CHAPTER VII

KINEMATIC BEHAVIOR ADAPTATION VIA ROBOTIC INTERACTIONS

7.1 Introduction

We define an individual's **kinematic behavior** as their behavior/performance relative to a set of kinematic parameters. Previous studies have shown that external corrective feedback provided to individuals undergoing physical therapy sessions increases the efficacy of their intervention protocols by prompting them to modify their kinematic behavior, thus allowing for individuals to facilitate sustained or complex play [109]. (Refer to Section 2.4 for more details on the benefits of feedback). In traditional physical therapy sessions, an expert therapist is able to achieve desired results from their patient through 1) guided instruction, 2) thorough observation, 3) real-time assessment, and 4) corrective feedback. The therapist first provides the patient with guided instruction, which is the initial description of the task/movement that is required of the patient to perform. The therapist observes the patient perform the task, assesses the movement, and provides the patient with corrective feedback for improvement. The cycle is repeated until the desired results are reached. However, direct feedback is typically provided by an expert therapist during weekly or monthly visits, which limits improvement on a daily basis. As such, we promote in-home rehabilitation protocols via robot interactions while using our *Super Pop VR*^{TM} system such that users can receive the necessary corrective feedback that prompts them to adapt their kinematic behavior to, ultimately, increase their rate of improvement.

This chapter focuses on the studies we conducted to support our claim that individuals can modify and adapt their kinematic behavior while interacting with our complete *Super Pop VR*^{TM} system. Our approach follows a procedure similar to the one shown in Figure 1. Instead of classifying the user's reaching kinematics to autonomously select the most appropriate baseline model, the studies described in this chapter assume a constant one (Figure 26). Using this approach, we are able to constrain the testing protocol such that we attribute any kinematic behavior adaptation solely to the corrective feedback provided by the system.

The first study is described in Section 7.2. Results show that both, able-bodied adults and typically developing children, can reach specific performance reference values for a given kinematic parameter via receiving appropriate corrective feedback from a robotic playmate. The second study is described in Section 7.3. Results show that both typically developing children and children who have cerebral palsy can decrease their movement time after a training session with a robotic playmate. Both studies measure the participants' outcome measures relative to the *Super Pop VR*^{TM} environment.

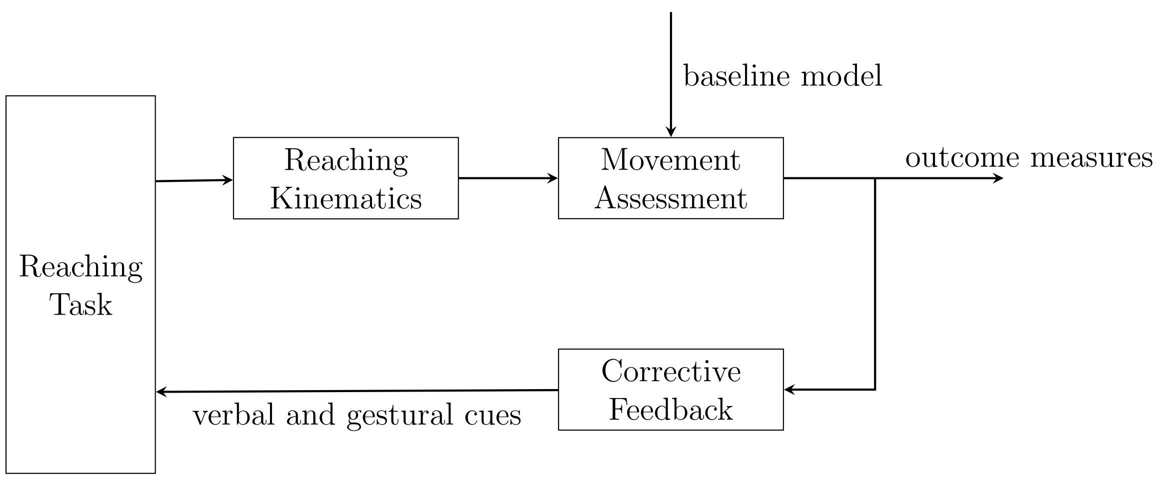


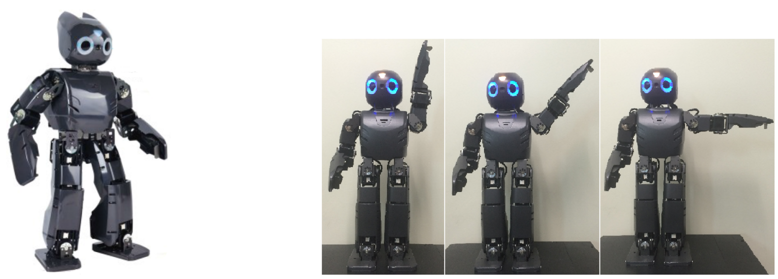
Figure 26: Diagram of our complete system with a constant baseline model.

