Usability Testing of a Developed Assistive Robotic System with Virtual Assistance for Individuals with Cerebral Palsy: A Case Study

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Abstract

This paper presents a novel application of an assistive robotic system with virtual assistance to enhance manual performance of individuals with cerebral palsy. Cerebral palsy affects one's voluntary motor movements resulting in limited opportunities to actively engage in physical manipulative activities that require fine motor movements and coordination. Lack of object manipulation and environmental exploration can result in further impairments such as cognitive and social delays. The proposed assistive robotic system has been developed to enhance hand movements of people with disabilities when performing a functional task- colouring. This paper presents the usability testing of the effectiveness of the developed system with an individual with cerebral palsy in a set of colouring tasks. Assisted and unassisted approaches were compared and analysed through quantitative and qualitative measures. The robotic-based approach was further compared with the participant's typical alternate access method to perform the same proposed tasks. The robotic system with virtual assistance was clinically validated to be significantly more effective, compared to both unassisted and typical approaches, by increasing the hand controllability, reducing the physical load and increasing the easiness of maintaining movements within the lines. Future studies will inform the use of the system for children with disabilities to provide them with assisted play for functional and playful activities.

Keywords:

Robotic system, virtual assistance, people with disabilities, cerebral palsy, and manual activities

Introduction

Cerebral palsy (CP) is associated with a group of permanent and non-progressive neurological sensorimotor impairments as a result of a brain damage prior, during or after birth [1]. Brain injuries can break the pathway between the sensory and motor systems, resulting in deficits in the sensory modalities including touch, vision and hearing. Individuals with CP have shown impairments in the detection touch feedback [2, 3]. CP primarily affects motor performance and is sometimes accompanied by other developmental disorders including cognitive, perceptual, and communicative deficits. Oftentimes, a diagnosis of CP is suspected if a child does not reach the motor developmental milestones such as reaching, grasping and crawling. Depending on the nature of motor abnormalities, CP has been classified into spastic, dyskinetic, and ataxic conditions. Spastic CP is the most commonly occurring condition, and is caused by damage to the motor cortex, which controls voluntary movements. Spasticity is characterized by stiff, tight, and hypertonic muscles resulting in reduced coordination and fine motor skills. Dyskinetic CP happens when basal ganglia, the balance control center, is damaged. It is characterized by involuntary, repetitive and hypotonic muscle tone. Ataxic CP refers to the unsteady, shaky movements due to damage to the cerebellum. Ataxia affects fine motor activities, coordination and balance control. Mixed CP refers to a condition in which an individual presents a combination of the abovementioned motor disorders. Overall, CP can significantly affect individuals' abilities for active object manipulation and environmental exploration and reduce their abilities in performing functional manual activities.

Coloring is a functional manual activity that requires interaction with the play environment (e.g. the coloring surface). It is generally advantageous in enhancing one's eye-hand coordination, focused attention and imagination, fine motor skills, and artistic thoughts [4, 5]. It begins with scribbling in toddlers and later, the obtained skills are used toward making meaningful symbols [4], and using writing tools through a rewarding and pleasurable experience [6]. The *circle* and *oval*, and later, the *square* and *rectangle* are generally the first four basic forms children scribble or draw [5], and are related to the next stages of writing and art. They initially develop when the child recognizes them in his scribbles and then, tries to repeat them. In the same way, writing is believed to usually start with imitating simple geometric shapes such as circles and squares [7]. Thus, provision of access to coloring the basic shapes can potentially reinforce children's learning of geometric shapes, drawing, and writing letters.

People with CP may lack the required skills for purposeful scribbling and coloring due to their fine motor deficits, such as hand tremor, spasm, or coordination difficulties. They may cross the borders, color a large area outside the picture instead of the desired picture. Failing to perform the task successfully or desirably could result in frustration, disappointment and reduced sense of self-efficacy. Self-efficacy (or self-perception of ability) is defined as "beliefs in one's capabilities to mobilize the motivation, cognitive resources, and courses of action needed to meet given situational demands" [8]. In other words, it describes how one perceives his/her ability to succeed in a task and is strongly linked to previous experiences, which can influence future performance.

