Analysis of arm movement strategy in virtual catching task

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ABSTRACT

In this paper, we explored how the arm movement pattern as well as the related strategy of the children with Cerebral Palsy (CP) and the healthy children can be changed in the virtual catching task on a previously proposed rehabilitation system. We recruited 50 healthy children from elementary school, and 3 children with CP as subjects to classify their arm movement pattern/strategy. As a result of the classification, we identified three arm movement stages: *Initial position*, *Reaching path*, and *Waving form*, as well as movement pattern strategy under each movement stage. Based on the classified pattern, we compared the differences in the time series changes of movement strategy between healthy children and the children with CP. The results show there is a significant difference in the strategy of arm movements in the *Initial position* between healthy and CP children.

1. INTRODUCTION

1.1 Cerebral Palsy Disease

Cerebral Palsy (CP) refers to various motor impairments caused by damage to the central nervous system during foetal development (Krageloh-Mann and Cans, 2009). This disorder affects approximately 0.3% of births (Krageloh-Mann and Cans, 2009) and often manifests itself during the early childhood as a difficulty to use aside of the body (hemiparesis). Motor deficits encompass difficulty in planning and executing movement.

Physical therapy is proposed to children with CP to help them to grow and physically develop as well as possible. Traditional approach of physical rehabilitation focuses on muscular strength and proposes repetitively simple and uncontextualized movement. However, such therapies are of little interest to children and offers limited functional value in daily living, affecting their motivation to continue the therapeutic activities (Halton, 2009; Schmidt and Lee, 2005). The constraint-induced movement therapy (CIMT) have been developed to improve movement patterns and to maintain the range of the affected arm and leg joints. This approach is often used to improve upper limb function (Hoare et al, 2007). In this therapy, impaired people are encouraged to use their affected hand by restricting the unaffected hand and asking for intensive movement with the impaired upper limb. However, having the unimpaired arm blocked for long periods of time can generate frustration in the child and might not be applicable in a long-term rehabilitation program. Thus, more child-friendly approaches are needed during the neuro-development of children with CP.

1.2 Upper-Body Interactive Rehabilitation System for Children with Cerebral Palsy

The field of Virtual Reality (VR) has grown dramatically as an emerging tool showing a great potential for use in physical medicine and rehabilitation (e.g., Berger-Vachon et al, 2006; Le Gall et al, 2008). VR system has a capability to achieve rehabilitative goals through the use of real-time feedback as well as adaptive strategy and/or difficulty (Burdea, 2003; Cikajlo and Matjacic, 2009; Rose et al, 2000), and several studies have shown hopeful results but few researches focus on cerebral palsy (CP) (for review see Rahman, Rahman and Shaheen, 2011). In the same vein, we have begun a technical and clinical project aiming to create an efficient VR-based game to improve the upper limb function of children with CP by encouraging them to use their affected hand as well as to improve their movement and motor control of the limb (Yamaguchi et al, 2012).

1.2.1 Virtual Rehabilitation System. Our system for rehabilitation propose a catching task (see Figure 1). Standing upright in front of a screen monitor, the user can control the upper limbs of a displayed avatar by moving their own upper limbs. A Microsoft Kinect™ sensor was placed at the bottom of the screen, to capture positional data of the user's left/right hands, wrists, elbows, and shoulders in 3D space. Our system maps the data to the movements of the avatar's limbs. The movements of the avatar's hands are represented on a circle displayed at the center of the screen. Positional data is converted to 2D positional data and rendered in real time to provide visual feedback to reduce motor errors. The sample rate of the Kinect sensor was simulated in the catching task. The sample rate data were collected while the catching task is played for 2 minutes. As a result of the simulation, the average sample rate was 20.67 Hz (SD = 2.51). According to the simulated average sample rate, the joint positions were recorded about 20 times per second.

1.2.2 Catching Task. In the proposed catching task, virtual objects appear randomly at the border of screen, one by one, and move toward the center. The user controls the virtual limbs of the avatar in an attempt to touch a virtual object moving around within the virtual space. The application emulates multiple properties of the virtual object, including direction and velocity of movement, size or shape. If the user catches one object before it arrives at the center, he or she wins one point. The system supports two interaction techniques: (a) One hand (only the left or right hand is used) and, (b) both hands (left/right hands are used simultaneously or separately). Each interaction technique trains the subject's arm movements though a virtual-object touching task in which a user is required to touch a target object traveling in various directions within the virtual space using their activated hand (e.g., left hand if the selected interaction technique is left hand interaction).