7.1.1 DARwIn-OP: Humanoid Robot

The two studies described in this chapter make use of an embodied physical robotic playmate to provide feedback cues to assist users in reaching their kinematic goals.

Both studies use the humanoid robot, **DARwIn-OP** (Darwin) (Figure 27). It has 20 actuators resulting in 6 DOF (degrees of freedom) for each leg, 3 DOF for each arm, and 2 DOF for the neck [56]. Darwin was pre-programmed with a library of verbal and nonverbal behaviors to enable interaction with the Super Pop environment and provide feedback to the user [17]. The different combinations of these behaviors are summarized in the studies' corresponding sections (7.2 and 7.3). In both studies, Darwin introduces himself with the script below to provide some low-level instructions.

> *"Hello. My name is Darwin, and I will be playing Super Pop with you today. I will ask you to complete a series of tasks, and I would love it if you would follow my instructions. When you're ready, please raise both of your hands as high as you can."*



(a) (b)

Figure 27: (a) Humanoid robot, DARwIn-OP (Darwin). (Image adapted from [56].) (b) Darwin performing a 90° reaching task.

7.1.2 Effect of Robot Feedback on Motor Skill Performance

We first conducted a pilot study to evaluate how various cues affect an individual's kinematic performance [17]. More specifically, we employed a between-groups experimental design to compare the effect of verbal versus combined verbal and nonverbal instructional feedback provided by the robotic playmate. The most effective combination of feedback cues (i.e. the combination that induced a greater rate of change in the participants' kinematic behavior) was selected to be used in the studies described in this chapter. For this pilot study, the participants' kinematic behavior was analyzed with respect to the movement time parameter. We tested the system using the procedure as shown Figure 28 with 20 able-bodied adults (5 females and 15 males ranging in age between 18 and 45 years old, mean = 28.4 years and standard deviation = 5.7 years). To assess the upper-body movements of adult participants with respect to the movement time parameter, the constant baseline model used for this study was the Fitts model described in Section 4.3.4.

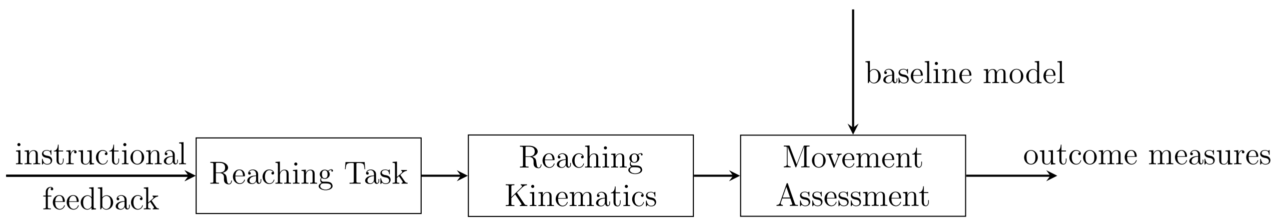


Figure 28: Diagram of our system with a constant baseline model and instructional feedback is received as input instead of corrective feedback.

Each participant was randomly assigned to one of two groups, and asked to perform the 90° exercise shown in Figure 3 as the reaching task, three times. Participants in Group 1 received verbal instructional feedback only, while participants in Group 2 received a combination of verbal and nonverbal instructional feedback. Participants in both groups received the following verbal instructions before each corresponding task: 1) move "*at a speed that feels normal*", 2) move "*as slow as possible*", and 3) move "*at a speed that is a little slower than normal*". Only participants in Group 2 received, in addition, the nonverbal instructional cues from Darwin (Figure 27b).

For each group and for Darwin, the normalized average movement times with respect to each task for Group 1, Group 2, and Darwin are shown in Figure 29. Participants form both groups were able to follow Darwin's instructions accordingly (i.e. both groups began at a certain baseline, were able to slow down for Task 2, and then speed up for Task 3). However, when examining Task 2 (Darwin instructs participants to ‘move as slow as possible’), the normalized average movement times were 0.38 ± 0.26 and 0.67 ± 0.30 for Group 1 and Group 2 respectively. Seeing as Group 2 performed closer to Darwin’s instructions (i.e. they took longer to perform the task), these results suggest that individuals receiving a combination of verbal and nonverbal feedback can perform closer to the robot’s guided instructions when compared to only receiving verbal instructional feedback. As such, we adhere to this study’s results and provide a **combination of verbal and nonverbal feedback cues** in the studies described in this chapter. For more detailed results, refer to [17].