Assistive technology can be used by people with disabilities to give them access to the coloring activity in a computer-based program [9]. Various computer control interfaces such as mini-joysticks, adapted mice or keyboards can provide access to computer applications for individuals with disabilities [9]. The type of interface used will depend on a person's abilities, desired tasks and preferences, and the interface may not be ideal for all tasks. For instance, if a person can access a keyboard, but not a mouse, then text entry is easily achieved, but cursor control must be done using methods like "mouse keys" where the keys on the number pad produce cursor movements. On the other hand, if a person can more easily access a pointer device (mouse, joystick) than a keyboard then cursor control is trivial, but text entry must be done using an on screen keyboard. Using cursor control, children with disabilities can use coloring software programs [9].

A compensatory assistive robotic system developed to enhance manipulative capabilities of people with CP in fine motor activities (i.e. coloring) could provide a more successful approach compared to the computer based. A user can operate the robotic system by holding a pen-shaped end-effector adapted for their grasp abilities (e.g. by attaching various grips to the interface), and haptics, bidirectional sensory modality involving the simultaneous exchange of information between a human and environment, can help to enhance their accuracy. People with CP or other severe disabilities have benefited from using a variety of haptic robotic technology to execute different functional activities. A review of haptics technology for people with physical disabilities, focusing on attributes affecting manual task performance, found the most common areas of use were in computer access and power wheelchair control [10]. Assistive robots can be used by people with special needs as a tool to improve their functional capabilities. In this case, the primary purpose of technology intervention is to compensate for a deficit or impairment (and not for rehabilitation and improvement of impairment) [9]. Common applications of compensatory assistive technologies are customized haptic interfaces for blind people to aid with computer interaction [11], or customized haptic joysticks for people with motor and cognitive impairments to better control power wheelchairs [12]. Similarly, another compensative assistive technology is robots using haptic interfaces to enable robot-mediated access to object play and manipulation, which can lead to overall task performance improvement [13].

The system proposed in this paper can facilitate motor movements by provision of virtual assistance, implemented as virtual walls on the borders of drawing pictures. Virtual assistance was developed and implemented in the form of virtual fixtures (VFs). VFs are forces generated by software that can either assist in maintaining the user's movements within a desired region or guide the movements towards a desired target. A preliminary evaluation of the system was performed with fifteen *adults without disabilities* [14]. The results validated the effectiveness of the virtual assistance as well as the system's *stability* (i.e. no vibration or noise was sensed on the robot) and *safety* (i.e. the system did not go out of control).

The current study with an adult with CP informs the research in a logical sequence from adults without disabilities [14] to an individual with CP by empirically evaluating how well the developed robotic platform can accommodate an individual with disabilities' manipulative skills. Studies with adult participants (with and without disabilities) allowed establishing and validating the platform before future studies with children with disabilities. Also, the effectiveness and usability of the system was assessed without the overlay of challenges concerned with research with children. Moreover, trials with adult participants can inform system performance and design, since adults are capable of providing feedback and articulating opinions, which are necessary to be integrated into the future version for use by children. Later, a systematic study with children can inform possible implications such as cognitive and perceptual demands.

This study evaluated through quantitative and qualitative measures whether the developed robotic system could accommodate the individual with CP's manual performance to accomplish the tasks more successfully. Additionally, the individual's *typical approach* to perform the same set of tasks was studied. This step was beneficial in understanding the individual with CP's experience using the *robotic-based approach* (i.e. using the proposed robotic system) and the *typical approach* that is generally available to the individual with disabilities. With the usability study, it was possible to evaluate the effectiveness of the two approaches and compare their advantages and disadvantages.

Methods

This study was approved by the Health Research Ethics Board < project ID # to be inserted after blind review>. A single-case study was conducted with a female individual, < author # to be inserted after blind review>, who is 49 years old and has quadriplegic CP. Her condition is mixed CP characterized by high and low muscle tone and involuntary movements. According to the Gross Motor Function Classification System Expanded and Revised (GMFCS-E&R) [15], she is classified at Level IV, meaning that she can perform self-mobility when using a powered wheelchair. Based on the Manual Ability Classification System (MACS) [16], she is at Level III, meaning that she has difficulty handling objects by hand but can perform manual tasks with help and/or adaptation of the activity.

