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Wrist range of motion and motion frequency during toy and game play with a joint-specific controller specially designed to provide neuromuscular therapy: A proof of concept study in typically developing children

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ABSTRACT

Upper extremities affected by hemiplegic cerebral palsy (CP) and other neuromuscular disorders have been demonstrated to benefit from therapy, and the greater the duration of the therapy, the greater the benefit. A great motivator for participating in and extending the duration of therapy with children is play. Our focus is on active motion therapy of the wrist and forearm. In this study we examine the wrist motions associated with playing with two toys and three computer games controlled by a specially-designed play controller. Twenty children (ages 5–11) with no diagnosis of a muscular disorder were recruited. The play controller was fitted to the wrist and forearm of each child and used to measure and log wrist flexion and extension. Play activity and enjoyment were quantified by average wrist range of motion (ROM), motion frequency measures, and a discrete visual scale. We found significant differences in the average wrist ROM and motion frequency among the toys and games, yet there were no differences in the level of enjoyment across all toys and games, which was high. These findings indicate which toys and games may elicit the greater number of goal-directed movements, and lay the foundation for our long-term goal to develop and evaluate innovative motion-specific play controllers that are engaging rehabilitative devices for enhancing therapy and promoting neural plasticity and functional recovery in children with CP.

1. Introduction

The prevalence of cerebral palsy (CP) has risen in the last 40 years and is now estimated at approximately 3 out of every 1000 children in the US (Boyle et al., 1994; Murphy et al., 1993; Odding et al., 2006). Although there is a wide range of presentations, the upper extremity function is commonly affected, and often more pronounced than the lower limb (Arner et al., 2008; Makki et al., 2014; Wiklund and Uvebrant, 1991). Wrist extensors/flexors and forearm supinator/pronator muscles are profoundly affected in most children with hemiparetic CP and are the major target of neuromuscular therapy efforts to restore useful hand functions (Wilton, 2003).

Therapy approaches vary widely, including intramuscular injections of botulinum toxin type A (Pfeifer et al., 2014), occupational/physical therapy (Elliott et al., 2011; Mayston, 2005, 2001; Wilton, 2003), various forms of constraint-induced movement therapy (Brady and Garcia, 2009; Eliasson et al., 2005; Taub et al., 2007), and robotic therapy (Fasoli et al., 2008; Frascarelli et al., 2009). While there are benefits and trade-offs among these therapies, one overriding principal is that more therapy leads to a better outcome (Damiano, 2006). A meta-analysis of 42 studies suggested that meaningful clinical outcomes may be correlated more with the dose of therapy than the specific treatment approach (Sakzewski et al., 2014). Additionally, there was strong evidence that goal-driven therapy programs – those that involved tasks motivated by achieving individualized objectives – were

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more effective than standard care in improving upper limb and individualized outcomes (Sakzewski et al., 2014).

Our approach was to develop a goal-directed therapy that is joint specific. The joint specific requirement stemmed from our observation that while whole-body exercise, facilitated with systems such as the Ninetendo Wii (Deutsch et al., 2008; Saposnik et al., 2010), has clear benefits, repetitive targeted therapy of specific muscle groups, especially in the hand and wrist, is essential in all stages of a rehabilitation program (Oujamaa et al., 2009). To maximize the dose of intervention, we turned to play as a motivator. Accordingly, we designed a toy and game play controller that requires specific joint movements to trigger play events. In its present configuration, the controller enables play with remote controlled toys and computer games using wrist extension and flexion. This approach could provide inexpensive home-based therapy to supplement institutional PT/OT, thus maximizing the dose of therapy received.

