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Quantifying Infant Physical Interactions using Sensorized Toys in a Natural Play Environment*

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Abstract

Infants with developmental delays must be detected early in their development to minimize the progression of motor and neurological impairments. Our objective is to quantify how sensorized toys in a natural play environment can promote infant-toy physical interactions. We created a hanging elephant toy, equipped with an inertial measurement unit (IMU), a pressure transducer, and multiple feedback sensors, to be a hand-grasping toy. We used a 3 DoF robotic model with inputs from the IMU to calculate multiple kinematic metrics and an equation to calculate haptic metrics from the pressure transducer. Six typical infants were tested in the gym set-up. Three infants interacted with the toy for more than half the trial time. The youngest infant exhibited the largest toy displacement with $D = 27.6$ cm, while the oldest infant squeezed the toy with the largest mean pressure of 4.5 kPa. More data on both typical and atypical infants needs to be collected. After testing atypical infants in the SmarToyGym set-up, we will be able to identify interaction metrics that differentiate atypical and typical infants.

I. Introduction

Cerebral palsy (CP), defined as a group of permanent disorders of the development of movement and posture due to non-progressive disturbances in the fetal brain [1], affects millions of children and adults worldwide. The most significant risk factor of CP, causing about 41.5% of diagnoses, is preterm birth, happening at the gestational age of 36 weeks or earlier [2], [3]. Encouraging the early diagnosis of CP in infants can lead to early intervention, which is vital for optimal development [3], [4]. At this early stage, plasticity is very high in the infant brain, allowing for easier reorganization [3]. However, most current methods of CP identification are qualitatively based and require an expert on-site for

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evaluation. One example is the Bayley Infant Neurodevelopmental Screener (BINS). The screener relies on a trained expert that provides the infants with specific tasks and scores the infant based on observation. In a literature review examining assessments used to discriminate, predict, or evaluate preterm infant neuromotor development, Spittle et al. discovered that the more predictive assessments were costly and time-consuming [5]. Approximately 50% of pediatricians do not even use these developmental screeners, citing time and costs as the most prominent hindrance [6]. Furthermore, assessment tools have improved predictive value for older infants, but this delays intervention and may not result in optimal developmental outcomes [5].

A quick and cost-effective quantitative assessment tool for at-risk infants could lead to better outcomes through early intervention. To address this need, we have developed the SmarToyGym, an advanced play gym used to detect and collect quantitative information on infant development in a natural, non-invasive play environment. Previous studies on infant kinematic interactions with toys had promising preliminary results. Cecchi et al. investigated the use of a biomechatronic gym with sensorized toys to assess infant grasp force. Results indicated that in typical infants, grasping stabilizes at around 8 months, inferring that any major deviation from this may be a sign of atypical development [7]. The long-term goal of this study is to collect data in a more ecological environment by letting infants engage in natural play while limiting external stimuli, as opposed to using prompts from the investigator or parents. The SmarToyGym (Fig. 1) provides a natural play environment for infants while collecting data on their interactions with sensorized toys. SmarToyGym also includes a sensorized mat and a vision system. The mat is used to capture infant motion, while the vision system is used for analyzing infant limb movements.

II. Interaction Metrics

We had to identify infant-toy interaction metrics that would differentiate typical and atypical infants. Reaching is an acquired skill at around 3-4 months [8]. In one study, ten typically developing infants were evaluated longitudinally from 4 to 9 months of age with a sensorized toy [9]. Results indicated that unimanual (one-hand) reaches increased with age while bimanual (two-hand) reaches decreased significantly [9]. Another study with preterm infants showed that these infants exhibit more bimanual reaching actions than full-term infants [10]. Grasping is acquired later than reaching at around 4-5 months [9]. Grasp pressure was also evaluated in the longitudinal study mentioned above. Mean grasp pressure increased significantly between 4.5 and 7.5 months but plateaued after [9]. The same toy was used in another study with three preterm infants, whose mean grasp pressure was significantly lower than that of typical infants [11].