System Description

Robotic-based Approach: The experimental setup (as shown in figure 1) consisted of a haptic robotic interface PHANToM Premium 1.5A (Geomagic, Cary, NC) as the user interface, and a tablet computer used as the colouring surface. In the proposed design, VFs were developed and implemented as spatial virtual walls on the borders of template pictures to help the individual with CP to colour inside the desired regions. The virtual walls were formulated such that the user did not sense any force while navigating inside the template picture, felt a small force when just coming into contact with the walls, and experienced a gradual increase of the force when pushing further against the walls. The rigidity of the virtual walls was set to medium and high levels, referred to as Soft-walls and Rigid-walls, respectively, in order to assess the participant's preferred level of assistance. Soft-walls feel like moving through gel when pushing against them while still being able to cross the borders if applying more force. Rigid-walls provide maximum control for maintaining movements inside the desired region, and thus, less ability to cross the borders. The detailed description of the system development and preliminary results is represented in [13].

---- Insert figure 1 about here ----

Typical Approach: The typical assistive technology setup consisted of the participant's standard keyboard with a key guard (as shown in figure 2) connected to a desktop computer. The colouring tasks were implemented on MS Paint and were displayed through a regular monitor. The built-in Mouse Keys function was turned on, which uses the eight keys on the numeric keypad to move the cursor up, down, left and right as well as on the diagonal.

The participant was interviewed prior to experiment day to identify her typical access method for performing cursor control activities. Our participant typically uses her keyboard to perform all computer tasks including the cursor control activities. She is proficient in using the keyboard and "mouse keys" for cursor control and interacting with graphical computer interfaces (GUI) through many years of experience. She commented that she would use the mouse keys function for a coloring task. On the experiment day, she was offered a trackball and a joystick as alternative options, since they were assumed to provide easier and faster movements for colouring, however, after trying all three interfaces, the participant preferred the keyboard.

---- Insert figure 2 about here ----

Procedure

The participant performed four coloring tasks (resembling a circle, square, ellipse and rectangle) under each assistance condition (unassisted, Soft- and Rigid-walls). The same tasks were performed using both robotic- and typical-based approaches. A reasonable amount of time, based on pilot tests, was given (i.e. 20 seconds). The participant performed each of the four coloring tasks under three randomized assistance conditions (i.e. unassisted, Soft- and Rigid-walls). There were two sessions, an hour for the first and three hours for the second session. Session 1 was to determine the best position and orientation to interact with the robotic system within the reachable and convenient workspace of the participant. As a result, a foam pad was placed around the robotic end-effector for easier grasp. Also, the robotic end-effector's calibration height was lowered to facilitate the individual's arm-hand position. Once the adjustments were made, both the robotic-based and typical approach were performed in session 2. The participant performed the same coloring tasks on the typical computer approach as the robotic one.

Data Collection

The robotic-based performance was quantified based on the following task measures (for detailed description of the measures and data acquisition, see [14]):

- The ratio of the colored area outside to the area inside the sample pictures, $Ratio_{out\text{-}in}$
- *Positional error* indicating the travelled distance outside the boundaries

The independent variable was the assistance condition (unassisted, Soft- and Rigid-walls), and the measures of $Ratio_{out\text{-}in}$ and positional error were the dependent variables. Quantitative analysis of the robotic-based performance was performed using paired-sample t-tests in order to assess the effect of unassisted performance compared to Soft-walls, and unassisted performance compared to Rigid-walls within the four tasks. The normality assumption for t-test was met.A subjective assessment of perceived force of each system on the hand and arm was made by the participant. The participant rated her perceived load based on the Borg Rated Perceived Exertion (RPE) Scale [17] (0 = nothing at all, and 10 = maximal, as shown in figure 3). Additional performance evaluation was carried out by responding to the following statements on a 5-point Likert scale [18]:

- The level of easiness in coloring inside the sample pictures is ..., where 1 = very difficult, and 5 = very easy
- The level of control of hand movements is ..., where 1 = very high and 5 = very low

The participant rated these items after every combination of the task and the assistance conditions (i.e., 4 tasks * 3 conditions=12).

In order to assess the participant's overall perception of the system, a usability questionnaire was administered at the end of the session. The questionnaire statements were taken from the System Usability Scale (SUS) [18] and modified to fit the current study (table 1).

---- Insert figure 3 about here ----

Results

In the following section, the results under each assistance condition are presented as assessed by the robotic measures ($Ratio_{out\text{-}in}$ and *positional error*), RPE scale, and survey questions. The effectiveness of the two approaches are evaluated, and discussed in terms of the participant's response to the survey questions and visual inspection of the coloring performance. Finally, the participant's overall opinion of the robotic system is presented based on the usability questionnaire.