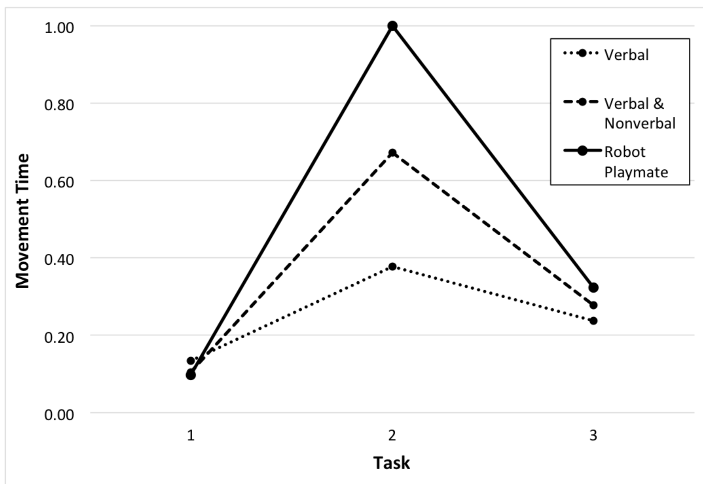


Figure 29: The normalized average movement times with respect to each task for Group 1, Group 2, and Darwin. (Image adapted from [17].)

7.2 Pilot Study I: Low-resolution Feedback from Robotic Playmate

An embodied robotic agent providing guided instruction to individuals during physical therapy sessions has been shown to improve individual kinematic performance [17] and increase overall engagement levels [124]. Given that the main objective of physical therapy with a human therapist is to reach a performance goal over an extended period of time, we aim to reach these long-term performance goals through implementation of a robotic playmate providing continuous feedback (Figure 26). As such, we conducted a study with the main purpose to determine if individuals can adapt their kinematic behavior via robot interaction while using our *Super Pop VR*^{TM} system such that they improve their performance at each iteration of feedback and, ultimately, reach an individualized performance goal [45].

7.2.1 Hypotheses

To better evaluate the efficacy of our system, we compare the effects of receiving feedback from the embodied robotic playmate versus the baseline effects of receiving feedback from a virtual agent. As such, the hypotheses of this study were:

H_1 : By interacting with our overall *Super Pop VR*^{TM} system, users will improve their kinematic performance at each instance of completing a reaching task and, ultimately, reach a targeted performance goal.

H_2 : Users will reach their individualized performance goals faster, on average, when receiving feedback from the embodied robotic playmate than when receiving feedback from a virtual agent.

7.2.2 Experimental Design

Fifteen able-bodied adults and fourteen typically developing children were recruited to interact with our *Super Pop VR*^{TM} system (Figure 26). There were six females and nine males in the adult group, ranging in age between 19 and 33 (mean age = 26.9 years, standard deviation = 3.4 years), and five females and nine males in the children group, ranging in age between 15 and 16 years (mean age = 15.5 years, standard deviation = 0.5 years). Adult participants and the parents of the child participants signed the IRB (Institutional Review Board) approved consent form allowing them to engage in the testing sessions.

This study focused on computing and correcting participants' movement time (MT) via feedback. As such, the targeted performance goal that participants were prompted to reach was the corresponding MT prediction computed by our Fitts model (refer to Section 4.3.4). For the first round of experiments, the adult participants were randomly assigned to one of two groups: **Group A** received feedback from a virtual agent while **Group B** received feedback from the robotic playmate (refer to Section 7.1.1 for more details on Darwin). For the virtual agent, we played Darwin's voice over external speakers. Both Darwin and the speakers were positions between the screen and the participant, and they both provided corrective feedback as described in Table 21. The purpose of the virtual agent is to establish a baseline comparison to evaluate whether an embodied agent can yield better results than a virtual agent (i.e. a virtual voice).

Table 21: Feedback provided during interaction with the *Super Pop* VR^{TM} game.

<table>
<tr><th>Movement Time, MT</th><th>Verbal</th><th>Nonverbal</th></tr>
<tr><td>$MT > target$</td><td>"Great job. Move a little faster like this..."</td><td rowspan="2">Darwin performs the gesture at the correct movement time. It extends his left arm above his head. It then moves his shoulder joint 90° until his arm is down and parallel to his torso (Figure 27b).</td></tr>
<tr><td>$MT < target$</td><td>"Great job. Move a little slower like this..."</td></tr>
<tr><td>$MT = target$</td><td>"Fantastic."</td><td></td></tr>
</table>

* *target* is defined as the MT reference window (i.e. the MT target value $\pm\epsilon$ to allow for small deviation from the actual MT target value).

All participants followed a variation of the protocol described in Appendix C. Each participant interacted with the system for one round. Before the game starts, the system computes the user's MT reference and a ± 150 ms margin of error is added to the final value. Each round consists of three main steps: 1) user performs the reaching task (i.e. the 90° exercise shown in Figure 3), 2) the system compares the user's MT to the reference, and 3) either Darwin or the virtual agent provides the corresponding corrective feedback until the user reaches the goal or until the time runs out (6 minutes). The flowchart describing the architecture of the testing sessions is shown in Figure 30.