1.2.3 Control/Display Ratio. The avatar is mapped directly to the user's movements with a 1:1 ratio. In addition, it is possible to increase/decrease the amplitude of the virtual movement (display) compared to the real movement (control). The control/display ratio can give children more or fewer degrees of freedom in the virtual environment with their non-paretic or paretic arm.

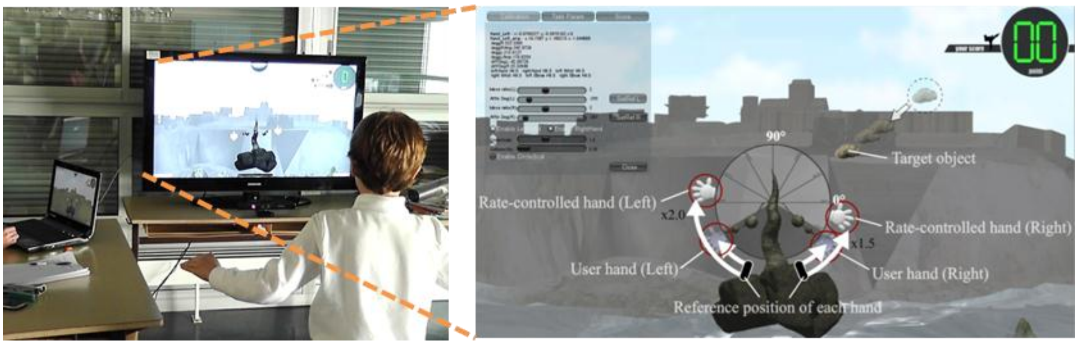

Figure 1. *An experimental setting of rehabilitation application (Left), and Screenshot of rehabilitation application – Control/Display Ratio is set up for both hands: 2.0 for the left hand, and 1.5 for the right hand. Both the left/right hand avatar disappear when the task begins. The degree of the object's direction is rotated counter-clockwise (Right).*

1.3 Arm Movement Pattern and Strategy

In our previous studies, we assessed the effectiveness of the proposed system as described above focusing on the possibility to increase the amplitude of the virtual movement (display) compared to the real movement (control).The first study conducted with 12 university students (mean age = 24.3 years, SD= 3.3) showed that the control/display ratio of the prototype application was related to task difficulty, movement strategy, and user motivation. The virtual catching task provides rehabilitation by reproducing the upper limbs movements. We also found that the user could be challenged, excited, and motivated to perform the task with a Control/Display (C/D) of 1.5 and 2.0 (Yamaguchi et al, 2012). Concerning the C/D 1.0 condition, the users commented that the movement was realistic, natural and simulated. This result indicates that user motivation as well as user's arm movement pattern can be changed with different C/D ratios, that is, with task difficulty. Pasch et al. (2008) have identified two strategies while gamers are playing the Nintendo Wii Boxing game: *Game* and *Simulation*, as well as the related movement patterns with these strategies. With the first strategy of *Game,* gamers aim for a high score, resulting in two different movement patterns: (1) low punch amplitude and corresponding low physical intensity, (2) high punch amplitude and high physical intensity. In the second strategy of *Simulation*, gamers appear to imitate real-life boxing.The results indicate that there is a relationship between arm movement pattern and its strategy based on task difficulty. In fact, there have been previous research works about the relationship between ability/level of learning and game difficulty (Greitzer et al, 2007; Hunicke et al, 2004). However, it is not clear how movement strategy could be changed corresponding to the movement pattern. Moreover, there is little research about the movement pattern based on time series data.The purpose of this study is to explore how the arm movement and the related strategy can be changed in the virtual catching task. We recruited elementary school children and children with CP to analyze their arm movement pattern.

2. EXPERIMENT WITH HEALTHY CHILDREN

2.1 Participants

Fifty healthy children, aged from 6 to 11 years were studied. All were recruited from the same French primary school, in a rural area. All the parents gave informed consent to participate in this study, according to the guidelines of the Institutional Review Board of Northwestern University Medical School. There were 25 girls and 25 boys. Their mean age was 8.79 years (SD = 1.39). There were 3 left handed children, 9 ambidextrous and 38 right handed children.

2.2 Apparatus

One Kinect sensor was employed for the virtual catching task. The Unity3D platform was used for graphic rendering. All children were placed in a standing position at a distance of about 3 meters from the Kinect sensor.