Robotic-Based Approach

The $Ratio_{out\text{-}in}$ indicated significant performance improvement (df = 3, $p < 0.05$) when either of the Rigid-walls (M = 0.01067, SD = 0.0083, *Cohen's d* = 1.8) or Soft-walls (M = 0.0235, SD = 0.029286, *Cohen's d* = 1.7) were provided, compared to the unassisted performance (M = 0.2406, SD = 0.1821). Although the measure of *positional error* was reduced in each individual task, there was no significant difference between the No-walls and either of the assistive conditions. Sample colouring performances under the three robotic conditions are illustrated in figure 4.

---- Insert figure 4 about here ----

The physical loads were, from highest to lowest: Rigid-walls (*Mdn* = 2.5, *Range* = 1 to 5), No-walls (*Mdn* = 1, *Range* = 1 to 2), and Soft-walls (*Mdn* = .75, *Range* = .5 to 1). The participant described the Rigid-walls as triggering her hand spasm and commented that the less rigid boundaries were more helpful.

In terms of the easiness of maintaining the movements within the desired regions, the Soft-walls were rated as the easiest approach (*Mdn* = 5, *Range* = 4 to 5), and No-walls and Rigid-walls were equally rated slightly less easy (*Mdn* = 4.5, *Range* = 4 to 5). Regarding controllability of hand movements, the Soft- and Rigid-walls were equally rated as giving the highest control (*Mdn* = 1, *Range* = 1 to 2) and No-walls was rated the lowest (*Mdn* = 1.5, *Range* = 1 to 4).

Typical Approach

The participant rated the keyboard, based on the RPE scale, as very weak in exerting physical load (*Mdn* = 1, *Range* = .5 to 1). As for the easiness of maintaining the movements within the desired regions, the keyboard was scored as being difficult (*Mdn* = 2, *Range* = 1 to 4). In terms of the controllability (i.e. moving fingers between keys), the keyboard was rated as giving low control (*Mdn* = 4, *Range* = 3 to 5). Based on visual inspection, the participant was not able to efficiently perform the coloring tasks using the keyboard (figure 5). In the same amount of time, she colored considerably less of the inside of the picture compared to when using the robot system. In addition, she had difficulties switching between the keyboard keys and thus, over-shot the borders. Figure 24 illustrates the participant's attempt in coloring two sample pictures.

---- Insert figure 5 about here ----

Usability Questionnaire

The participant's responses to the usability questionnaire are summarized in table I. The statements were rated on a 5-point Likert scale (1 = strongly disagree and 5 = strongly agree).

---- Insert table 1 about here ----

Discussion and Conclusion

This study evaluated the usability of the developed robotic system with virtual assistance in enhancing the functional manipulative performance of an individual with CP in a coloring task. Overall, the quantitative and qualitative results confirmed the effectiveness of the system under Soft- and Rigid-walls assistive conditions compared to the unassisted as well as the typical approaches.

The objective analysis of the results in terms of the $Ratio_{out\text{-}in}$ showed relatively the same performance improvement under either of the Soft- and Rigid-walls conditions. These results are consistent with the study with 15 abled-bodied adults where the Soft- and Rigid-walls contributed to relatively the same performance improvements [14]. Interestingly, the performance improvement for the Soft- and Rigid-walls were rated *roughly* the same as assessed by the *subjective* measures of controllability and easiness in the current study. For the measure of perceived physical load, the Soft-walls were rated better than the Rigid-walls; even though both assistive conditions objectively showed the same effectiveness. In the same way, some able-bodied participants preferred the Soft-walls despite the higher effectiveness of the Rigid-walls in citation [14].

Regarding the measure of *positional error* being insignificant, this is in contrast to how it was significantly reduced in the presence of either Soft- or Rigid-walls in the study with adults without disabilities [13]. Likely, the amount of data collected for the individual with CP was not sufficient to pool the reductions that occurred in each single case (i.e. combination of the tasks and conditions) to lead to an overall significant difference.

The typical approach was noticeably less effective as compared to the robotic approach, as visually evidenced by the coloring performance (figure 5). Likewise, the keyboard was given the lowest score in easiness compared to all three assistive conditions of the robotic system. Interestingly, this was despite the fact that the resting position of the individual's hand seemed less awkward when using the keyboard (figure 2) compared to the angled arm posture when operating the robotic arm (figure 1). In addition, previous familiarity of the participant with the keyboard and its required movements did not make the keyboard more preferable over the robotic system.