According to Galloway, et al., feet reaching precedes hand reaching in typical infants by at least one month [12]. A study with very preterm infants (born at <33 weeks gestational age) investigated whether movement training would improve feet reaching [13]. Specifically, the researchers wanted to know whether the number of foot-toy contacts and contact duration would increase. Results indicated that movement training helped increase foot-toy contacts. However, contact duration did not increase [13]. From this study, we identified kick frequency, time to toy contact, and toy contact duration as metrics.

Physical interactions with the toy can be split up into kinematic and haptic interactions. Table I consolidates the wide range of possible metrics analyzed in this study; metrics with an asterisk denote those gathered from observation. We have designed three hanging toys for infant play. The toy column in Table I reveals which toy is applicable to which metric. This paper will cover the results from one specific prototype, a hanging elephant toy.

III. Design of SmarToys

Previous studies that have used toys to quantify infant-toy interactions have been good sources for the development of SmarToys. Maestro et al. outlined the development of a toy that used a pressure sensor to quantify infant grasping forces [7], [15]. First, the law of affordance was taken into account. The basic definition of this concept is that objects should be designed in such a way to suggest their use [16]. They made a soft air-filled chamber shaped as a ring and connected it to a piezoresistive pressure sensor. The sensor measured internal pressure changes from atmospheric pressure at any point in the chamber. Additionally, Campolo et al. investigated the use of a sensorized block-box toy to evaluate and monitor infant behavior. The researchers extracted raw data from an IMU to calculate relevant orientation angle and acceleration data. Their design was meant to assess spatial cognition in young toddlers, a neural function that has great potential to be different between typical and atypical infants [16]. The basic concepts from these studies were taken into account when developing the SmarToys.

A. First Generation Prototype

The first SmarToy prototype was a small toucan toy with two data sensors: an e-textile force sensor to measure grasp force (1361, Adafruit, New York City, NY) and a LilyPad accelerometer (DEV-09267, LilyPad) to quantify toy movement. The toy also contained a LilyPad MP3 player for sound feedback (DEV-11013, LilyPad) and a LilyPad vibe board (DEV-11008, LilyPad) for haptic feedback. When the infant grasped the toy at a certain threshold pressure, feedback would occur to engage infant attention and encourage interaction. To power and control the sensors, we used a LilyPad Arduino microcontroller (Arduino, Italy).

However, we discovered many problems with the prototype after testing with a typical infant subject. The force sensor was not sensitive enough to capture infant grasps. Additionally, the raw acceleration signals from the accelerometer were too noisy for double-integration to obtain toy position. The biggest problem was the outside design of the toy itself. The infant did not grasp the body of the toy that held the force sensor often, instead focusing on the colorful tail. Thus, we decided to develop the second iteration of the SmarToy prototypes to address these problems.

B. Second Generation Prototype

In the second-generation prototype toys three hanging toys (orangutan, elephant, lion) were developed (Fig. 2). There are three basic parts to the hanging toys: the 3D-printed box, rigid link, and toy itself. The box is used to hang the toys, and also holds the toy batteries. This box also holds a sync cable port, which allows for syncing between the toy and vision

system. The rigid link contains necessary wiring down to the toy. Each toy carries its own electronics. Since standard Arduino boards have limited capabilities, we created a custom-made standard PCB. The ‘Smartie’ PCB is run on 3.3V and contains an ATMEGA328P with digital pins and I2C connections for sensors. This PCB also has an SD card port to store data. Any additional prototyping boards, called ‘Annies,’ are used to consolidate electronic connections.

The elephant toy (Fig. 3) has a cylindrical air chamber in its trunk, which stands out to promote infant grasps. This air chamber is connected to a pressure transducer (MS4525 3.3V 015 DS Type A, TE Connectivity, Switzerland) that measures the differential pressure between the air chamber and atmospheric pressure, allowing for grasp detection. A soundboard (Audio FX SoundBoard, Adafruit, New York City, NY), vibe boards (DEV-11008, LilyPad), and LEDs trigger feedback once a pressure threshold is crossed. To measure toy position, we placed an inertial measurement unit (MPU-9150, InvenSense, San Jose, CA) in the toy.