The equipmentsused for the VR-based game was a Toshiba laptop running on Windows 7 (Processor: Intel Core i7 720QM, RAM: 4GB), a 1920x1080 pixels 42" Samsung screen (to improve immersion and provide real-life scale) and a Kinect as motion sensor.

2.3 Outcome Measures

Quantitative and qualitative data were collected during this experiment, as follows: i) The performance on the VR-based game was measured by the system in the three conditions, namely *dominant hand* (DH), *non-dominant hand* (NDH) and *independent hand* (IH, either dominant or non-dominant hand, or both); ii) The children's motion was recorded by the system in real time; iii) and as qualitative data, children's behavior during interaction with our VR-game was categorized by analyzing video recordings of the game sessions.

2.4 Task Procedure

Children were asked to stand upright at a distance of about 3 meters from the screen and were given a brief phase of familiarization. They were encouraged to move around while looking at the avatar and given additional explanations about the interaction without any specifications that could constrain their movements in order to observe the most natural motor behavior. Children were required to perform the virtual catching task as described in 1.2.2 by setting the focus hands used to catch target objects. The focus hands consist of three game sessions as following, in randomized order:

(i) DH session including 52 objects to touch with the dominant hand;

(ii) NDH session including 52 objects to touch the non-dominant hand;

(iii) IH session including 52 objects to touch with any hand (i.e., dominant *and/or* non dominant).

2.5 Results

2.5.1 Classification of arm movement pattern. Firstly we reviewed video recordings that were taken during the experiment to explore the behavior of the participants during the experimental task. Based on the result of the review process, we found a number of feature pattern of arm movements. We assumed that children chose their movement pattern based on their physical limitations. In order to automatically extract their movement patterns, we carried out rough pattern classification from the video recordings of the experimental task.

As a result from the classification using video recording data, we categorized the arm movement pattern into three behavior stages:

- *Initial position*: the initial arm position at the beginning of a virtual catching task and when catching a virtual object.
- *Reaching path*: the path of arm movement when reaching a target virtual object.

- *Waving form*: the form of arm waving when reaching a target virtual object.

In each of the three stages, we divided into some movement patterns of the ways the children moved their arms.

2.5.2 The movement pattern in "Initial position (IP)"stage. Initial position stage is defined as the position at the start of the catching task. The *Initial position* stage consists of three patterns: **IP1** is the pattern that occurs when the child keeps the arms at the position of the previously caught object, **IP2** is when the arms return to a fixed position, and **IP3** is when the child puts his or her arms down (Figure 2).

As described in *3.4*, subjects were required to catch 52 objects in each session. We analyzed the video recordings and counted the number of time each of the three patterns in the *Initial position* were observed. This process is applied to all tasks in each session.

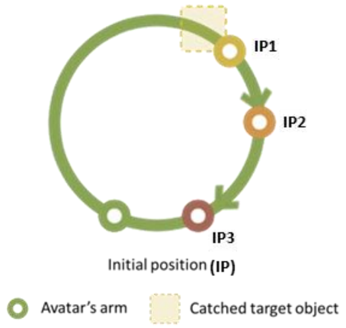

Figure 2. *Classified arm movement patterns stage: Initial position*

2.5.3 The movement pattern in "Reaching path" stage.Reaching path stage is the stage when the child is making a strategy on how to catch the target object. The *Reaching path* stage consists of two patterns: **RP1** is the pattern when the child moves his or her arms by the shortest distance to the object, and **RP2** is the pattern when they move the arms in the reverse direction to reach the target object. Table 3 shows the details of the pattern classification (Figure 3). We performed similar video analysis and counted the number of occurrences of each of the *Reaching path* patterns in all the catching tasks.

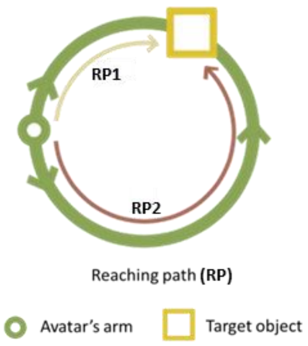

Figure 3. *Classified arm movement patterns stage: Reaching path*

2.5.4 The movement pattern in "Waving form (WF)" stage.Waving form stage is a form of waving arm to catch target objects. The *Waving form* consists of two patterns: **WF1** is the pattern of large swinging movements, and **WF2** is the pattern of small swinging movements. We performed similar video analysis and counted the number of occurrences of each of the *Waving form* patterns in all the catching tasks.