According to the overall perception of the system, the participant strongly agreed with the safety, stability, and effectiveness of the system as well as the implemented assistance feature. Furthermore, the participant strongly agreed that the robotic system performed better than the typical approach in terms of the controllability, effectiveness, efficiency, and ease of use.

Provision of forbidden region VFs, as needed, can potentially improve the overall accuracy of task performance. Additional assistive features such as dampening, the approach taken by Atashzar et al. [13], could facilitate movement difficulties such as hand tremor, or coordination deficits.

In future studies with children with disabilities, we would expect the robotic system to function the same in accommodating and improving hand movements in the manual tasks. By letting children experience more success than failure or dissatisfaction in the task execution, children may feel an increased sense of self-efficacy, and motivation. Taking into account diversity of finger, hand and wrist movement capabilities of children with physical disabilities, the haptic interfaces could be adapted to accommodate each individual's abilities such as range of motion and grasp type. Different grips could also be used on the robotic interface to match the child's grasp ability. We have investigated and designed alternative grip adaptations interfaces to take into account the specific needs of a diverse group of children with disabilities. The designed interfaces can be used in subsequent studies or can be easily modified using the developed procedure. <A link to our website for a video of the robots grips adaptations as well as the design and 3D printing files (SolidWorks and SLT) will be provided after the blind review>.

The current system offers a limited number of drawings as the preliminary stage of development. Present work includes advancing the technology to provide more complicated drawing shapes (e.g. random polygon shapes by picking arbitrary vertices points on the drawing surface) . It is assumed that children's engagement in the play activates can be increased by inclusion of more playful and meaningful drawings (e.g. a snowman) with an option to initially try the assistance conditions, Soft- and Rigid-walls, and then select their preferred assistance level. Thus, since both Rigid and Soft conditions led to significant performance improvements, choosing their preference approach could increase the child's satisfaction and level of physical comfort. The individual with CP in this study further commented that "children would have fun with the system. There should be a way to change the color on their own though"; flexibility to the system may be important to encourage exploration and individuality. Further development of the system will include integration of artificial intelligence so the system will adaptively tune the level of assistance (i.e. the rigidity of the walls), according to the participant's performance.

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Figures and tables

Table 1. The usability questionnaire administered to evaluate the overall perception of the system, with regards to the robotic-based approach

SUS Category: Feature of the system & virtual assistance	Associated robot feature	Usability robot questionnaire	Results
Ease of use	Ease of use	The system can be used without much training.	4
		It was easier to hold on (or control) the robotic arm compared to the keyboard	5
Reliability of the system	Safety	I felt confident using the system.	5
	Stability	The system was stable (there was no vibration).	5
Effectiveness of the system	Effectiveness	I found the coloring task easier when using the robotic system compared to the keyboard	5
	Complexity	I found the system unnecessarily complex	1*
	Efficiency	I found the coloring task faster when using the robotic system compared to the keyboard	5
Effectiveness (or usefulness) of actions taken by the system	Controllability	I had more control over my hand movements when using the computer interface than the robotic arm.	1*
	-	The virtual forces were effectively applied for the coloring tasks.	4
	Perceptibility of virtual walls	The contours and edges of virtual objects were clearly tangible on the robot.	5
	-	I did not feel any forces when I was moving the robot inside the virtual objects.	5

Figure 1. The individual with CP operating the robotic system, equipped with the virtual assistance, by holding the robotic end-effector