Engagement through play is crucial to maximizing the dose of intervention. Therefore, identifying what kinds of toys and games are most engaging and which elicit the greatest number of goal-directed movements with the controller is particularly important for our approach. As a first step, we sought to examine these factors in a control population of children with no diagnosis of a neuromuscular disorder. The aim of this study was to evaluate play activity recorded by the controller for two toys and three computer games. We sought to determine if play activity, quantified by range of motion (ROM) and motion frequencies, differed among specific toys and games. We also sought to determine if the child's feedback from a discrete visual scale (DVS) questionnaire of fun and difficulty of play would correlate with measures of play activity.

2. Methods

2.1. Subjects

With IRB approval, children ($n=20$, 15 male, 5 female, 5–11 years, 19 right handed, 1 left handed) were recruited to participate in the study. Eligibility requirements specified that the children have the cognitive ability to follow instructions and no limitations of upper extremity function. The mean (1SD) active wrist ROM for these children was 137°(12°). All children participated in a structured in-clinic play session, during which they played with 4 of 5 different toys and computer games for approximately 5 min each. The order of the toys and games was randomized prior to subject arrival. The sessions were conducted in designated rooms with ample floor space for playing with the remote controlled toys, and a table for a laptop computer that contained the games.

2.2. Device

A specially designed play controller was used to interface wirelessly with the toys and games, to provide programmable thresholds for play ROM, and to log data of wrist motion during play (Fig. 1a) (Crisco et al., 2015). The play controller was designed to accommodate children of various ages and levels of contractures among children with CP. The controller (approximately 185 g) is composed of four main components: a removable and customizable foam handle, plastic wrist hinge, soft fabric forearm cuff, and electronics closure. The handle is composed of closed-cell foam tubing (1" diam.) wrapped over a malleable aluminum alloy wire (0.14" diam.) connected to the wrist hinge. The length of the foam and the length and shape of the removable wire are readily customized to fit each child's hand and wrist. The single axis wrist hinge is 3D-printed ABS plastic (25 mm diameter) and houses a potentiometer (10 kΩ linear taper, 300 ± 5°) to measure wrist flexion/extension motion. The wrist hinge is rigidly attached to a thin sheet of aluminum that is embedded within the fabric forearm cuff. The fabric for the forearm cuff and two straps is breathable, open-cell foam bonded to a smooth nylon tricot on one side and a high-nap fabric on the other side to accommodate hook-and-loop fasteners (AirFlex, Eastex Products Inc., Holbrook, MA). An additional strap assists in securing the child's hand to the foam handle grip. The electronics of the controller are encased within a 3D-printed ABS plastic shell (82 mm × 75 mm × 34 mm, 55 g) and attached to the forearm cuff with a hook-

Fig. 1. Controller, remote controlled toys, and computer games. (a) Specially designed play controller used to wirelessly control toys and games. A potentiometer in-line with the flexion–extension axis records wrist motion. Wrist position thresholds to trigger play are set using buttons on the electronics case. (b) Remote controlled toys: BounceBack Racer® (Toy 1) and GoGo® (Toy 2). (c) Computer games: Bouncing Balls® (Game 1), Snowman® (Game 2), and Lineup® (Game 3).

and-loop fastener. During the fitting process the handle was customized to visually align the axis of the rotary potentiometer with the palpated distal tip of the radial styloid and then the controller was secured in this position using the forearm cuff system.

For each child, a play threshold position was set in flexion and in extension using the controller's software. This feature was specially designed to allow children with limited wrist motion to have a complete play experience, while also providing the therapist with an easy approach to expanding the child's play thresholds as their ROM progresses with treatment. For wrist movements greater than 4°, wrist position was logged and time-stamped. The design of the controller has been previously detailed and the accuracy of wrist measurements was found to be within 5° of a typical optical motion capture system (Crisco et al., 2015).

2.3. Study design

At the start of the play session, the dominant wrist and forearm of each subject were fit with the controller. Play thresholds, defined as the wrist flexion and extension positions that triggered toy/game response, were each set at a comfortable position within the child's maximum range of motion in each direction by placing the controller into a specific sampling mode and then holding the child's wrist in the desired position.