To obtain toy position throughout the trial, we developed a robotic model, which assumes three revolute joints (RRR) connecting the toy by a rigid link (Fig. 4) based on DH parameters (Table II). Inputs to the model were the gyroscopic yaw, pitch, and roll angles obtained from the IMU. This model can be applied because the toy is rigidly connected to the electronic box and is able to rotate about its defined xyz axes at one fixed point. This model was validated with experimental trials by moving the toy along one axis to a fixed distance. Errors to the model are between 3-5 cm. These errors are attributed to the fact that the IMU is not rigidly fixed in a straight position and to 2% cross-axes error of the sensor itself. For clarification, for any movement about the y-axis, the IMU would pick up about 2% of the angle measured in the other two axes. Equation 1 relays how to calculate position and translate it to the toy’s base frame. At rest, $u_x = p_x$, $u_y = p_y$, and $u_z = 35 - p_z$.

$$\begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} = \begin{bmatrix} 35\cos(\theta_1^* + 90)\sin(\theta_2^* + 90) + p_x \\ 35\sin(\theta_1^* + 90)\sin(\theta_2^* + 90) + p_y \\ 35\cos(\theta_2^* + 90) - p_z \end{bmatrix} \quad (1)$$

IV. Methods

A. Patient Recruitment

Infant subjects were recruited through the Childrens Hospital of Philadelphia. Infants went through a pre-screening process to determine eligibility. Inclusion criteria for full-term infants (born at a gestational age of >37 weeks) detailed infants between the ages of 3-11 months with no history of significant cardiac, orthopedic, or neurological condition. Infants who could walk were excluded. Parents of eligible participants were then consented and gave permission for their infants to participate. The human subject ethics committee at both the University of Pennsylvania (UPenn) and Childrens Hospital of Philadelphia (CHOP) approved this study.

B. Data Collection

Data was collected from infants at the CHOP, the Honeyland Daycare in Willow Grove, PA, and at the Rehabilitation Robotics Lab. Before testing, a trained expert evaluated the infants level of risk using the BINs. This screener includes specific tasks that experts use to observationally score infants based on the Bayley Scales of Infant Development [4]. In each trial, the infant was laid in a supine position inside the gym. The order of the toys was randomly chosen; toy order was reversed for infants tested twice. Once the trials start, we minimize external stimulus by only allowing the toy to engage with the infant. If the infant did not interact with the toy within an 28-second window, then the toy will attempt to engage infant attention through auditory stimuli. Video and mat data of each trial was collected along with raw toy data stored in the SD card. Sensor data from the elephant toy included xyz acceleration, yaw, pitch, roll angles, and ADC pressure values.

We tested six full-term infants in the gym. Table III summarizes infant demographic information. Four infants were between 4-5 months of age, while two infants were between 9-11 months. Only two infants were male. The majority of infants were at moderate risk for motor delays according to the BINS assessment, which we took to mean typically-developing.

C. Data Analysis

Physical infant interactions with the elephant toy were quantified using the identified metrics in Table I. Where possible, the results were confirmed using videos. Arm reaching was the only metric gathered solely from video observation. There was one coder with multiple experts confirming metric definition. Arm reach was counted if the infant had not been in contact with the toy for >2 seconds. Both the left and the right arm were looked at to determine reach type. Any reaches solely by one arm were unimanual and any reaches with both arms were bimanual.

Custom Matlab algorithms were used to post-process the data collected. Model inputs to calculate toy position include the yaw-pitch-roll angles from the IMU. Before using them, we used a median filter to get rid of irregular spikes, a consequence of the IMU sensor itself. Then, the average of the first few settled data points was subtracted from the trial data in order to zero the IMU axes. Once we calculated toy displacement with the robotic model (Fig. 4), the points were translated to reflect movement as seen by the gym base frame (Equation 1).