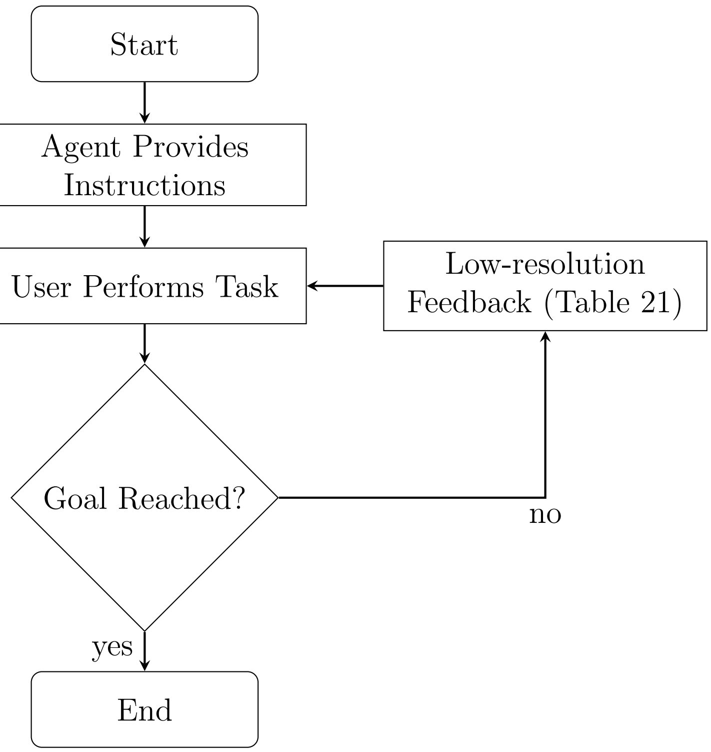


Figure 30: Flowchart describing the interaction between the user and the system.

For all participants, at the beginning of each round we make sure that the participants' starting MT is much greater than the reference MT by having the virtual voice or Darwin speak the following:

> *"Please pop bubbles one through three and move as slow as you can. Like this..."*

For all sessions in Group B, Darwin also performs the nonverbal gesture that is 10 times slower than the one described in Table 21 to show the user how the reaching task should be completed. These instructions prompt the users to move as slow as they can thus defining a common starting point between all participants.

For the second round of experiments, child participants interacted with the version of the system that provides feedback via the robotic playmate to see if a younger demographic could also reach their performance goals by interacting with the system.

7.2.3 Quantitative Results (Adults)

All adult participants from both groups reached their corresponding MT references. For each participant, the number of trials children needed to reach their corresponding MT references, and their averages and standard deviations, are shown in Table 22 organized by groups. Moreover, boxplots showing how the number of trials needed to reach the MT references are distributed per group are shown in Figure 31.

Table 22: Trials to MT references for all participants from each group.

Participant	**Adults (Virtual Agent)**	**Adults (Darwin)**	**Children (Darwin)**
1	5	1	5
2	7	4	3
3	4	1	4
4	4	2	3
5	5	4	3
6	2	2	4
7	2	2	7
8	3	-	3
9	-	-	5
10	-	-	N/A*
11	-	-	4
12	-	-	2
13	-	-	1
14	-	-	8
AVG	4.0	2.3	4.0
STD	1.7	1.3	1.9

*Participant did not reach his/her MT reference.

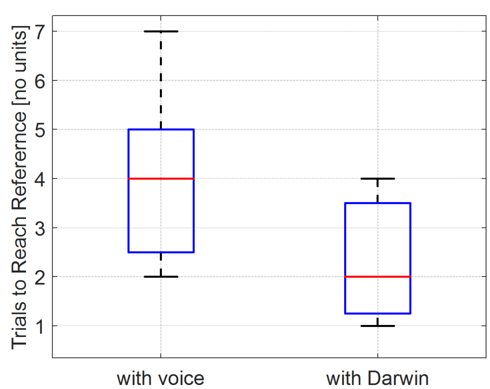
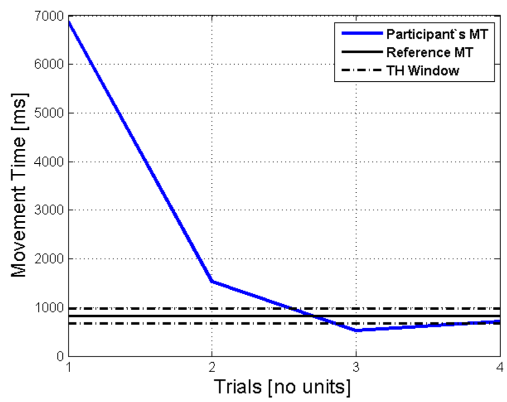


