively in a therapy room with a clinician present, and not at home, by a patient unassisted. As for the therapy surface, clinicians agreed that it was productive for elbow and wrist flexion and extension rehabilitation.

In PHASE-3, the research team also evaluated its then-most-current, lower-fidelity, ART prototypes with a patient bed within a patient room at RCP (see figure 2 – "Proto A"). The primary objective of this activity was to gain a better understanding of several fundamental aspects of the interactive furniture in the patient room: the constraints that a bed places on ART, such as the floor area required for ART and the bed together; the height of ART necessary from a bed-ridden patient's perspective; the amount of space available to the patient on the work-surface of ART; the maneuverability of ART by the patient when bed-ridden; and the storage options provided by ART.

Finally as part of PHASE-3, clinicians evaluated two pairs of prototypes, with one design iteration between them (figure 2 – "Proto A-D"). Initially, clinicians evaluated ART cardboard Prototypes A and B. Subsequently, the design team redesigned ART based on the evaluations, and clinicians then evaluated ART cardboard Prototypes C and D. The clinicians provided valuable insights for the overall ART design, such as: the appropriate size for the mechanical column, the correct interaction of the patient with ART's tilting surface, and how ART might be mechanically controlled. The researchers also learned that the therapy surface: should be used in conjunction with a patient seated in a wheelchair, should adjust to patient's movement, should account for a patient's inattention, and should *not* be utilized to manipulate the patient's shoulder.

**PHASE-4: Formative evaluation with medium- and high-fidelity prototypes [Prototypes E and F]**
Initially in PHASE-4, clinicians evaluated features of a medium-fidelity, cardboard ART Prototype "E" as well as a therapy-surface prototype (figure 2 – "Proto E"). Clinicians used low, medium, and high-functioning stroke patient personas to aid in their evaluations (see Table 1). Because the characteristics of the stroke patient population are so broad, the goal of the personas was to capture a breadth of

| Patient Persona | Description |
|---|---|
| **Low-Functioning Patient** | Ted is a 71-year-old male with hypertension, admitted one week ago after suffering a severe ischemic stroke. Ted has no movement in his left arm, and he has "tunnel vision." |
| **Medium-Functioning Patient** | Ginny is a 64-year-old female with diabetes, admitted two weeks ago after suffering an ischemic stroke. She has no fine motor control in her right arm, and she forgets recent events. |
| **High-Functioning Patient** | Bob is a 52-year-old male with a family history of hypertension, admitted one week ago after suffering a mild ischemic stroke. He lacks full fine motor control. |

**Table 1. Patient personas used during the formative evaluation phase.**

patient characteristics to be used by the clinicians to evaluate ART. It was intended that all patient types, despite their cognitive or physical limitations, could make productive use of ART. For each feature of cardboard Prototype-E, clinicians offered their ratings of *likes* (4.39/5.0), *needs* (4.18/5.0) and *thoughts about ease of use* (4.18/5.0), as well as any anticipated problems. It was revealed, for one, that low-functioning patients might require the assistance of clinicians or family members to maneuver the ART prototype presented in this phase, while high-functioning patients would require little to any help maneuvering it. In addition, the research team gained an understanding that the therapy surface: would be used with clinician supervision; would require an arm restraint; should afford additional arm movements (i.e. supination and pronation); and should record clinical data of the rehabilitation process (i.e. degrees of movement, ranges of motion, and forces applied by the patient).

Later in PHASE-4, a higher-fidelity ART Prototype "F" responsive to our earlier activities and findings was presented to clinicians for their evaluation (figure 2 – "Proto F"). Additionally, four re*search-and-design subject matter experts* (RD-SMEs) completed a heuristic evaluation. The research team captured clinicians' *likes* (3.32/5.0), *needs* (2.83/5.0) and *thoughts about ease of use* (4.01/5.0) for each feature of this ART prototype. Furthermore, the research team learned the clinicians' *likes* (4.14/5.0), *needs* (4.14/5.0), and *thoughts about ease of use* (3.79/5.0), and also learned about any anticipated problems for each of the features for ART. Additionally, the research team learned: whether the clinicians would use the designed therapy surface (with mixed results); if the therapy surface provided enough variability (82% stated it did); and if the therapy surface would improve therapy sessions (73% stated it did).

**Figure 3. The Assistive Robotic Table in the patient room at RCP. Here, a therapist is simulating therapy with a patient.**

The research team, based on the expertise of research-and-design subject-matter experts, learned how the key ART features violated heuristics for assistive robotics, as developed by Tsui, Abu-Zahra, Casipe, M'Sadoques and Drury (see [24]).

