Using Socially Assistive Robot Feedback to Reinforce Infant Leg Movement Acceleration

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***Abstract*—Learning movement control is a fundamental process integral to infant development. However, it is still unclear how infants learn to control leg movement. This work explores the potential of using socially assistive robots to provide real-time adaptive reinforcement learning for infants. Ten 6 to 8-month old typically-developing infants participated in a study where a robot provided reinforcement when the infant's right leg acceleration fell within the range of 9 to 20 m/s^2. If infants increased the proportion of leg accelerations in this band, they were categorized as "performers". Six of the ten participating infants were categorized as performers; the performer subgroup increased the magnitude of acceleration, proportion of target acceleration for right leg, and ratio of right/left leg acceleration peaks within the target acceleration band and their right legs increased movement intensity from the baseline to the contingency session. The results showed infants specifically adjusted their right leg acceleration in response to a robot-provided reward. Further study is needed to understand how to improve human-robot interaction policies for personalized interventions for young infants.**

I. Introduction

One indicator of the ability to regulate one's movement is the voluntary adjustment of movement acceleration, the rate of speed. To achieve an optimal movement velocity, control of acceleration requires motor strategies [1], [2]. It is proposed that, through a dynamic exploration and discovery learning process, infants gradually adapt their movements to perform task-specific actions [3], [4]. Across months of practice, infants reduce the variability in arm accelerations and hand trajectories to achieve stable patterns of acceleration/ deceleration and smooth hand trajectories during reaching to a target [5].

Apart from reaching, leg movement patterns also show significant difference between typically-developing infants and infants at risk of developmental disabilities. For example, acceleration analyses of leg movements for preterm infants exhibiting developmental delay at 3 years of age shows they have slower and less stable movements at 36-44 weeks postmenstrual age based on data from wrist and ankle worn sensors [6]. It is still not known how exploratory strategies are different between typically-developing infants and infants at risk of developmental disabilities. It is important to understand how typically-developing infants learn to control their legs; this fundamental knowledge is needed to understand neuromotor control of movement during infancy and to create interventions for infants at risk of developmental disabilities.

Socially assistive robots (SARs) have been used to design interventions for children with autism spectrum disorder and children with cerebral palsy to improve their social interaction or motor skills [7]–[9], among other user populations. SAR has recently been introduced for use with infants [10] because it has the potential to support both the study of and interventions in early infant motor development. SARs are appealing to infants and can deliver repeatable stimuli and collect data. In particular, they are well suited for use in contingency studies, which are commonly used to test infant responsive behavior [11]–[13]. In those study paradigms, certain infant behavior activates pre-programmed rewards, as a reinforcement to change infant behavior.

Infant-sized humanoid SARs with human face-like stimuli are a salient attractor for infants [14]–[16]. Infants have been found to visually attend to such a humanoid robot for longer intervals than to a person or an android modeled on the human [17]. Previous studies have repeatedly shown that robots have the potential to encourage free play for typically-developing children and provide personalized interventions for infants at risk of developmental disabilities [18]–[20]. In those studies, the robots were either reinforcing the infant's movement frequency [18], [20] or a specific gesture [19].

To our knowledge, no study to date has shown whether infants are able to adjust one of the main characteristics of leg movement, leg acceleration, in a defined range within a brief motor learning session. The first acceleration and deceleration phase of the movement is important for evaluating motor control and motor planning [21], [22]. Our previous study showed that infants were able to increase their movement frequency in a SAR-reinforced contingency paradigm using a NAO robot with a low acceleration threshold (3 m/s^2), where almost all infant leg movements activated the robot's response [23]. In order to explore the control of leg acceleration, we updated the robot's reinforcement policy from a low acceleration threshold to a challenging acceleration range [23]. In this new design, infants need to accelerate, and also need to

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control their acceleration under the high threshold in order to activate the robot. This task is therefore more difficult to perform than in the previous task design [23].

Therefore, this work is addressing whether infants are able to appropriately adjust their leg peak acceleration (the highest acceleration in a movement) using a contingency learning paradigm with reinforcement being provided by a SAR.

We hypothesized that:

H1: Infants will adjust the magnitude and distribution of leg peak acceleration to activate the robot.

H2: Infants will selectively adjust only right leg acceleration (not left leg or arms) to activate the robot.

II. Related work

A. NAO Robot

The NAO robot is an infant-sized socially assistive humanoid robot that has been used widely in human-robot interaction research, including to create interventions for patients with arm dysfunction and children with autism spectrum disorder [24]–[27]. Introducing a robot in an intervention has the potential to extend the intervention to the daily environment and hence increase the often-less-than-optimal intervention dosage. Due to its toy-like appearance, the NAO is particularly attractive for use with children. Our previous study showed that infants were more likely to be alert when the NAO robot moved [28]. In recent work, we designed a contingency task that reinforced infant leg movement using the NAO robot [23], [28]. In addition to increasing leg movement frequency, 9 out of 12 infants showed imitation of the robot's ball-kicking behavior. The infant-sized humanoid shape of this robot may be more likely to encourage infants to imitate the robot's behavior due to the mirror neuron system (neurons that fire when observing an action performed by another) [29], [30]. This effect supports the use of the humanoid NAO robot when designing an intervention for infants, since imitation is a key element for infant motor development. Therefore, we used the NAO robot for the experimental study presented in this work.