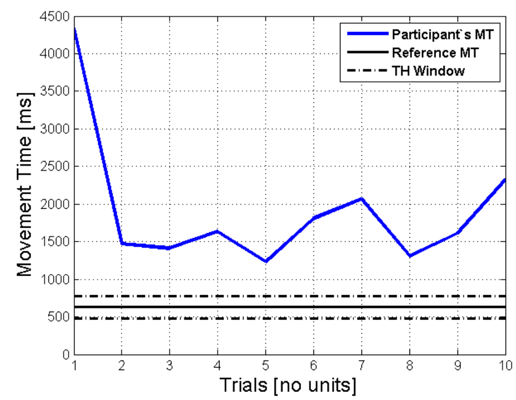
Figure 31: Boxplots showing how the number of trials needed to reach the MT references are distributed with respect to each group of adult participants.

7.2.4 Quantitative Results (Children)

Thirteen out of the 14 child participants reached their corresponding MT references. As an example, the response of Participant 4, who reached the MT reference in 3 trials, is shown in Figure 32a. On the other hand, the response of Participant 10, who did not reach the MT reference, is shown in Figure 32b. We discuss some of the potential reasons for this participant not reaching his MT reference in the *Discussion and Conclusions* section. The number of trials children needed to reach their corresponding MT references, and their averages and standard deviations are shown in Table 22, and a boxplot showing how the number of trials needed to reach the MT references are distributed is shown in Figure 33.



(a) Partcipant 4 (child)



(b) Participant 10 (child)

Figure 32: MT response curves of a) Participant 4 (child) who reached the MT reference at trial 3, and b) Participant 10 (child) who did not reach the MT reference.

7.2.5 Discussion and Conclusions

The first round of experiments consisted of comparing the responses between the two adult groups that received feedback from the virtual agent (Group A) and from the robotic playmate, Darwin (Group B). Group A and Group B needed an average of **4.0 ± 1.7 trials** and **2.3 ± 1.3 trials**, respectively, to reach their respective MT references (Table 22). These results, together with the boxplots in Figure 31,

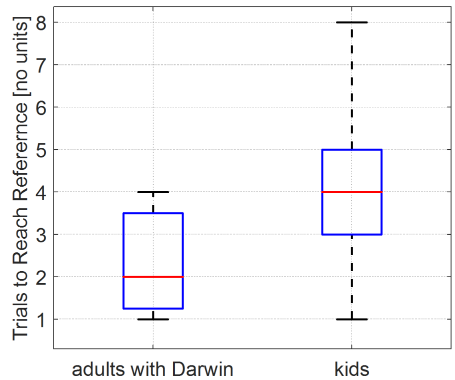


Figure 33: Boxplots comparing the number of trials needed to reach the MT references for child and adult participants.

validate our second hypothesis (H_2): individuals that receive corrective feedback from a robotic agent (Group B) need, on average, less trials to reach their respective MT references than individuals that receive feedback from a virtual agent (Group A). We performed a two-tailed unpaired t-test at a 95% confidence level on the adults' results to determine if the difference between the groups' amount of trials needed to reach the MT references is statistically significant. We define our null-hypothesis as: the two independent samples come from distributions with equal means (i.e. the participants in the two groups needed, on average, the same amount of trials to reach their respective MT references). Our t-test analysis results in a **p-value = 0.046**. As such, we reject the null-hypothesis and confirm the statistical significance of the difference between the number of trials needed to reach the respective MT references between the two adult groups.

Because the results support the robotic playmate over the virtual agent, the second round of experiments involved children interacting with the version of the system that provides feedback via the robotic playmate. Results show that 13 out of the 14 children participants reached their corresponding MT references (Table 22). Thus, we performed a two-tailed paired t-test analysis at a 99% confidence level on the child participants' results to determine if the amount of participants that reached their references is statistically significant. Let $\vec{v}$ and $\vec{w}$ be two vectors containing the absolute difference between the child participants' MTs and their corresponding MT reference for their first and last trials respectively, where each element belongs to a different participant. Let $\vec{d}$ be the vector containing the difference between $\vec{v}$ and $\vec{w}$ (39).

$$\vec{d} = \begin{bmatrix} d_1 \\ d_2 \\ ... \\ d_n \end{bmatrix} = \begin{bmatrix} |Ft_1 - Rt_1| \\ |Ft_2 - Rt_2| \\ ... \\ |Ft_n - Rt_n| \end{bmatrix} - \begin{bmatrix} |Lt_1 - Rt_1| \\ |Lt_2 - Rt_2| \\ ... \\ |Lt_n - Rt_n| \end{bmatrix} \tag{39}$$

where n is the number of the participants being analyzed, Ft_i and Lt_i are the i^{th} participant's MT in the first and last trials respectively, and Rt_i is the i^{th} participant's MT reference. Thus, we define our null-hypothesis as: the sample mean of $\vec{d}$ is equal to zero (i.e. there is no statistical difference between $\vec{v}$ and $\vec{w}$). Our t-test analysis on $\vec{d}$ results in a **p-value $\ll$ 0.01**. As such, we reject the null-hypothesis and conclude that there is a statistical difference between the participants' performance in their first and last trials. This suggests that the participant that did not reach their MT reference does not affect our claim that children will reach their performance goals by interacting with our system. This, together with the fact that all adult participants reached their corresponding performance goals, validates our first hypothesis (H_1). After observing the session and response curve of the participant that did not reach their performance goal (Figure 32b), we hypothesize that one of the reasons might be because the participant did not understand Darwin's feedback cues.