Two remote control toys used during the play session were the BounceBack Racer® (Toy 1) and GoGo® (Toy 2) (Hasbro Inc., Pawtucket, RI, USA) (Fig. 1b). Toy 1 is a two-sided (i.e. no top or bottom), one degree of freedom remote controlled (RC) car that moves either forward or backward at a constant speed. If the subject's wrist position is within the range of the play thresholds, the car does not move. If the subject's wrist position reaches or exceeds the flexion or extension play threshold, the car will drive either forward or backward. The direction of travel is reversed when the wrist position crosses the opposite threshold. Switching rapidly between the flexion and extension thresholds can cause Toy 1 to flip over and continue driving on the other side. Steering (turning left or right) cannot be controlled; however, slop in the housing of one wheel mount allows the toy to drive in a straight path in one direction and in a curved path in the opposite direction. GoGo® (Toy 2) is an animatronic RC dog that turns left or right when the subject holds his/her wrist beyond the flexion or extension threshold set on the controller. The dog does not move when the subject's wrist is within these thresholds. Toy 2 makes panting, barking, and whimpering sounds autonomously. Toy 2 also moves at a constant but slower speed than Toy 1. Plastic cups emulating cones were set on the floor to be knocked over or maneuvered through to further increase engagement for both toys.

Three computer games used during the play sessions were selected from a collection of simple and adaptable games (Nanogames Inc., Christchurch, New Zealand) (Fig. 1c). In Bouncing Balls® (Game 1), mouse movement is used to aim a cannon that shoots colored balls at a conglomerate of balls moving from the top of the screen downwards. The child steers the cannon with the controller and shoots a ball by pressing the space bar with his/her other hand. When groups of 3 or more identically colored balls are created, the group disappears. Snowman® (Game 2) is a downhill skiing game where the child steers a snowman left and right using the play thresholds to collect snowman body parts (sticks, coal, carrots) on the ski slope while avoiding trees. When all the body parts are collected the game progresses to the next level and the snowman speeds up. Game 2 is the only computer game of the three in which play events are triggered by the controller thresholds, and solely activated by the controller (i.e. no additional keystrokes). Lineup® (Game 3) is a Connect Four® style game where the controller simulates analog mouse movement to move a pointer over the desired column. The child must then press the spacebar to drop a piece. The child plays against a virtual opponent.

The duration of play with each toy and game was approximately five minutes, but this time varied because it was influenced by the time constraints of the child/parent/clinic schedule for some participants, and therefore was unlikely to be representative of the child's engagement.

2.4. Data analysis

Wrist flexion–extension motion during play was recorded and downloaded for analysis by toy/game. For each toy/game, the play motion was reduced to three variables: average wrist motion, play frequency, and ROM frequency. The average wrist motion was computed as the sum of the mean peak flexion and mean peak extension angles across all cycles of motion during play. Play frequency was computed as the number of flexion–extension cycles divided by the time over which play occurred. The peak flexion and extension values were reduced to values that were within 10% of the child's maximum ROM. The frequency of these cycles was computed as the ROM frequency.

After each play session the child was asked to answer a series of questions. These questions were administered using a discrete visual scale (DVS) with colored smiley faces corresponding to ratings 1 through 5, with 5 being the most favorable. The same three play-rating questions were asked for each toy/game. The questions asked were (1) "How much fun was this toy?", (2) "How hard was it to use this toy?", and (3) "How much do want to play with this toy again?".

2.5. Statistical analyses

Comparisons of the play motion variables (average wrist motion, play frequency, and ROM frequency) among toys and games were done using independent Kruskal–Wallis tests with a post-hoc Dunn's test for multiple comparisons. Significance in the mean differences was set a priori at $p < 0.05$ and when multiple comparisons are described only the largest p value is reported. To examine if the DVS questions differed with toy/game and if they correlated with the ROM frequency, generalized models were used with repeated measures from the same participants modeled as having correlated error (generalized estimating equations). Differences in DVS scores were modeled using a binomial distribution (highest endorsement out of highest positive). The generalized model predictions of the DVS score of each question are reported as means and 95% CI. Alpha was maintained at 0.05 across comparisons using the Holm method to adjust p-values.

