A Pediatric Motor Training Environment Based on Human-swarm Interactions

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Abstract—**Providing opportunities for movement to young populations with or at risk for motor delays is critical, as independent mobility in the first years of life can affect other developmental systems. Our goal was to create an assistive environment that combines dynamic body weight support technology and robotic swarms as a means of engaging infants in perceptual-motor activities. This paper describes the overall system configuration and feasibility. Pilot data from an infant participant were analyzed to extract information on mobility and human-robot swarm interactions. While the swarm formations were activated, the infant tended to move for longer periods and explore new areas in the environment. These preliminary findings inform future implementation of swarm robots in assisted environments to enhance perceptual-motor development.**

Index Terms—**mobility, body weight support, socially assistive robot, rehabilitation, infant**

I. Introduction

Motor training environments designed to leverage the plasticity of the developing nervous system have the potential to enhance developmental outcomes if applied early in life [1]. The use of robots in motor training applications with young children has become increasingly popular in recent years, with studies exploring the benefits of applying such training on movement as early as infancy [2]–[7]. The motor task of interest, and robot at hand in these studies, may vary; from encouraging kicking movements through imitation with a humanoid [2], to promoting mobility through the use of ride-on robots [6]. Nonetheless, greater opportunities for interaction between infants and robots seem to arise when the latter operate in an active rather than a passive mode [8].

An unexplored area in infant-robot interaction is the use of robot swarms for motor training. In adults, work on human-swarm interfaces incorporating movement has been previously reported. For example, brain-machine interfaces combining brain signals and joystick inputs to control quadrotor swarms could potentially aid individuals with motor impairments to interact with the world [9], [10]. In children, robot swarms have been primarily used in educational settings to enhance children's spatial skills; the objective was to improve the children's understanding of collective robot behavior designed to achieve a common goal [11], [12]. More recently, a couple of studies implemented the concurrent use of more than one robot for infant motor training [3], [5], but have not fully utilized the complex dynamics that are typical of a swarm. The dispersion of multiple objects within a physical environment can influence the exploration patterns of infants within that space [13]. Thus, the domain of infant engagement with robot swarms, especially within physical rehabilitation contexts, while potentially impactful, remains largely unexplored.

Physical rehabilitation paradigms to promote postural and locomotor actions in children have utilized body-weight support (BWS) technology, a model largely taken from adult rehabilitation [14]. BWS partially compensates for gravity which helps users overcome physical limitations and enhances the opportunities for engaging in a variety of activities. In young children, training with BWS has been shown to have an effect on overall mobility and gross motor function [15]–[17]. BWS has also been used in motor training paradigms with infants, showing the latter's capability of instantly using the BWS to explore the environment by using various forms of locomotion (e.g., crawling, walking, etc.) [18], [19]. In another longitudinal, in-home, case study in which an infant with motor delays used BWS, improvements in the infant's mobility and motor development were noted [20]. Integrating robots with BWS is a newer type of motor training paradigm that has shown promise in enhancing the aforementioned benefits on mobility by adding another layer of engagement, the socially assistive robots [3], [4], [21].

The work outlined in this paper extends prior motor training paradigms by combining a swarm of robots with BWS. In this paradigm, small spherical robot swarms are deployed in synchronized formations. The robots are programmed to execute simultaneous movements, aiming to capture infants' attention and encourage exploration in the area. The algorithms allow the robot swarm to perform group movements, potentially influencing infant's actions. Similarly to human-animal interaction, motion-based non-verbal interaction can still convey intent and purpose, and robot swarms through their motion have the potential for play-based social interaction with infants. The contribution of this paper is twofold: 1) the implementation of a first infant-swarm interaction system that integrates BWS and a multitude of robots, and 2) to provide pilot data on its use by an infant. This work lays the foundation for the potential application of infant-swarm interaction in interventions for infants with or at risk for motor delays.

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II. METHODS

A. System Overview

The system comprises a BWS device, a collection of five Sphero robots, and a network of sensors that provide the necessary information to close a control loop with the robot swarm. The infant-swarm interaction area is confined within a 13×10 ft^2 envelope, covered with foam pads to ensure safety and comfort for the infants.