The features that violated the most heuristics included: the adjustable legs (9), therapy surface (8), flip-up surface (5), and table controls (5). The statements fell into four main categories: *ensuring safety*, *decision making*, *supporting flexibility*, and *preventing errors*. By using the heuristic evaluation inspection method, research-and-design subject-matter experts found feature areas not addressed by our clinical healthcare subject matter experts (i.e. issues of safety, user interaction, and error prevention) to improve in successive prototypes over the iterative design and evaluation process.

## PHASE-5: SUMMATIVE ANALYSIS – PROTOTYPE "G"

PHASES 1-4 of our research arc informed the revision, fabrication, and evaluation *in-situ* of ART as a high-fidelity, fully-functioning Prototype "G" (figure 1), fabricated digitally in lightweight steel and wood.

## PHASE-5 METHODS

### Participants

Eleven healthcare subject matter experts (H-SMEs) from the RCP rehabilitation hospital, including doctors and occupational and physical therapists, participated in this study. In the interest of protecting the privacy of this small exploratory sample population, and based upon the conditions of approval for this study-design by the RCP's institutional review board, demographic data for these participants cannot be presented here.

### Procedure

The study was conducted in a patient room at RCP. This double-occupancy RCP patient room includes two patient beds, four chairs, two nightstands, and two over-the-bed tables (see figure 3). Present for each study session was a research moderator, a recorder, and the individual participant. Approval from the appropriate institutional review boards was obtained prior to data collection.

Prior to the start of the experimental session, the research moderator welcomed the H-SMEs, handed out an information sheet describing the purpose of the study, asked each participant to review it, and answered any questions the participant had about the study.

To begin the study, the moderator introduced the three-part study to the participant. For Part-1 of the study, the H-SME maneuvered ART Prototype "G" (figure 1) around the bed, and he or she evaluated the interaction. In Part-2, the H-SME maneuvered ART around a patient chair, and he or she evaluated the interaction. Finally, for Part-3, the H-SMEs evaluated ART and its individual components as singular entities. Before beginning Part-1, and to simulate a "real world" condition, ART Prototype "G" was positioned against the wall, at the foot of the bed, at its lowest operable height. Additionally, the moderator gave the H-SME a printed sheet with the medium-functioning post-stroke patient persona. The moderator had the H-SME read the patient persona description before beginning Part-1.

Initially, the H-SME maneuvered ART from against the wall over to the patient bed. This required the H-SME to roll ART to the bed, press the "up" button to raise ART to the correct height, open the adjustable legs to maneuver ART around the bed's control box, and finally position ART over the bed. Once ART was positioned over the bed, the moderator asked the participant to maneuver the Flip-up surface into the correct position for a patient to read a book. The H-SME manually pushed-back the table covering the Flip-up surface, and manually positioned the Flip-up surface in-place. After completion of this task, the participant provided his or her thoughts about positioning ART around the bed and completed a System Usability Scale (SUS) scale [3].

After completion of the SUS scale, the moderator asked the H-SME to maneuver ART in front of a patient chair to conduct therapy on the patient's left-upper extremity. The moderator also asked the H-SME to maneuver the plug-in components in-place to conduct therapy. After completion of this task, the participant provided his or her thoughts about positioning ART around the chair for therapy, and completed an SUS scale.

After completion of the SUS scale, the moderator asked the H-SME to maneuver ART and the plug-in components back to their original starting position. Next, the H-SME evaluated ART and its components based on the medium-functioning patient persona using three 5-point Likert scales for LIKE, NEED, and EASY TO USE (as we developed for [20]) to triangulate the desirability and usability of each feature. Finally, the H-SME evaluated ART using Travis' *Measuring satisfaction* [23] based on the Benedek and Miner *Desirability Toolkit* [2]. Here, the H-SME selected all the words that he or she felt described ART, then narrowed that list to his or her top-five choice words, and finally, used each word in a sentence.

At the end of each session, the moderator answered any questions the participants had about the session, asked the participants not to speak about the session with their colleagues (who might participate in future sessions), and thanked the participants for their participation.

## PHASE-5 RESULTS

After completing part-1 of the experimental session with H-SMEs, focused around the bed, the participants completed an SUS. Results suggested that ART Prototype "G" should be further improved before it can be used around the bed (truncated M=44.58, SD=13.17). Nine participants reported that they had difficulties maneuvering ART around the bed due to the wheels not rolling correctly. One H-SME specified that "[ART] needs to roll way easier if someone is pushing it. I literally sling the current [over-the-bed table we use at RCP] around the room." Three participants reported that ART felt too heavy in weight to maneuver it easily. Two participants revealed that they appreciated the ability to swivel ART's legs to an open or closed position to help maneuver ART around objects. One H-SME wanted the leg adjustments to have more resistance (friction). Finally, two participants recognized table controls (i.e. the up/down and tilt up/tilt down buttons) as much improved. As one H-SME expressed, "The button is vastly superior to the [previous] lever because people have different strengths and use different forces."