3. Results

There were significant differences in average wrist motion during play between several of the toys and games (Fig. 2). There

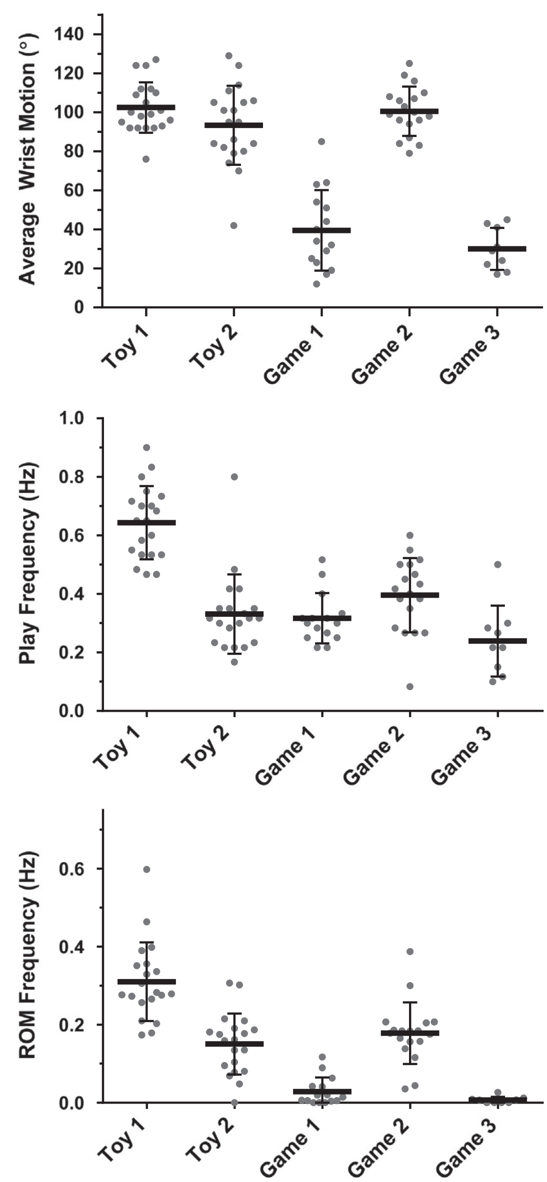

Fig. 2. Biomechanical measures of play activity among each of the toys and games. Significance of the differences in the means among the toys and games are described in Section 3.