The BWS device is a commercial device (Oasus™; Enliten, LLC) that consists of an overhead support rail structure and a counterweight. The rail structure consists of two parallel beams along with a movable beam of equal length connected to a wearable harness. The harness is linked to a counterweight via a pulley system; manipulating the counterweight produces adjustable levels of upward force that partially offsets gravity, thus allowing for various levels of support provided to the user. This flexibility is useful for two reasons. First, it can facilitate a variety of motor actions as a higher amount of support may be needed to keep the infant in an upright posture (e.g., standing, etc.) than in horizontal motion (e.g., crawling, etc.). Second, in longitudinal training with the BWS device, the amount of support may be reduced over time to ensure that the user does not become completely dependent on the device for mobility.

The Sphero BOLT (Sphero Inc, Boulder, CO), a small differential drive robot enclosed in a transparent plastic ball, is selected for the collective. The robot can move with a maximum speed of approximately 7 ft/sec (depending on terrain) and maneuver horizontally almost omnidirectionally. The robots are covered with colorful material in an effort to attract the infants' attention.

The collection of robots can be autonomously controlled in the environment; each robot contains an inertial measurement unit (IMU) (consisting of a 3-axis accelerometer, gyroscope, and magnetometer), while bidirectional communication is established via Bluetooth. Sphero's IMU data are not of sufficient resolution and accuracy to enable on board real-time closed-loop control, so we rely on vision-based exteroceptive perception for robot localization. A ZED stereo camera is attached to the ceiling at the center of the area. The real-time position of robots is obtained via a multi-object detection YOLO v8 algorithm and built-in functions of the OpenCV library.[1]

With a human (infant) in the loop, our system needs a means of assessing human reaction in real-time. To this end, a palm-size motion tracker (MetaMotionR, MBientLab) is attached to the harness. This sensor connects to the rest of the system via Bluetooth and provides real-time acceleration data of the infant's trunk in all three dimensions. These data are used to detect any state changes of the infant (e.g., from crawling to walking) in an autonomous way, without input from a researcher. Two additional web cameras (Logitech) are placed around the environment to give us visual data from additional angles. All three cameras record with a frequency of 15 frames per second and are synchronized through software developed in house. The overall system architecture is illustrated in Fig. 1 with the arrows in the block diagram indicating the information flow between the different modules of the system.

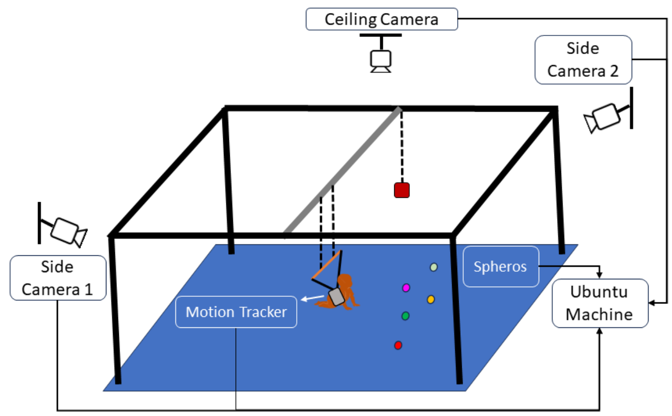

Fig. 1: Diagram of the overall system architecture. The main coordinator of the system is a PC (running Ubuntu 20.04.6 LTS). The coordinator sends motion commands to the robots after receiving information about their position (ceiling camera) and the estimated state of the human (motion tracker).

B. Interaction Dynamics

Information obtained from the sensors is utilized to trigger swarm behaviors that may be perceived as inviting infant interaction. Chasing games, for example, are instances of serious games employed to captivate the interest and enhance engagement in therapy sessions, especially for children who are prone to distractions or face mobility challenges [22], [23]. One potential robot behavior that our earlier work [24] has indicated that has the potential of triggering a chasing game is one that involves a dynamic variation of the distance between the robot and the infant. The current system incorporates this insight and embodies it in the robot collection dynamics.

To design trajectories that are likely to trigger such interaction, dynamic artificial vector field methods are used to steer the whole collective leveraging results from bifurcation theory [25]–[27]. The back-and-forth motion identified as a possible invitation to chase can be defined using a bifurcation-based approach to design a limit cycle that steers the robot towards and away from the infant. In such an approach, a dynamical system of differential equations is defined to generate the steering vector fields. It consists of interconnected navigation, motivation and value dynamics subsystems. The navigation dynamics represent the resulting vector field for the desired limit cycle which is a convex combination of two component circular limit cycle vector fields. The motivation dynamics is the bifurcation-based decision-making mechanism of the dynamical system, deciding how the two component vector fields should be combined to form the desired result, and finally, the value dynamics give the notion of urgency into our dynamical system to ensure that it will reach the desired behavior and remain close to it. By appropriately resetting a

[1]Information on the different components can be found at: https://www.stereolabs.com/products/zed-2; https://docs.ultralytics.com/; http://opencv.org

single scalar parameter of the system, the overall dynamical system can exhibit a limit cycle that will steer the collective of robots towards and away from the infant [28], [29].