After completing Part-2 of the experimental session, focused around the chair to simulate a therapy session, H-SME participants completed the SUS. Results suggested that ART needed to be improved before it can be used around the chair for therapy (truncated M=36.25, SD=17.73). Similar to the bed scenario, eight participants mentioned that they had difficulties maneuvering ART around the patient's chair to conduct therapy. One H-SME stated, "[ART] needs to slide back [e.g. roll across the floor more easily]. At this point in the game, I'm moving my patient to the table because [patients] are easier to move [than ART]. […] Whatever casters or wheels on the bottom need to be able to swivel or turn more."

More positively, five participants referenced the easy positioning of ART for conducting therapy session. One H-SME said, "I'm able to get a good position for the patient – where I need them to be [for me] to work on the arm." Three participants positively reported the added functionality provided by the therapy surface plug-in component. Two participants positively mentioned the improved, mechanized up-and-down capabilities of ART. Finally, two participants discussed their use of the plug-in components. As one H-SME reported, "It was pretty simple, as far as putting all the pieces together and putting it where it needed to be." However, one H-SME stated, "The only thing about rolling [ART about the patient room] is that there are a lot of things in the way – telephone cords and such."

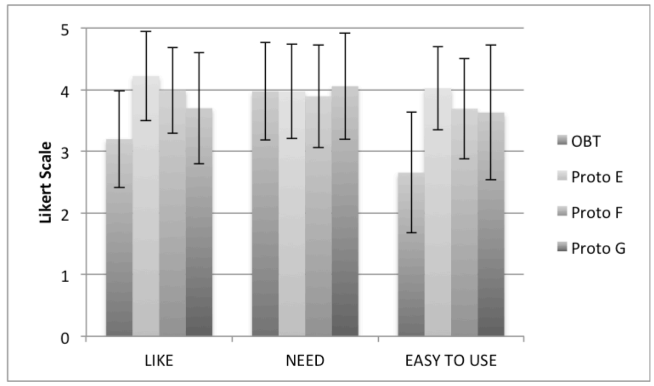



**Figure 4. Comparison mean ratings (1 strongly negative – 5 strongly positive scale with anchors) for the over-the-bed table (OBT), Prototype E, Prototype F, and Prototype G.**

At the close of the experimental session, participants rated ART Prototype "G" by using rating scales for LIKE, NEED, and EASY TO USE. As shown in Figure 4, Prototype "G" rated considerably higher in LIKE and EASY TO USE as compared to the current over-the-bed table routinely used at RCP.

A comparison of the individual components of ART Prototype "G" to our earlier, high-fidelity prototype "F" shows the Up/Down mechanism was rated higher in all three categories. Also for Prototype "G," its table controls and its surface shape (i.e. physical form) were rated higher for EASY TO USE when compared to those of Prototype "F". As well, the Flip-up surface and Adjustable legs for Prototype "G" were rated higher for NEED as compared to the same of Prototype "F". However, the Therapy surface and Mechanical column of Prototype "G" rated lower in all three categories as compared to those of Prototype "F". (See Figure 5 for all results for the individual components of Prototype "F" as compared to the same of Prototype "F".)

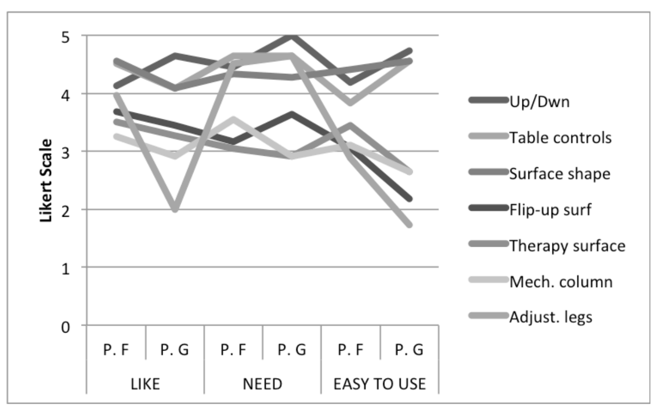



**Figure 5. Comparison mean ratings (1 strongly negative – 5 strongly positive scale with anchors) between Prototype F (P. F) and Prototype G (P. G) for each ART component.**