Moreover, even though the child participants received corrective feedback via the robotic playmate, they performed at a lower level (i.e. greater MT average) than the adults that interacted with the same version of the system. We attribute this observation to the fact that, in general, children have slower movements than adults

[111].

One of the limitations of this work is related to the demographic of the volunteers recruited to participate in this study. Namely, even though the target population for our system are children with motor limitations who are enrolled in some physical therapy protocol, we recruited able-bodied adults and typically developing children. On a similar note, the performance of the children participants was evaluated against the same Fitts model as the adults participants were (Section 4.3.4). As such, future studies will include sessions with participants of the target population, and participants will be compared against their corresponding baselines. Another limitation of this work is the number of kinematic parameters used to evaluate the participants' performances. Further studies will be conducted with additional kinematic parameters as well as combinations of parameters.

7.3 Pilot Study II: Decreasing Users' Movement Times

The purpose of this pilot study was to examine whether instructional and corrective feedback cues provided by a robotic playmate could improve the kinematic performance of typically developing children and children who have cerebral palsy. In general, one of the main objectives of a physical therapy session with a human therapist is to improve patient performance and maintain the performance after the session has ended [62, 120]. As such, we designed our *Super Pop VR*^{TM} system such that it can allow for such interactions in the home environment. In this manner, users can continuously interact with the system towards maintaining their improvement in performance.

7.3.1 Hypotheses

For this study, participants' kinematic performance is evaluated with respect to the movement time (MT) parameter (i.e. the amount of time needed to complete a reaching task). As such, the hypotheses for this study were:

H_1 : Participants will effectively decrease their MTs while receiving feedback cues from a robotic playmate while interacting with our *Super Pop VR*^{TM} system.

H_2 : Participants' MTs will still be reduced even after the feedback cues provided by the robotic playmate are withdrawn.

7.3.2 Experimental Design

Seven children with cerebral palsy (CP) and ten typically developing (TD) children were recruited to interact with our *Super Pop VR*^{TM} system (Figure 26). There were four females and three males in the CP group (mean age = 9.86 years, standard deviation = 1.35 years), and seven females and three males in the TD group (mean age = 9.60 years, standard deviation = 1.26 years). The children's parents signed the IRB (Institutional Review Board) approved consent form allowing them to engage in the testing sessions.

To validate the study's hypotheses and determine if and how participants modified their kinematic behavior, their performances before, during, and after a training session with our *Super Pop VR*^{TM} system were compared to each other. The setup of the game settings is described in Appendix C. Participants' performances were evaluated with respect to the 90° reaching task described in Figure 3. Each participant interacted with the system for three rounds and performed the reaching task 20-30 times for each round. For the first and third rounds, participants performed the reaching task without receiving feedback. For the second round (training session), participants received instructional and corrective feedback from the robotic playmate (refer to Section 7.1.1 for more details on Darwin). The architecture of the testing sessions is similar to the one described in Figure 30. However, instead of evaluating if the participant reached a goal, the testing session stops when the participant completed the required amount of reaching tasks. Moreover, instead of following the feedback cues described in Table 21, Darwin would say *"Keep up the good work.*

Move a little faster." if the participant's MT was greater than the targeted threshold (TH). Similarly, if the participant's MT was less than or equal to the TH, Darwin would say *"Fantastic. Let's move at the exact same speed."*. For each participant, the movement time threshold (MT_{TH}) was defined as 80% of his/her baseline MT (i.e. the participant's average MT from round 1). In this manner, we prompt the participant to continually move at a pace faster than their natural speed.