Such an approach provides us with an advantage of including the "point of interest" around which the robots will evolve, as an input to the dynamical system of equations. More specifically, in our case, such point of interest can be the position of the infant that can be imported in our dynamical system and adaptively steer the robots towards the infant even when the latter is moving in the space.

III. Experiment

A. Protocol

Developing the experimental testbed of the system with infants as the primary agents needs careful co-design of all components. For example, the task type, targeted duration of engagement as well as the rewards given should be strategically chosen to reflect the levels of perception and attention reached by that age. Therefore, pilot sessions were conducted to evaluate the overall feasibility of the system and collect preliminary data on the infant's mobility actions and interaction with the robot swarm. The University of Delaware Institutional Review Board approved the study (IRB ID# 1640064-7) and the caregivers provided written informed consent for their infant's participation and use of images for publication.

A neurotypical 8-month-old female infant participated in two consecutive sessions. The infant was able to sit and crawl but not walk independently at the time of the experiment, as these are typical developmental milestones for this age. The level of BWS provided by the device used in both sessions was 20%, allowing the infant to perform a variety of postures (e.g., sitting, prone, etc.), mobility actions (e.g., crawling, etc.) as well as transitions (i.e. sit-to-crawl). In both sessions, the researcher and caregivers remained present in the area. Caregivers were instructed to remain in that location and let their infant interact with the robots freely on their own. The first session was dedicated to the infant's familiarization with the system by providing them time in the harness and exploring the robots in passive mode. In the second session, data were collected under three conditions: "Passive 1" (1 minute), "Active" (3 minutes), "Passive 2" (1 minute). In the "Active" condition, the collection of robots was activated on a time-based switch (every 30 seconds). Due to technical issues with the motion tracker in this pilot session, an event-based switch (i.e., robot activation based on the state change of the infant) was not possible. The motion of the collective was implemented using the navigation dynamics described in subection II-B. Their positional information captured from the ceiling camera was used to close the loop and minimize any tracking error occurred. In the "Passive" conditions, the robotic swarms were inactivated. In "Passive 1", the researcher manually moved the Spheros in the area to elicit the infant's mobility as in a typical play scenario whereas in "Passive 2" Spheros remained inert, without providing any stimuli for interaction.

B. Variables of Interest and Data Analysis

Video recordings were used off-line to extract data on the infant's mobility and interaction with the robots. The frequency and duration of events of interest were annotated: robot stimuli, infants' attention, reaching and gesturing to robots, and crawling. The inter-rater reliability (% agreement) between the two coders was 99.6 %, 89.22%, 98.35%, 99.81%, 92.75% for all the aforementioned annotated categories, respectively. In addition, the recording of the ceiling camera was used to track the motion of all agents in the scene offline and to obtain their x, y coordinates at every frame (Kinovea 0.9.5). The infant's path was tracked only if the infant performed independent locomotion. In instances where the researcher lifted and/or relocated the infant (e.g., if the infant went outside the play area) the tracking was temporarily suspended. From these raw data, we evaluated time in motion, total distance traveled and new areas of exploration (areas visited for the first time during each condition). The new area explored was calculated by summing up the regions within a 15 cm radius around the infant's head (cf. [13]); whenever the infant moved to a part of the area that they hadn't been before, this was considered an increase in the total new area explored. Movements that involved either postural sway or revisiting previously explored locations did not count toward the exploration of new areas.