In the final evaluation of ART Prototype "G" using Travis' *Measuring satisfaction* metric [23], 37 unique words were chosen by participants to describe it. Eleven words chosen more than once by participants included: *hard to use* (5), *awkward* (3), *complex* (3), *unrefined* (3), *useful* (3), *difficult* (2), *frustrating* (2), *innovative* (2), *responsive* (2), *time-consuming* (2), and *usable* (2). A summation of all the words shows that negative words were used 32 times while positive words were used 24 times. When analyzing the entire list of words chosen to describe ART Prototype "G", six participants chose positive words to describe it while five participants chose negative words to describe it. However, when asked to pick the five most important words to describe ART Prototype "G", four H-SMEs chose a majority of positive words to describe it, and seven H-SMEs chose a majority of negative words to describe ART Prototype "G".

A further analysis of these results shows that 16 words focused on **maneuverability,** including *hard to use* (5), *awkward* (3), and one each for *annoying*, *difficult*, *frustrating*, *inconsistent*, *overwhelming*, *rigid*, *slow*, and *time consuming*. One H-SME stated "[ART was] hard to use in a small confined space."

Additionally, nine words chosen by participants referenced the **general use** of Prototype "G", including *creative*, *easy to use*, *innovative*, *illogical*, *meaningfu*l, *non-standard*, *relevant*, *understandable*, and *useful*. One H-SME offered that "[ART] addresses needs that have not [yet previously] been addressed." Another H-SME reported that "[ART] allows the therapist to do much more in a [rehabilitation] setting than we were able to do."

Also, seven words pertained to the **added functionality** ART Prototype "G" provided, including *usable* (2), and one each for *advance*, *complex*, *comprehensive*, *effective*, *useful*, and *difficult*. One H-SME offered, "ART is too technical, too advanced for the basic uses of a bedside table – [it is too] large and cumbersome." Another H-SME stated: "[ART] is effective. […] It does what you need it to do."

Six words chosen by participants referenced the **design** of ART Prototype "G": *cutting-edge*, *exciting*, *professional*, *straightforward*, *innovative*, and *useful*. One H-SME stated, "The ideas and technologies – modifying the [table] – are exciting." Another H-SME stated, "Simple. The design is similar to what we use, so it's easy to adapt to it." Finally, one H-SME stated that ART Prototype "G" represents "a new design … that will take us into the next century." However, five words chosen by participants refer to the **need for a more refined prototype**, including the words *unrefined* (3), *faulty*, and *unpredictable*. One H-SME stated, "The whole [of Prototype "G"] felt not quite there yet."

Finally, three words were associated with the **positioning** of ART Prototype "G", including *convenient*, *responsive*, and *time consuming*. As one H-SME stated, "[ART] is responsive to the anticipated task of positioning the table." However, another H-SME challenged, "Try to adjust the table to move – to adjust the [patient's] arm [efficiently]."

## DISCUSSION

This paper presented motivations for an Assistive Robotic Table (ART), a next generation, assistive, cyber-physical artifact, and presented five phases of iterative design and evaluation outcomes.

Throughout the five phases of our investigation, the research team sought to understand clinician and perceived patient usability issues associated with our development of an assistive robotic table in the context of stroke patients and their clinical staff in a rehabilitation hospital patient room, both around a bed and while conducting therapy in a chair. Participants' comments and SUS ratings provided evidence that a more refined prototype is needed. However, Figure 4 showed that ART was subjectively rated higher than the current OBT. Additionally, the study methodology employed in our investigation provided the research team with a broadened understanding for the successes of ART. *Measuring Satisfaction* [23] metric identified aspects where ART required refinement, but also characterized ART as innovative — overall, and in its features (its adjustable legs, flip-up surface, and therapy surface).

Elaborated most fully in this paper is PHASE-5 of our research, conducted in three parts (within a hospital room, around the patient's bed, and around the patient's chair) in the context of a clinical session involving rehabilitation therapy. Healthcare subject matter experts (H-SMEs), including doctors and occupational and physical therapists, maneuvered ART around the bed, around the patient's chair, and evaluated each interaction. The H-SMEs also evaluated ART and its individual components by using 5-point Likert scales for LIKE, NEED, and EASY-TO-USE, and by employing the Travis' *Measuring satisfaction* metric [23]. On the negative side, results of our studies revealed frustrations about the maneuverability of ART Prototype "G", as evidenced by the overall lower ratings for LIKE, NEED, and EASY TO USE, the low SUS evaluation scores, and the choice of *unrefined* to describe it. Furthermore, two comments in particular illustrate this point: "It needs to roll way easier if someone is pushing it" and "It was hard to use in a small confined space." On the positive side, results of our studies suggest that the added functionality afforded by ART was perceived as mostly successful, particularly with respect to the clinician's ability to adjust the legs, the improved table controls, and the functionality of the therapy surface in supporting clinical sessions involving rehabilitation.