In addition, the pressure transducer data in the elephant required filtering. We used a low-pass filter with a cutoff frequency of 3 Hz (determined by FFT analysis) followed by an envelope detector to isolate clear peaks. The applied pressure was calculated using Equation 2.

$$P_{app} = [(V_G - 0.33) \times \frac{P_{\max} - P_{\min}}{0.80 \times V_S}] + P_{\min} - P_{off} \quad 2$$

In this equation, P_{app} is the calculated infant grasp force. V_G is the raw voltage data. P_{max} is equal to the maximum pressure that the transducer will output, 279.2 kPa, while P_{min} is 31.02 kPa. V_s is the supply voltage of 3.3V. Subtracted at the end is a steady offset of about $P_{off} = 154.5$ kPa.

V. Results

Three of the infants (1, 4, and 6) did not engage with the toy for more than half the trial time, due to reasons such as irritable moods and disinterest. Thus, results are displayed for infants 2, 3, and 5.

A. Kinematic Metrics

Table IV relates the relevant kinematic variables for all of the infants. Infant 5, the youngest infant of the three, had the largest displacement (ΔD) at 27.6 cm. The majority of reaches were bimanual. All infants contacted the toy within the first few seconds of the trial and had a contact duration of >100 seconds.

Fig. 5 shows resulting displacement magnitude (ΔD) vs. time plots for each infant trial. The plots have digital hand reaching signals overlayed, with the left hand represented by the black dashed line and the right hand represented by the solid gray line.

Fig. 6 shows xy-excursion ellipses for all the infants. The excursions capture the full movement in the xy-plane, the equivalent of looking at the toy gym from the top-down in the base frame's z-axis. Full displacement data is shown for the first trial of infant 2 with a fitted ellipse. Table V displays the area of each ellipse. Infant 5 had the largest toy movement space at 776.0 cm^2 , while infant 2 increased this space from trial 1 to trial 2.

B. Haptic Metrics

Table VI relates the relevant haptic variables. While arm reaches were mostly bimanual (Table IV), grasps were not—infant 2 was able to grasp the trunk with one hand. This infant increased the number of grasps from trial 1 to trial 2, and had the largest mean grasp pressure and area of 4.5 kPa and 451 kPa-s, respectively. Infant 3 is starred in the table because she grasped the toy with her mouth. Infant 5 did not grasp the toy at all.

Fig. 7 shows pressure vs. time plots for each infant trial. Any dips in pressure below atmospheric pressure are because the system acts as a vacuum, re-filling the chamber after a grasp. Black triangular markers represent grasps.

VI. Discussion

Out of the six infants tested, three of them were engaged with the toy for more than half the trial time. Of those infants, two of them were drawn to the affordance of the toy as a grasp toy. The onset of reaching is typically around 4 months, and is considered a consolidated skill by 5 months [17]. It perhaps makes sense that the older two infants of the three were able to reach for the toy and manipulate it purposefully, while the younger infant displayed more spontaneous movements as seen by the larger toy displacement. All of the infants

exhibited mostly bimanual reaching and grasping behavior, typical for infants of those ages [7]. One study determined that two-year old toddlers were able to grasp within a range of 0-20.68 kPa [15]. For haptic measurements, both infant 2 and 3 grasped the toy within this range. Additionally, there is a clear increase of toy feedback events from first trial to the second trial for infant 2, signaling that perhaps this infant learned the toy's cause-and-effect relationship. Studies have shown that infants as young as 3 months can recognize such relationships [18].