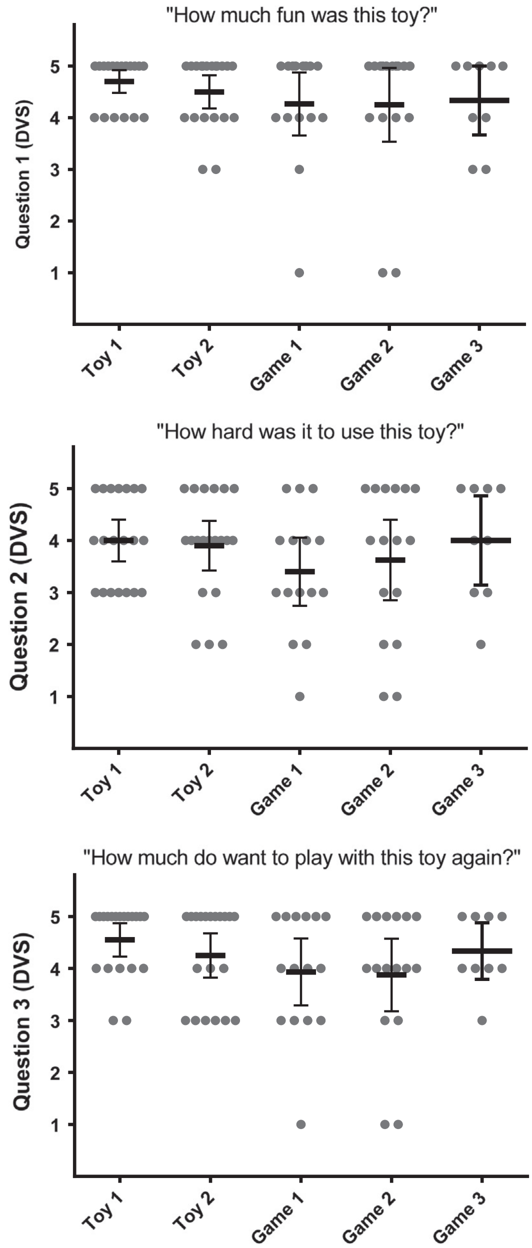

Fig. 3. DVS data and mean and 95% CI for each of the three questions. The score of 5 was the most favorable and 1 was the least. Toys 1 and 2 and Game 3 tended to evoke more fun and less difficulty, but these differences were not significant.

were no differences among Toy 1, Toy 2, and Game 2, and each had significantly greater average wrist motion than Games 1 and 3 ($p < 0.05$), which were not different from each other.

Play frequency was greatest for Toy 1 with a mean of 0.6 Hz and this mean was significantly higher than the mean play frequency for Toy 2 and all three games ($p < 0.01$) (Fig. 2). Mean ROM frequency was again greatest for Toy 1 (0.3 Hz) and significantly more than Toy 2, Game 1, and Game 3 ($p < 0.05$), but the mean ROM frequency of Toy 1 was not significantly greater than that for Game 2 (0.2 Hz) (Fig. 2). The mean ROM frequency of Toy 2 was significantly more than that for Games 1 and 3 ($p < 0.05$), but it was not different than the mean ROM frequency Game 2. The mean ROM frequencies for Games 1 and 3 were not different.

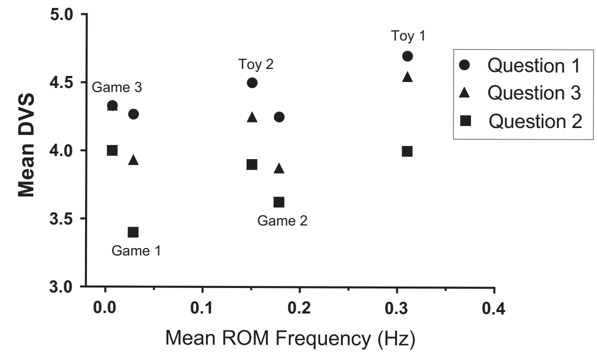

Fig. 4. There was a general trend of higher ROM frequency with more favorable DVS scores.

The mean DVS scores (Fig. 3) ranged from 3.4 to 4.7 and did not differ significantly among the toys or games for Question 1 ($p = 0.237$), Question 2 ($p = 0.530$), or Question 3 ($p = 0.246$).

There was a general trend in which increasing ROM frequency was associated with increasing DVS score for each question (Fig. 4). Correlations between ROM frequency and DVS score were only significant for Question 1 of Toy 1, in which a DVS score of 4 was associated with a higher value of ROM frequency than a DVS score of 5 ($p = 0.0032$).

4. Discussion

Our long term goal is to develop and evaluate innovative motion-specific play controllers that are engaging rehabilitative devices for enhancing therapy and relying on neural plasticity to promote functional recovery in children with CP. The aim of this study was to evaluate different toys and games that can be controlled by these motion-specific play controllers, to determine what toys are the most engaging, and which would elicit greater numbers of goal-directed movements. We evaluated play activity, wrist motion and time, recorded by the play controllers for two toys and three computer games. We sought to quantify play activity to determine if it differed among toys and games. We also sought to determine if child feedback from a discrete visual scale (DVS) questionnaire of fun and difficulty of play would correlate with measures of play.