## FUTURE WORK

We have three specific aims for furthering ART (potentially in collaboration with an industry partner):

First: Improve the maneuverability of ART, and evaluate the prototype in the rehabilitation setting again. This would allow users to address aspects of ART beyond maneuverability, which became the preoccupation of participants responding to our current prototype.

Second: Invite patients with various physical and cognitive challenges to serve as participants in future evaluation activities. This would ensure that ART accommodates wide-ranging needs.

Third: Evaluate ART in domestic settings, focusing on longitudinal studies. Indeed, ART may prove more successful at home and in assisted living settings, given the constraints and complexities of clinical settings.

## FIVE LESSONS LEARNED

Our research arc provides insights for multi-disciplinary design teams who, inevitably, for an increasingly digital society, will be charged with designing future cyber-physical artifacts at larger scale, aimed at supporting and augmenting our daily lives. We identify five key lessons drawn from the investigation reported here.

First: Design teams developing cyber-physical artifacts as complex as ART must ensure that later phases of iterative testing of the artifact occur within its most challenging, targeted environment prior to conducting a final evaluation. Due to hospital restrictions, our research team did not have access to patient rooms during the high-fidelity evaluation of PHASE-4; issues of maneuverability identified in PHASE-5 might otherwise have been identified prior to conducting the final test.

Second: Towards realizing the most promising artifact, experimental conditions should be maintained throughout the iterative phases of design and evaluation (as we did in our investigation), ensuring that all participants encounter the same contextual stimuli. While this point might seem pedestrian, our practice differs somewhat from more typical usability testing methods, where major issues might be corrected between participant sessions.

Third: Design team members who may be new to the processes of user-centered design methods widely used in HCI need to ensure that their artifacts adequately address basic needs (such as maneuverability), even when seeking to provide advances in technology and the interactions these technologies afford (for ART, e.g. its up/down/tilting positioning, its table controls, and foremost, its novel compliant "therapy surface" component as elaborated in [11]).

Fourth: Design teams developing assistive technologies for, in particular, healthcare and home should develop technologies that grow and adapt with the user, as user needs may change unexpectedly in clinical settings, and will inevitably change at home over time.

Fifth: Design teams of cyber-physical artifacts for healthcare must design user experiences that promise patients and their caregivers minimal complications as they come to adopt them.

## CONCLUSION

While somewhat mixed, the outcomes of our five phases of investigation were overall promising, and yielded important lessons as our communities – design, computing, and psychology – come to develop complex, cyber-physical artifacts supporting everyday activities. Arguably, in terms of demonstrable results, ART might have proven more successful had we confined our evaluations to the domestic environment, supporting users aging in place, rather than subjecting ART to the clinical setting and those with cognitive and physical deficits. In any case, our team made a commitment early-on to develop ART for the demands of critical care – to accept the challenge of creating interactive furniture for this most difficult condition.

For the larger CHI community, ART is a design exemplar characterized by Christopher Frayling as *research through design* in which designers, "addressing under-constrained problems," develop a novel artifact through a careful and communicated process of design [26]. "What is unique to this approach to… research is that it stresses design artifacts as outcomes that can transform the world from its current state to a preferred state" [26]. Repeatedly throughout our study, our research team received evidence of this promise of design from participating clinical staff. Among the more poignant remarks made by clinicians:

• "[ART] allows the therapist to do much more in a [rehabilitation] setting than we were able to do."

• "The ideas and technologies [of ART are] exciting."

• "[ART] will take us into the next century."

Such comments, offered by the clinical staff of a large university medical center, suggest a bright future for designers designing complex, larger-scale, cyber-physical artifacts like ART and the home+ suite to which it belongs. Inevitably, cyber-physical artifacts at larger scale will be an integral part of our everyday lives; but no matter whether they co-habit our clinical settings, workplaces, schools or homes, public spaces or transportation systems, cyber-physical artifacts like ART must be made attractive, intuitive, integral with human users of wide-ranging capabilities and interests, and adaptable as vehicles for human-computer interaction.

## ACKNOWLEDGMENTS

The U.S. National Science Foundation under award IIS SHB-116075 supported this research. The ART research team wishes to thank the clinical and facilities staff at the *Roger C. Peace Rehabilitation Hospital* of the *Greenville Health System*.

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