During game play, the system recorded the MT taken by participants to complete each reaching task. For each round, let random variable X be a participant's MT after completing a reaching task. With no prior information about the underlying distribution of a participant's MTs, we adhere to the Central Limit Theorem (i.e. the sum of many random variables will have, approximately, a normal distribution), and assume $X \sim N(\mu, \sigma)$ to be normally distributed, where μ and σ are the mean and standard deviation, respectively, of the participant's MTs for the corresponding round. For each round, we compute the probability that a participant will complete a reaching task with a MT less than or equal to his/her corresponding MT_{TH} (i.e $F_X(x) = P(X \leq x)$, where x is the participant's MT_{TH}). By definition, this is the CDF (cumulative distribution function) of X, which is given by (40), given our assumption that X is normally distributed.

$$\Phi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-t^2/2}\, dt \tag{40}$$

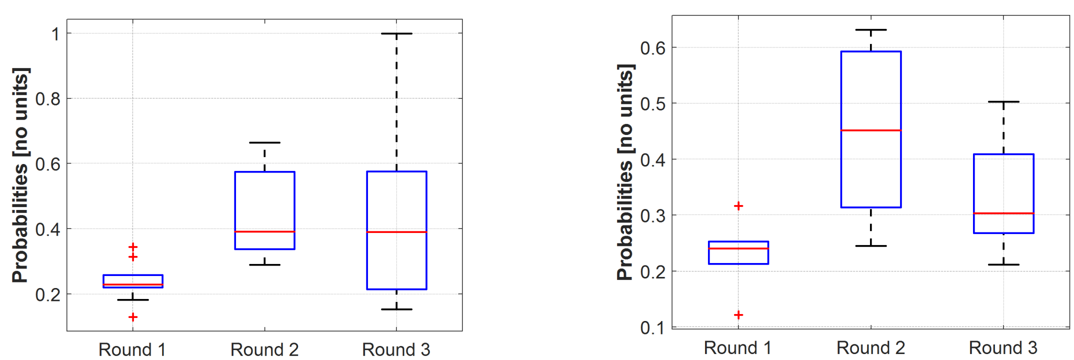
7.3.3 Results

Based on the collected MT data for each round, the probabilities that a participant will complete a reaching task with a MT less than or equal to his/her corresponding MT_{TH} are shown in Table 23. Moreover, we aggregate the results and organize them by group: typically developing (TD) kids and kids who have cerebral palsy (CP). For each group, boxplots showing how the probabilities are distributed with respect to each round are shown in Figure 34. As an example, boxplots showing how the MTs of one participant, from each group, are distributed with respect to each round are shown in Figure 35.

Table 23: Probabilities that the participants' MTs will be less than or equal to their corresponding THs for each phase.

Typically Developing Children				Children with Cerebral Palsy			
Participants	**R1**	**R2**	**R3**	**Participants**	**R1**	**R2**	**R3**
1	0.232	0.289	0.161	1	0.240	0.312	0.290
2	0.224	0.664	0.446	2	0.253	0.319	0.341
3	0.224	0.580	0.575	3	0.213	0.245	0.261
4	0.314	0.574	0.999	4	0.122	0.594	0.212
5	0.257	0.348	0.385	5	0.214	0.631	0.432
6	0.243	0.372	0.369	6	0.317	0.590	0.503
7	0.129	0.423	0.214	7	0.252	0.452	0.303
8	0.344	0.455	0.797	-	-	-	-
9	0.182	0.337	0.153	-	-	-	-
10	0.219	0.359	0.395	-	-	-	-
AVG	0.237	0.436	0.450	**AVG**	0.230	0.449	0.335
STD	0.061	0.129	0.275	**STD**	0.059	0.159	0.101

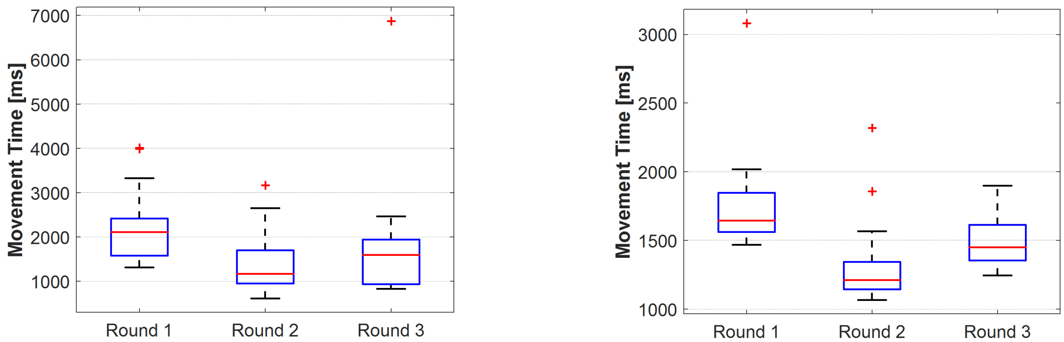
*R1, R2, and R3 make reference to rounds 1, 2, and 3 respectively.



(a) Typically Developing Children

(b) Children with Cerebral Palsy

Figure 34: Boxplots with the distributions, with respect to each round, of the probabilities that a participant will complete a reaching task with a MT less than or equal to his/her corresponding MT_{TH}.



(a) Typically Developing Child: Participant 2

(b) Child with Cerebral Palsy: Participant 4

Figure 35: Boxplots with the MTs for one participant organized with respect to each round.