IV. Results

No signs of discomfort or adverse effects during the sessions were reported. Overall, the infant was mobile in the environment and engaged in various actions with the robots throughout the second session (Table I, Fig. 2, Fig. 3)

TABLE I: Frequency and Duration of Infant Actions

	Crawl	Reach	Gesture	Visual Attention
Frequency	18	13	2	15
Duration (s)	126.35	12.51	12.4	42.58

Comparing differences across conditions, the total distances traveled by the infant were found to be 1945.12 cm, 3130.95 cm and 1439.06 cm respectively (Fig. 3). After normalizing the distance to account for the different duration of the conditions, we get rates of 32.24 $\mathrm{cm\,s^{-1}}$, 53.18 $\mathrm{cm\,s^{-1}}$ and 25.57 $\mathrm{cm\,s^{-1}}$ respectively (Fig. 4A). In "Passive 1", the infant was locomoting for 37.41%, in "Active" for 50.75%, and in "Passive2" for 22.03% of the time (Fig. 4E). The total area covered by the infant while crawling, including postural sway and revisited areas in the play-mat, was 391.25 cm^2, 86.50 cm^2 and 36.97 cm^2 respectively. Out of the area covered, 1.04%, 14.26% and 1.29% were the new areas explored (Fig. 4B). The percent of the total area explored was 4.08%, 12.33% and 0.47% respectively (Fig. 4C). Accounting for time, the rate of new area explored was 85.48 $\mathrm{cm^2\,s^{-1}}$, 86.35 $\mathrm{cm^2\,s^{-1}}$, and 10.68 $\mathrm{cm^2\,s^{-1}}$ respectively (Fig. 4D). Overall, it seems that the mobility and exploration for this particular subject were greater when the swarm of robots was in active mode.

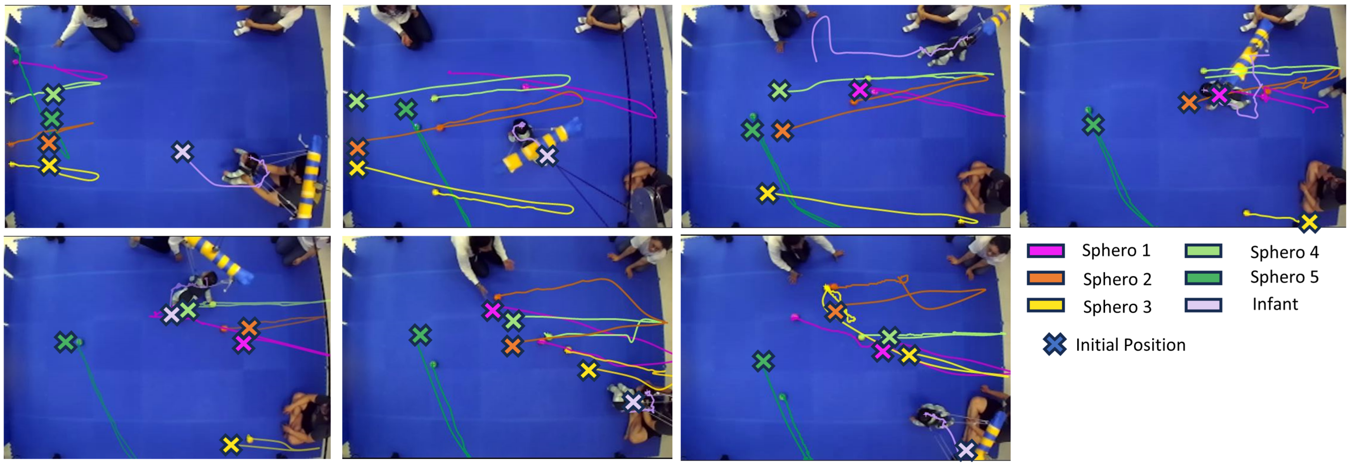

Fig. 2: Snapshots of the infant interacting with a swarm of Sphero robots during the ”Active” condition. Initially, the robots are arranged by the researcher into a straight line, marking the beginning of the ”Active” condition. Throughout the ”Active” condition, the robots moved toward and then away from the infant, repeating this pattern seven times. The robots do not return to their starting positions after each movement. This results in a fluid and evolving interaction between the infant and the robots.