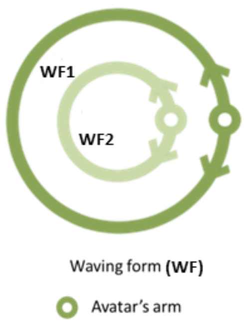

Figure 4. *Classified arm movement patterns stage: Waving form*

3. EXPERIMENT WITH CP CHILDREN

The following section describes the experiment with children diagnosed with CP. The previous section outlines the selected participants, the materials, the procedure and the data analysis of the first study. As a next step, we conducted experiment targeting children with CP. Cerebral palsy may affect children's posture, balance and ability to move, communicate, eat, and sleep. Children with cerebral palsy may have specific learning difficulties, motor planning difficulties such as organization and sequencing, perceptual difficulties and language difficulties. They may have uncontrolled or unpredictable movements. Their muscles can be stiff, weak or tight and in some cases they may have shaky movements.

3.1 Participants

We have recruited 3 children with CP in this study. There were two female with left dominant hands, and one male participant with right dominant hand. Their mean age was 7 years (SD = 2.08).

3.2 Apparatus

We employed exactly the same apparatus as we used in the experiment for healthy children as described in 3.2.

3.3 Task Procedure

Children with CP were asked to perform the virtual catching task in the same way as described in 3.4 for several times in 10 days, during the morning and afternoon of the day. In this study, we added one more focus hand condition: BOTH condition (BH) when the children used *both* left and right hands simultaneously, and INDEPENDENT condition (IH) when the dominant hand *and/or* non dominant hand could be used separately.

3.4 Results and Discussion

We determined the pattern incidence rate in each stage from the data of 50 healthy children as well as from the data of three children with CP in10 days. The pattern incidence rate was calculated using an equation as follows:

$$Pattern\ incidence\ rate[\%] = \frac{The\ number\ of\ occurrence\ of\ the\ pattern*100}{The\ sum\ of\ number\ of\ occurence\ of\ all\ pattern\ in\ the\ category} \qquad (1)$$

3.4.1 Time series changes of movement pattern distribution of children with CP. Figure 5 illustrates the time series changes of pattern incidence rate of each movement pattern in *Initial position* stage. *Initial position* stage consists of three patterns as described above. Each bar chart shows the average ratio of movement pattern of three children with CP**.**

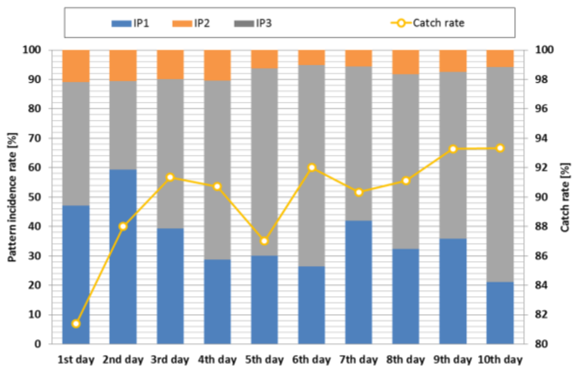

Figure 5. *Time series changes of averaged pattern incidence rate of each movement pattern in* Initial position *stage (The focus hand is LEFT).*

A chi-square test was performed to compare the ratio of movement pattern between CP 1st day and CP 10th day data, and we found a significant trend (Chi-square = 19.9299, *df* = 2, *p* value < 0.001). The pattern IP3 has a trend to be increased with the catch rate (successful rate of the virtual catching task). As for the pattern IP1 and IP2, there was a trend to be decreased over time. From the result of the significant trend, we assumed that the children with CP have a tendency to select a strategy that has a low physical workload to increase the performance of the catching task.

Figure 6 illustrates the time series changes of pattern incidence rate of each movement pattern in *Reaching path* stage. *Reaching path* stage consists of two patterns. Each bar chart indicates the average ratio of movement pattern of three children with CP.

The bar chart on the 1st day includes 80% (SD = 3.54) of pattern RP1 and 20% (SD = 1.13) of pattern RP2.These patterns did not dramatically change on the 10th day with RP1 at 77% (SD = 2.74) and RP2 at 23% (SD = 1.88). A chi-square test was conducted to compare the ratio of movement pattern between CP on the 1st day and on the 10th day and no significant difference was found (Chi-square = 0.0478, *df* = 1, *p* value = 0.827). It can be concluded that movement strategy of CP children has not changed after10 days. However, RP1 pattern was mostly selected by CP children.