7.3.4 Discussion and Conclusions

The averages in Table 23 and the boxplots in Figure 34 show that, for both TD children and children who have CP, the probability for a participant to complete a reaching task with a MT less than or equal to the corresponding MT_{TH} is greater in rounds 2 and 3 than in round 1. As such, while receiving corrective feedback during game play in round 2, participants are more likely to complete a reaching task with a lower MT than their baseline from round 1, thus validating our first hypothesis (H_1). Similarly, after removing the feedback cues in round 3, although the probability for completing a reaching task is lower than the training session in round 2, it is still higher than the baseline from round 1. This validates our second hypothesis (H_2) since participants are still more likely to complete a reaching task with a lesser MT even after withdrawing the feedback cues.

We conducted four separate unpaired two-tailed t-tests at a 95% confidence level to determine if the probabilities in Table 23 and Figure 34 are statistically different between rounds. The null-hypothesis is the same for the four tests: the probabilities between two rounds come from distributions with equal means. The resulting p-values are shown in Table 24. Seeing as $p < 0.05$ for all tests, we reject all null-hypotheses and conclude that there is a statistical difference between the rounds for both groups. Namely, between round 1 and round 2 showing that participants are more likely to decrease their MTs while receiving corrective feedback during game play (hypothesis H_1), and between round 1 and round 3 showing that participants still have a higher probability to decrease their MTs even after withdrawing the corrective feedback (hypothesis H_2).

Table 24: p-values at a 95% confidence level for testing statistical difference in probabilities from Table 23 between rounds.

	R1 : R2	**R1 : R3**
Typically Developing Children	$\ll 0.05$	0.028
Children with Cerebral Palsy	0.005	0.036

*'R1 : R2' and 'R1 : R3' refer to the t-tests between Round 1 and Round 2, and Round 1 and Round 3 respectively.

These trends are observed when analyzing each participant's MT distribution individually. For example, the MTs of Participant 2 (from the TD group) and Participant 4 (from the group with CP) decrease in round 2 when the participants receive the corrective cues during game play (Figure 35). Moreover, their MTs increase in round 3 but are still less than their baseline from round 1. These observations further support the study's hypotheses. Thus, by prompting participants to complete the reaching tasks at a pace faster than their baseline (i.e. to complete the reaching tasks with a MT less than 80% of their baseline), they were able to improve their performance while receiving feedback and maintain their improvement after removing the feedback cues.

There are a few limitations with this study. The first limitation is that participants' performance was evaluated with respect only to the movement time parameter. Future studies should be conducted to evaluate if the hypotheses still hold with respect to other kinematic parameters and/or combinations of parameters. Another limitation is in the number of reaching tasks completed by each participant. Results are obtained based on the assumption that the participants' MTs in a given round are normally distributed. We would have better information about the underlying distribution if participants completed more reaching tasks for each round. Finally, all rounds were performed one after another on the same day. As such, longitudinal studies should be conducted to determine whether participants can maintain their improvements over longer periods of time after interacting with our system.

7.4 Summary

It is our ultimate goal to develop a system that can provide targeted feedback for any and all kinematic parameters of interest for individuals with some form of motor skills disorders. Such a system, designed for an in-home environment, would increase the frequency at which users receive feedback regarding their kinematic performance thus increasing the efficacy of the their intervention protocols. As such, this chapter focused on evaluating if our system has the capability of prompting users to modify and adapt their kinematic behavior via feedback. We conducted two pilot studies in which our system provided different types of corrective feedback and evaluated the behavior response of the participants. Both studies evaluated the system as described in Figure 26, used the humanoid robot DARwIn-OP as the robotic playmate that provides corrective feedback (Section 7.1.1), and adhere to the findings of our independent study that showed that a combination of verbal and nonverbal cues is the most effect manner for providing corrective feedback (Section 7.1.2).

The first pilot study focused on determining if individuals that interacted with our system can reach a specific performance goal (Section 7.2). Not only do results show that adults interacting with the version of the system that provides the corrective feedback via a virtual agent can reach their individualized movement time (MT) references, results also show that receiving corrective feedback from an embodied robotic playmate will help individuals reach their MT references faster (i.e. in a less amount of trials) than receiving feedback from a virtual agent. Results from the second round of experiments show that typically developing children that interact with the version of our system that provides corrective feedback via the robotic playmate can reach their individualized MT references as well. The results from this study suggest that our system can accomplish one of the main objectives of physical therapy with a human therapist: to reach a performance goal over an extended period of time.

The second pilot study focused on evaluating if participants could improve their performance during a training session with our system (Section 7.3). Results show that both typically developing children and children who have cerebral palsy can, not only improve their kinematic performance (i.e. decrease their MTs for this study) during a training session with our system, but also maintain their improvement after the corrective cues are removed. The results from this study suggest that users can improve their kinematic performance by interacting with our *Super Pop VR*^{TM} system, as well as maintain it afterwards.