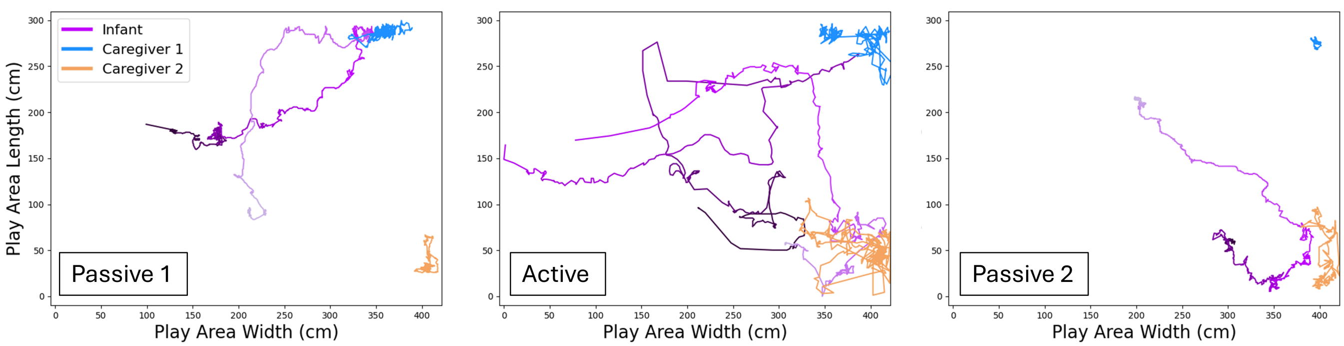

Fig. 3: Total path traveled by the infant and each of the caregivers during the whole session. The gradient color of the infant’s trajectory indicates the temporal progression, with the darker color marking the beginning of the path.

In the initial minute of the session, 18 s of activity were spent in the most visited area. This was followed by 17 s and 12 s in the second and third minutes, respectively. The fourth minute marked the lowest concentration, with the area receiving only 4 s of presence. In the fifth minute, 18 s were spent in the most visited area. Thus, the infant in both “Passive 1” and “Passive 2” swarm conditions, spent more time in a more localized area (Fig. 5B).

V. Discussion

This paper introduces a methodology for infant-swarm interactions in motor training environments. The pilot findings lay the foundation for future studies in this field. Our results indicate an increased mobility and exploratory behavior during the ”Active” swarm condition for this infant. In ”Passive 1” condition, as the researcher interacted with the infant using the robots as typical toys, the infant displayed higher activity levels compared to ”Passive 2” condition, where the researcher did not engage in play. Regarding the exploration of new areas, the infant explored the largest percent of the areas during the ”Active” phase. In ”Passive 2” as the researcher did not captivate the infant’s attention, a decrease in the rate of exploratory behavior was observed and the infant showed a preference for staying close to one of the the caregivers. This could be attributed to the lack of stimuli but also the familiarization of the infant with the environment in the previous conditions.

Furthermore, in the “Passive 1” condition, the infant’s presence is centered around the middle of the play area, while in the “Passive 2” phase, the presence is concentrated at corner points where one of the caregivers was seated. In the “Active” condition, a more distributed pattern is generated. The spread of the high-density regions in the play area indicates a dynamic presence, moving from one place to another, as opposed to the passive conditions where the infant is more static.

A number of limitations of this work may warrant future consideration. Although the ecological nature [30] of the experimental design is a strength, it did lead to infant having

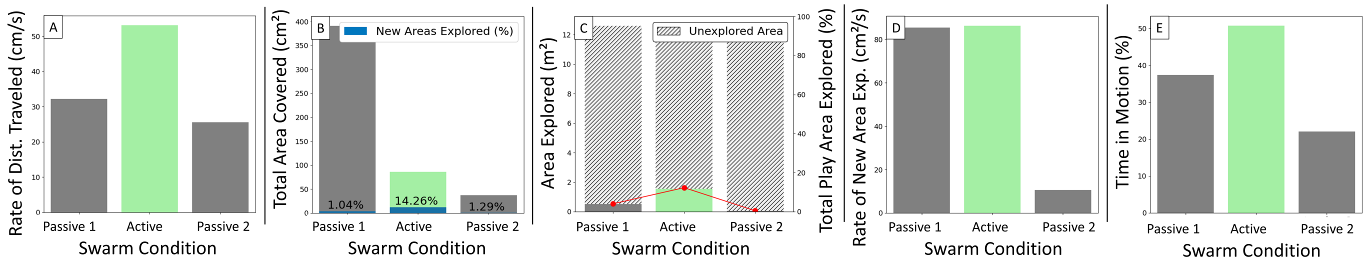

Fig. 4: A) Distance traveled per second by the infant during each swarm condition. B) Total area covered by the infant during each swarm condition. C) Areas of the play-mat explored by the infant during each condition. D) New areas of the room explored per second during each swarm condition. E) Percent of time locomoting (crawling) during each swarm condition.