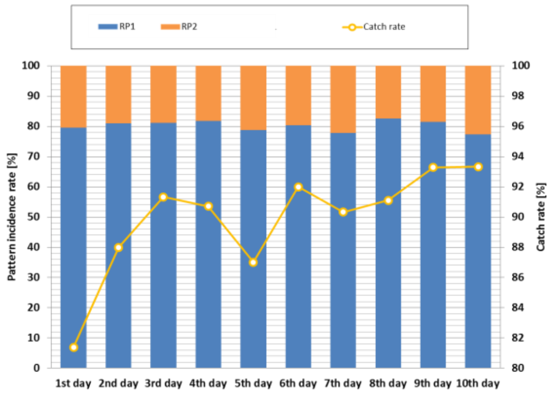

Figure 6. *Time series changes of averaged pattern incidence rate of each movement pattern in* Reaching path *stage(the focus hand is LEFT).*

Figure 7 shows the time series changes of pattern incidence rate of each movement pattern in *Waving form* stage. *Waving form* stage consists of two patterns. The bar chart on the 1st day shows 49% (SD = 4.82) of pattern WF1 and 51% (SD = 7.38) of pattern WF2, and the patterns were not dramatically changed on the 10th day with WF1 at 58% (SD = 5.81) and WF2 at 42% (SD = 8.81). A chi-square test was performed to compare the ratio of movement pattern between the 1st day and the 10th day and there was no statistically significant difference (Chi-square = 1.1937, *df* = 1, *p* = 0.2746). CP's movement strategy did not change after 10 days.

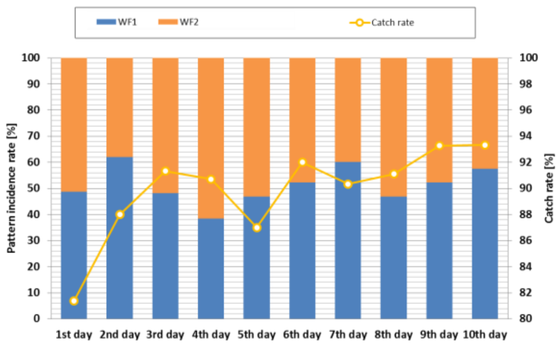

Figure 7. *Time series changes of averaged pattern incidence rate of each movement pattern in* Waving form *stage (the focus hand is LEFT).*

*3.4.2 Comparison of the movement pattern distribution.*Figure 8 illustrates the comparison between the movement pattern distribution of the children with CP and that of healthy children. The first two columns on the left represent the average ratio of movement pattern of the CP children on the 1st and the 10th day. The rightmost column indicates the average ratio for the healthy children.

A chi-square test was performed to compare the ratio of movement pattern between CP on the 10th day and healthy children data and there was a significant difference (Chi-square = 45.9485, *df* = 2, *p* < 0.001). We previously expected that both CP children and healthy children would eventually have the same strategy of opting for a low physical workload. However, the data shows that they are different. Healthy children prefer IP1 movement pattern. With IP1, the healthy children can optimize their reaching distance to a target object so that they can touch the next object easily with less arm movement. CP patients changed their strategy to IP3 instead, opting to a fixed position to return their hands. We assume that it was hard for them to keep the hands at the same position where they catch a target object since they have difficulty moving their arm.

Figure 9 illustrates the comparison of the movement pattern distribution of the children with CP and that of healthy children. The first two columns on the left represent the average ratio of movement children with CP on the 1st and the 10th day. The rightmost column indicates the average ratio for the healthy children. Pattern RP1 was the most selected movement strategy by the healthy children as well as the CP children.

A chi-square test was performed to compare the ratio of movement pattern between CP children on the 10th day and healthy children data, and there was no significant trend (Chi-squared = 0.017, df = 1, p = 0.8964). The ratio of movement patterns of the patients did not change from the 1st day of the training to the last day, as previously described in *4.4.1*. The result indicates that the *Reaching path* stage does not affect the physical condition as well as the achievement rate of the applied task.