Despite no differences in the fun of playing among the toys and games we found differences in average wrist motion between several of the toys and games. The remote control toys (Toys 1 and 2) and Game 2 had greater wrist motion that Games 1 and 3. Interestingly, Game 2 is the only computer game that utilized the play thresholds set for each individual child. Games 1 and 3 were an analog representation of the child's wrist motion mapped to the screen. While Games 1 and 3 may have a benefit in that they require fine motor control, this difference attests to the fact that goal directed therapy (where thresholds are set and must be met for toy/game response) may promote individuals to target larger movements of the affected joint. Differences in frequency measures were also found between the toys and games. Not surprisingly, Toy 1 had the highest frequency as we observed that the fast pace of Toy 1 play and goals such as trying to flip it over by quickly switching between flexion and extension elicited excitement and hence rapid wrist movement. It was clear that certain toys and games promoted larger range of wrist motions, and larger number of flexion/extension cycles.

The extent of flexion/extension motion elicited during the play sessions, specifically for Toy 1, suggests potential for this system to yield functional recovery if implemented as an extended therapy program. Mean play frequency elicited by Toy 1 (0.6 Hz) is of comparable magnitude to repetition frequency facilitated by a robotic arm trainer that showed improvement in upper limb motor control in severely affected stroke patients in a 4-week training program (Hesse et al., 2005).

DVS scores were generally favorable for all toys and games and provided a quantifiable measure for fun and difficulty of use. There was an interesting trend in which increasing ROM frequency was associated with increasing DVS score for each question (Fig. 3). Intuitively, a toy or game that elicits more wrist movements closer to an individual's maximum range of motion should be more challenging than one that does not. That both "fun" and "ease" measures increased as ROM frequency increased may indicate that challenging play is more engaging. While this is an interesting postulation, it should be noted that these results may be specific to the population of this study and may differ in a cohort of children with upper extremity impairment.

This study has several limitations. The play sessions were administered in a clinical setting as opposed to a home setting and an inherent bias was introduced as the children seemed to want to please the researchers by answering the questions positively. This study only presents data from children with no diagnosis of a neuromuscular disorder. While this study was an important first step in identifying which toys and games are the most engaging and elicit the highest frequency of targeted motion, the expansion of this study to children with CP is necessary to fully understand these parameters in our target population. We recognize that many children with CP may have contractures and or spasticity that may prevent them from fully engaging in play with this controller. Because of this we note that the play threshold positions for the controller can easily be set to any position by the therapist. Ideally, therapists will adjust these thresholds as the goals for child's ROM change during the course of therapy. All the toys and games in this study were performed at a constant speed. We also note that these toys and games are limited in that each child plays them with a single controller; a play experience that requires peers would likely further engage the children. The wireless protocol for the controllers and toys allows for multiple pairs of controllers and toys to be used in one room. This was not tested as part of the study, but an informal group play session generated positive reactions from children. In the current design of the controller the wrist movements are time stamped at 4° increments in order to conserve data storage. This limits the accuracy with which we can compute the speed of wrist motion and therefore these measures were not reported.

Our long term goal is to develop and evaluate innovative motion-specific play controllers that are engaging rehabilitative devices for enhancing therapy and promoting neural plasticity and functional recovery in children with CP. In a population of typically developing kids, the specific goals of this study were to evaluate different toys and games that can be controlled by these motion-specific play controllers to determine what toys and computer games are the most engaging and which would elicit the greater number of goal-directed movements.

Conflict of Interest:

An author (JJC) is an inventor on a patent describing a method for facilitating fitting of the play controller to the child's forearm using a malleable inner structure. The patent is owned by his employer, Rhode Island Hospital, Providence, Rhode Island, USA.

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