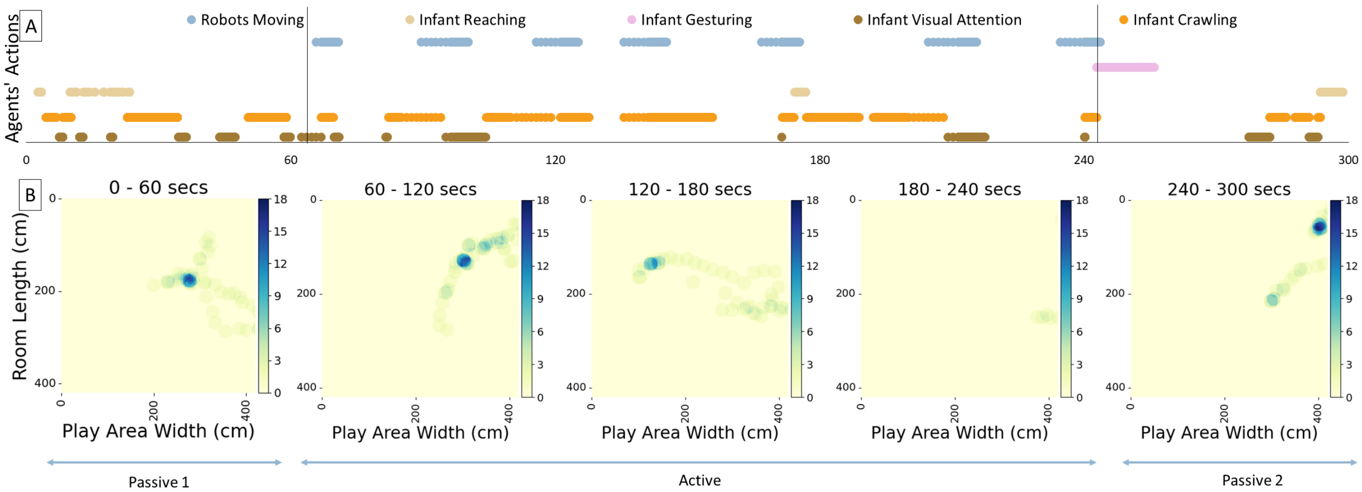

Fig. 5: A. Timeline of robot and infant actions during the session. B. Heatmaps depicting the average time spent in each location of the area (estimated as a 15-cm radius circle centered on the infant's head [13]) at each minute into the session.

somewhat random opportunities for interaction (i.e., levels of stimulus given). The unpredictability of the interaction in this setting highlights a well-known challenge in human-robot interaction research: achieving balance between precise experimental protocols and the variable conditions of a natural environment [31]. Additionally, the issue of color and texture preference in infant-swarm interactions calls for further investigation [32]. Finally, the study involved a single subject, thus the number of observations was limited. Such limitations can impact the development of human-robot interaction models; thus, further large-group studies are needed.

VI. FUTURE WORK

When we design infant-robot interaction paradigms, we need robots that keep different elements of the social interaction novel, interesting, dynamic, and challenging; highly agile robotic swarms have the potential for such actions. In this paper, we propose a novel infant-robot swarm environment and describe the interaction of an infant with the robots. We showed that multiple synchronized stimulus sources offered indications of increased mobility and exploration. However, for how long and in which way we can sustain the infant-swarm interaction and re-engage infants after a period of inactivity still remains unknown. Future work involves the examination of different swarm behavior patterns (Fig. 6). These swarm patterns could offer insights into how infants perceive different types of patterns in three-dimensional space, complementing prior work on visual pattern perception [33]. For instance, they could reveal whether infants have a preference for more complex patterns as opposed to simpler ones, or how they respond to novel patterns compared to familiar ones.

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REFERENCES

[1] I. Novak and C. Morgan, "High-risk follow-up: early intervention and rehabilitation," *Handbook of clinical neurology*, vol. 162, pp. 483–510, 2019.

[2] N. Fitter, R. Funke, J. C. Pulido Pascual, L. E. Eisenman, W. Deng, M. R. Rosales, N. Bradley, B. Sargent, B. Smith, and M. Mataric, "Socially Assistive Infant-Robot Interaction: Using Robots to Encourage Infant Leg-Motion Training," *IEEE Robotics & Automation Magazine*, pp. 1–13, 2019.