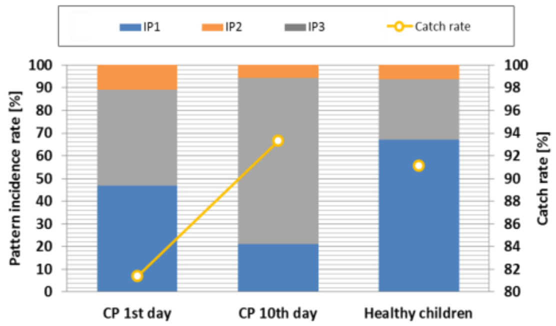

Figure 8. *Comparison of each pattern incidence rate of healthy students and patients in* Initial position *stage (The focus hand is LEFT).*

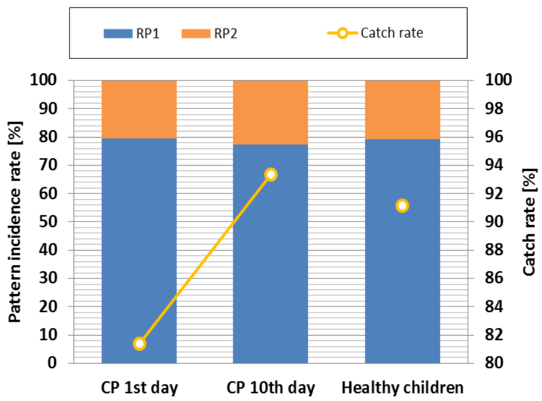

Figure 9. *Comparison of each pattern incidence rate of healthy students and patients in* Reaching path *stage (The focus hand is LEFT).*

Figure 10 illustrates the comparison between the movement pattern distribution of the children with CP and that of healthy children. The first two columns on the left indicate the average ratio of movement pattern of the CP children. The rightmost column shows the average ratio for the healthy children. A chi-square test was performed to compare the ratio of movement pattern between CP children on the10th day and healthy children. There was no significant trend (Chi-squared = 0.7247, df = 1, p = 0.3946).The pattern of the CP children did not change from the 1st day of the training to the last day as described in *4.4.1*. The result indicates that the *Waving form* stage does not affect physical condition as well as achievement rate of the applied task.

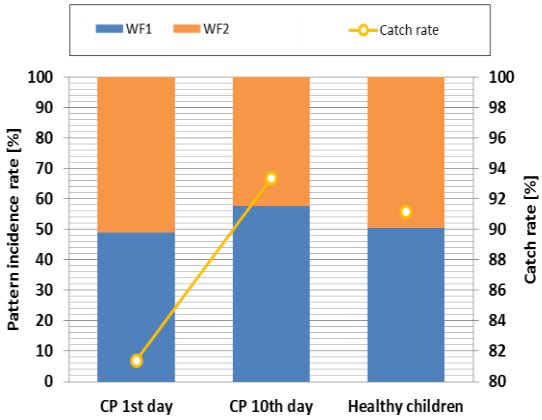

Figure 10. *Comparison of each pattern incidence rate of healthy students and patients in* Waving form *stage (The focus hand is LEFT).*

4. CONCLUSION

Cerebral palsy refers to various motor impairments caused by damage to the central nervous system during foetal development. Our VR-based game is been designed to encourage children to use their affected limb. In this paper, we explore how the arm movement pattern as well as the related strategy of children with Cerebral palsy and healthy children can be changed in the virtual catching task on the previously proposed rehabilitation system. We analyzed video recordings during the virtual catching task for both healthy children and CP children over 10 days and categorized arm movement stages into: *Initial position*, *Reaching path*, and *Waving form*, as well as movement pattern strategy under each movement stage.

For the CP children's data, we found that movement strategy in *Initial position* stage was changed at the last day of training from the pattern IP1on the 1st day where the child keeps the arms at the position of the previously caught object to pattern IP3 where they put his/her arms down. The most selected movement pattern in *Reaching path* stage was pattern RP1 when the child moves the arms by the shortest distance to the object, and the trend was not changed at the last day. For *Waving form* stage, the most selected movement pattern was pattern WF1 of large swinging movements, and the trend was not changed at the last day.

For the healthy children's data, the most selected movement pattern in *Initial position* was pattern IP1 where the arms are kept at the position of the previously caught object. This is a different trend from the CP children. The most selected movement pattern in *Reaching path* stage and in *Waving form* for healthy children were the same as that of the CP children.

As a future works, we plan to analyze the relationship between movement pattern/strategy and their motivation changes during rehabilitation task. We also plan to extend our system to enable dynamically adjusting a task difficulty based on patient movement pattern/strategy.

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