There are technical improvements that can be made to the toys. While the toys are able to collect data, they are not completely robust. Future toy iterations will include an inner shell to organize toy sensors compactly. This will allow for sensor stability, too, which is especially important for minimizing toy displacement calculations errors from the RRR model. Additionally, we have seen that some infants are drawn to parts of the toys with no relevant sensors-for example, some infants are drawn to grasp the elephant toy ears, even though there aren't haptic sensors inside to capture this information. Thus, future toys will circular be in shape, making attachments such as the elephant trunk more obvious to manipulate.

In the future, we will need to test more typical infants, especially those between 6-8 months. Though we have thus far only collected data on typical infants, we are in the process of expanding this study to atypical infants. Eventually, we want to identify specific interaction metrics that will be able to distinguish typical infants from atypical infants. In the future, we plan to run more studies that test the predictability and accuracy of these metrics against current diagnosis assessments.

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Fig. 1.

An infant in the toy gym set-up. The video system and sensorized mat with its four pressure sensors in the corners are labeled.

Fig. 2.
The three hanging toys inside the toy gym

Fig. 3.

A side-by-side figure of the hanging elephant toy model on the left and the real toy on the right. The model is labeled with the important toy components.

Fig. 4.
The 3 DoF RRR toy model used to measure toy position

Fig. 5. Toy displacement magnitude graphs as measured in the gym base frame. The digital signals represent left (black) and right (gray) reaches.

Fig. 6.

An xy-excursion plot for Infant 2, T1 with a fitted ellipse around the data, to show that the ellipses capture infant excursion on the xy-plane rather than the density of the points. The other infant fitted ellipses are also displayed. The x- and y-axes roughly represent the size of the mat.

Fig. 7. Pressure vs. Time plots for each trial. The black horizontal line in each plot represents atmospheric pressure (equal to 101.325 kPa).

TABLE I

INTERACTION METRIC TABLE

Type of Interaction	Metric	Toy	Analysis
Kinematic	Frequency of arm reach to toy* [9], [14]	EO	Bimanual/Unimanual
	Frequency of leg kick to toy* [13]	L	Bimanual/Unimanual
	Max. toy displacement (cm)	ELO	d_x , d_y , d_z & resulting magnitude
	Time to toy contact (s) [13]	ELO	Time to first infant-toy contact
	Toy Contact Duration (s) [13]	ELO	Total infant-toy touch interaction
Haptic	Frequency of toy grasps [9], [14]	E	Bimanual/Unimanual
	Mean grasp pressure (kPa) [9]	E	Mean of grasp peaks
	Mean grasp area (kPa·s)	E	Mean of area under grasp peaks

TABLE II

DH PARAMETERS FOR THE ELEPHANT TOY

Link	a (cm)	α (°)	d (cm)	θ (°)
1	0	180	0	0
2	0	90	0	$\theta_1^* + 90$
3	0	90	0	$\theta_2^* + 90$
4	0	180	35	θ_3^*

TABLE III

INFANT SUMMARY STATISTICS

Infant #	Age (Mos.)	Sex	BINS Score	Risk Level
1	4.8	F	10	Moderate
2	4.5	F	10	Moderate
3	5.3	F	10	Moderate
4	9.0	M	10	Moderate
5	4.0	M	10	Low
6	10.6	F	8	Moderate

TABLE IV**KINEMATIC METRICS**

Metric	Arm Reach		Max. Disp. (cm)	Time to Contact (s)	Contact Duration (s)
Infant	Uni.	Bi.			
2, T1	2	1	12.5	0	120
2, T2	2	0	19.2	2	118
3	0	3	14.4	2	113
5	0	3	27.6	2	110

TABLE V

XY-EXCURSION ELLIPSE AREAS

Infant	Area (cm ²)
2, T1	245.0
2, T2	427.3
3	445.3
5	776.0

TABLE VI**HAPTIC METRICS**

Metric Infant	Grasp Frequency		Mean Grasp (kPa)	Mean Grasp Area (kPa·s)
	Uni.	Bi.		
2, T1	0	9	2.4	187
2, T2	9	9	4.5	451
3*	0	0	2.8	222
5	0	0	0	0