[3] E. Kokkoni, E. Mavroudi, A. Zehfroosh, J. C. Galloway, R. Vidal, J. Heinz, and H. G. Tanner, "GEARing smart environments for pediatric motor rehabilitation," *Journal of NeuroEngineering and Rehabilitation*, vol. 17, no. 1, p. 16, 2020.

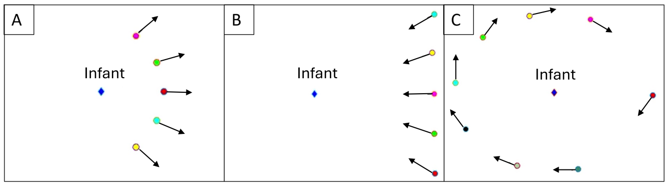

Fig. 6: Examples of three group robot motion patterns that might enable perceptual-motor actions by infants. The diamond represents the infant's position, the colored circles depict the positions of the Sphero robots, and the arrows indicate the direction of the latter's motion. A) Scattering pattern: Robots move away from the infant to initiate a chasing game. B) Convergent pattern: Robots approach the infant to elicit touching and/or other close physical interactions. C) Circular pattern: Robots move in a circle to imitate a peek-a-boo game (particularly when obstacles are present).

[4] J. Raja Vora, A. Helmi, C. Zhan, E. Olivares, T. Vu, M. Wilkey, S. Noregaard, N. T. Fitter, and S. W. Logan, "Influence of a Socially Assistive Robot on Physical Activity, Social Play Behavior, and Toy-Use Behaviors of Children in a Free Play Environment: A Within-Subjects Study," *Frontiers in Robotics and AI*, vol. 8, pp. 1–12, 2021.

[5] G. Kouvoutsakis, K. Baxevani, H. G. Tanner, and E. Kokkoni, "Feasibility of using the robot sphero to promote perceptual-motor exploration in infants," in *17th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, 2022, pp. 850–854.

[6] J. C. Galloway, J. C. Ryu, and S. K. Agrawal, "Babies driving robots: Self-generated mobility in very young infants," *Intelligent Service Robotics*, vol. 1, no. 2, pp. 123–134, 2008.

[7] V. Emeli, K. E. Fry, and A. Howard, "Robotic System to Motivate Spontaneous Infant Kicking for Studies in Early Detection of Cerebral Palsy: A Pilot Study," in *8th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, 2020, pp. 175–180.

[8] A. Peca, R. Simut, H. L. Cao, and B. Vanderborght, "Do infants perceive the social robot Keepon as a communicative partner?" *Infant Behavior and Development*, vol. 42, pp. 157–167, 2016.

[9] G. K. Karavas, D. T. Larsson, and P. Artemiadis, "A hybrid bmi for control of robotic swarms: Preliminary results," in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2017, pp. 5065–5075.

[10] C. H. Nguyen, G. K. Karavas, and P. Artemiadis, "Adaptive multi-degree of freedom brain computer interface using online feedback: Towards novel methods and metrics of mutual adaptation between humans and machines for bci," *PloS one*, vol. 14, no. 3, p. e0212620, 2019.

[11] A. Vitanza, P. Rossetti, F. Mondada, and V. Trianni, "Robot swarms as an educational tool: The thymio's way," *International Journal of Advanced Robotic Systems*, vol. 16, no. 1, p. 1729881418825186, 2019.

[12] M. Jdeed, M. Schranz, and W. Elmenreich, "A study using the low-cost swarm robotics platform spiderino in education," *Computers and Education Open*, vol. 1, p. 100017, 2020.

[13] J. E. Hoch, S. M. O'Grady, and K. E. Adolph, "It's the journey, not the destination: Locomotor exploration in infants," *Developmental science*, vol. 22, no. 2, p. e12740, 2019.

[14] D. L. Damiano and S. L. DeJong, "A systematic review of the effectiveness of treadmill training and body weight support in pediatric rehabilitation," *Journal of neurologic physical therapy: JNPT*, vol. 33, no. 1, p. 27, 2009.

[15] L. A. Prosser, L. B. Ohlrich, L. A. Curatalo, K. E. Alter, and D. L. Damiano, "Feasibility and preliminary effectiveness of a novel mobility training intervention in infants and toddlers with cerebral palsy." *Developmental neurorehabilitation*, vol. 15, no. 4, pp. 259–66, 2012.