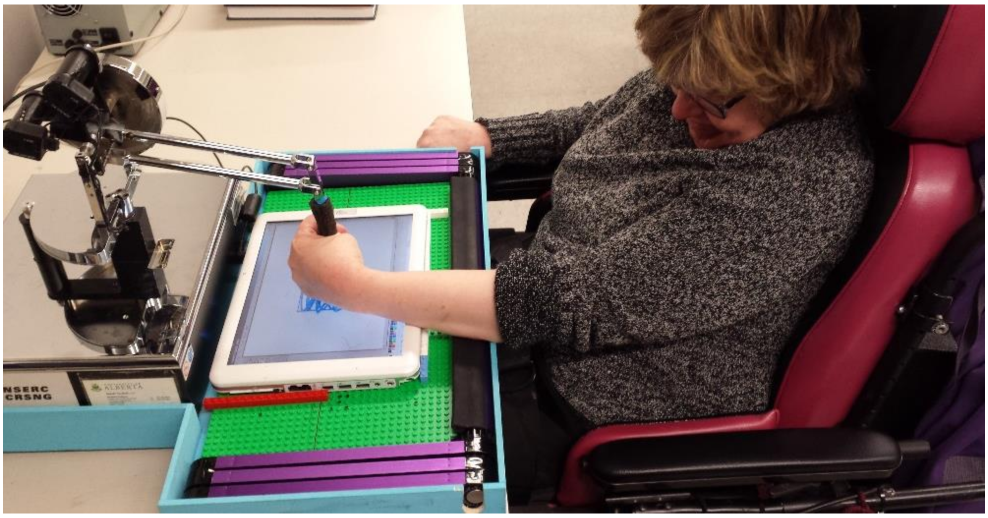

Figure 2. Individual with CP using her typical computer interface, a keyboard with a key guard, to perform the task on the computer (typical approach)

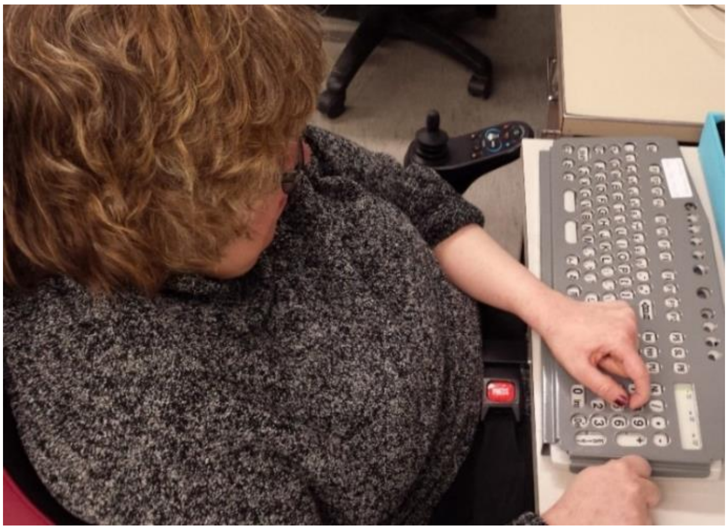

Figure 3. Borg Rated Perceived Exertion (RPE) Scale to quantify the perceived physical load

Borg's RPE scale

0	Nothing at all
0.5	Very, very weak (just noticeable)
1	Very weak
2	Weak (light)
3	Moderate
4	Somewhat strong
5	Strong (heavy)
6	-
7	Very Strong
8	-
9	-
10	Maximal

Figure 4. Illustration of the color-coded movement trajectories inside and outside the sample drawing pictures under No-walls (left plot), Soft-walls (middle plot) and Rigid-walls (right plot) robotic assistive conditions

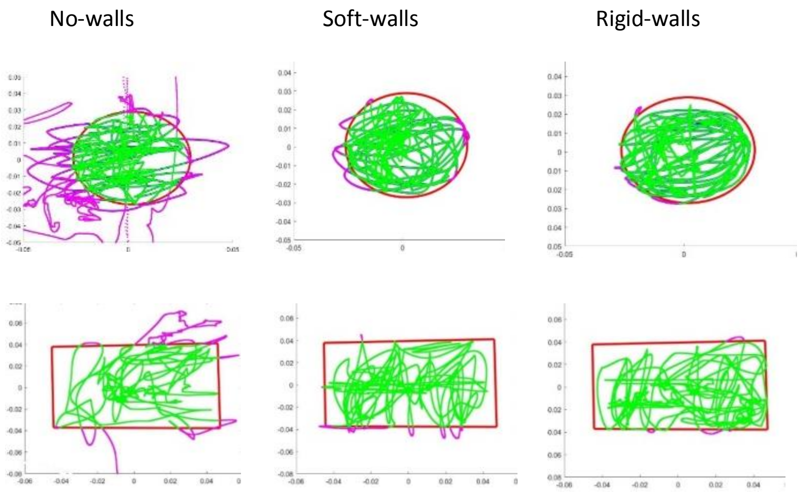

Figure 5. Performance of the individual with CP when using her typical computer interface