[16] E. Kokkoni, S. W. Logan, T. Stoner, T. Peffley, and J. C. Galloway, "Use of an in-home body weight support system by a child with spina bifida," *Pediatric Physical Therapy*, vol. 30, no. 3, pp. E1–E6, 2018.

[17] S. R. Pierce, J. Skorup, M. Alcott, M. Bochnak, A. C. Paremski, and L. A. Prosser, "The use of dynamic weight support with principles of infant learning in a child with cerebral palsy: a case report," *Physical & Occupational Therapy In Pediatrics*, vol. 41, no. 2, pp. 166–175, 2021.

[18] T. Kornafel, A. C. Paremski, and L. A. Prosser, "Unweighting infants reveals hidden motor skills," *Developmental Science*, vol. 26, no. 2, p. e13279, 2023.

[19] E. Kokkoni and J. C. Galloway, "User-centred assistive technology assessment of a portable open-area body weight support system for in-home use," *Disability and Rehabilitation: Assistive Technology*, vol. 16, no. 5, pp. 505–512, 2021.

[20] E. Kokkoni, T. Stoner, and J. C. Galloway, "In-home mobility training with a portable body weight support system of an infant with down syndrome," *Pediatric Physical Therapy*, vol. 32, no. 4, pp. E76–E82, 2020.

[21] A. Helmi, T.-H. Wang, S. W. Logan, and N. T. Fitter, "Harnessing the power of movement: A body-weight support system & assistive robot case study," in *IEEE International Conference on Rehabilitation Robotics (ICORR)*, 2023, pp. 1–6.

[22] B. Bonnechere, B. Jansen, L. Omelina, M. Degelaen, V. Wermenbol, M. Rooze, and S. V. S. Jan, "Can serious games be incorporated with conventional treatment of children with cerebral palsy? a review," *Research in developmental disabilities*, vol. 35, no. 8, pp. 1899–1913, 2014.

[23] K. P. Michmizos and H. I. Krebs, "Serious games for the pediatric anklebot," in *2012 4th IEEE RAS & EMBS international conference on biomedical robotics and biomechatronics (BioRob)*. IEEE, 2012, pp. 1710–1714.

[24] A. Zehfroosh and H. G. Tanner, "Reactive motion planning for temporal logic tasks without workspace discretization," in *Proceedings of the IEEE American Control Conference*, 2019, pp. 4872–4877.

[25] P. B. Reverdy, "A route to limit cycles via unfolding the pitchfork with feedback," in *Proceedings of the American Control Conference*, 2019, pp. 3057–3062.

[26] C. Thompson and P. B. Reverdy, "Drive-based motivation for coordination of limit cycle behaviors," in *Proceedings of the IEEE Conference on Decision and Control (CDC)*, 2019, pp. 244–249.

[27] P. B. Reverdy and D. E. Koditschek, "A dynamical system for prioritizing and coordinating motivations," *SIAM Journal of Applied Dynamical Systems*, vol. 17, pp. 1683–1715, 2018.

[28] K. Baxevani and H. G. Tanner, "Multi-modal swarm coordination via hopf bifurcations," *Journal of Intelligent & Robotic Systems*, vol. 109, no. 2, p. 34, 2023.

[29] ——, "Bifurcating vector fields driven by time-scale separated motivational dynamics," *IFAC-PapersOnLine*, vol. 56, no. 2, pp. 3930–3935, 2023, 22nd IFAC World Congress.

[30] U. Bronfenbrenner, *The ecology of human development: Experiments by nature and design*. Harvard university press, 1979.

[31] S. Maruyama, E. Dineva, J. P. Spencer, and G. Schöner, "Change occurs when body meets environment: A review of the embodied nature of development," *Japanese Psychological Research*, vol. 56, no. 4, pp. 385–401, 2014. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1111/jpr.12065

[32] C. Taylor, K. B. Schloss, S. Palmer, and A. Franklin, "Color preferences in infants and adults are different," *Psychonomic Bulletin & Review*, vol. 20, pp. 916–922, 2013.

[33] G. K. Humphrey, D. E. Humphrey, D. W. Muir, and P. C. Dodwell, "Pattern perception in infants: Effects of structure and transformation," *Journal of Experimental Child Psychology*, vol. 41, no. 1, pp. 128–148, 1986.