B. Contingency Learning Paradigm

Studies using the contingency learning paradigm, the reinforcement of a select spontaneous behavior [31], have shown that infants can discover and modify targeted movement attributes when they are reinforced by an attention-attracting event. Prior work found that infants can increase their leg movement frequency, as well as change their inter-limb and intra-limb coordination after receiving 2 to 8 minutes of positive reinforcement from a moving mobile [11], [31], [32]. Researchers have been using this paradigm with robots in order to explore the potential of early detection of cerebral palsy (CP) and to create intervention for infants at risk of CP [19], [20]. In this study, we explored whether infants are able to adjust the magnitude and distribution of leg peak acceleration based on SAR feedback.

Moreover, previous studies used the traditional conjugate contingency paradigm where targeted behavior and reinforcement happen together and with the same intensity. In those studies, the infant's leg directly attached to a moving mobile through a rope that provided additional tactile feedback beyond the visual and auditory feedback. We decided to use a SAR to provide non-direct-contact episodic contingency paradigm (targeted behavior and reinforcement happen at different time with different intensity) as a previous study showed that the delayed reinforcement may improve the learning result [33].

C. Speed and Acceleration

Previous studies demonstrate that infants can adjust their arm and leg acceleration or speed in the first year of life. Even fetuses demonstrate accelerated-decelerated movements, and newborns show preference for biologically accelerated-decelerated movement patterns over non-biologic movement patterns with constant velocity in a preferential looking paradigm [34]–[37]. At 3 to 5 months of age, through practice, infants achieve a relatively stable and smooth pattern of reaching by modulating the velocity and acceleration of their arms [38]. This modulating process appears to continue to 3 years old, when they achieve adult-like patterns [5]. In a longitudinal study measuring leg movements, Goldfield found that infants around 8 months old adjusted their leg movements from irregular and variable to produce a sustained bouncing movement at the resonant frequency of the mass spring system [39]. Although our study is not based on a spring system, infant leg movements shared a similar biological accelerated-decelerated pattern. We aimed to explore whether infants 6 to 8-months old have the ability to learn to change their behavior from a short interaction with a socially assistive humanoid robot.

D. Selective Control

Perception, action, and representation are fundamental processes that empower infants to learn adaptive control of their body as they interact with the environment. Before 2 months of age, infants respond to a movement-based contingent reinforcement by increasing movement frequency in all four limbs [40]. They gradually learn to differentially increase the movement of the limb that is linked to the contingent reinforcement from 3 months of age, as opposed to increasing the movement frequency of all limbs [40]–[44]. However, previous studies examining laterality, the selective use of one or both limbs on one side of the body, only focused on the change in relative movement quantity over time. Specific characteristics of acceleration and movement intensity have not been assessed. In this work, by using a reinforcement policy in a difficult acceleration range, we studied whether infants can selectively control the acceleration of leg movements as they learn the reinforcement contingency paradigm and, if so, if they can adjust the range of acceleration for movements of all four limbs or only the limb activating the robot's feedback?

III. Experimental study

A. Participants

We recruited 12 typically-developing infants (3 females and 9 males). Inclusion criteria were age 180 to 240 days old and an Alberta Infant Motor Scale (AIMS) score ⩾10th percentile [45]. We chose infants in this age range because they were able to sit independently and generate enough spontaneous movement. We excluded infants who were born at less than 37 weeks of gestation, or with known visual, cognitive, orthopedic or neurological impairment. Infants were recruited by fliers, online postings, and word of mouth in the Greater Los Angeles area in the US during 2018 and 2019. Two infants recruited were excluded. One of the infants cried at the very beginning of data collection leading us to end the session early. The other infant was born before 37 weeks of gestation. Ten infants met all requirements for inclusion in the final sample. Table I provides a detailed description of the sample.

TABLE I. DEVELOPMENTAL STAGE AND ANTHROPOMETRICS FOR ALL INFANTS (MEAN ± SD).

Age	228 ± 11 days
Gender	3 females, 7 males
Thigh length	14.48 ± 1.77 cm
Shank length	13.29 ± 0.98 cm
Weight	8.06 ± 1.21 kg
AIMS total score	36 ± 5
AIMS percentile	59.5% ± 25.3%

*AIMS: Alberta Infant Motor Scale.

B. Procedure

This research was approved by the Institutional Review Board of the University of Southern California (HS-14-00911). A parent or legal guardian signed an informed consent form. Data were collected on the University of Southern California Health Science Campus. We collected infants' anthropometric data (thigh length and circumference, shank length and circumference, foot length and width, weight) and assessed their motor development using the AIMS.

For the contingency paradigm, the infant sat in a chair in front of the robot (see Figure 1). The infants were secured and supported at the trunk with a cloth band. A caregiver was asked to sit next to the infant and not to interact with the infant unless necessary (to minimize infant fussiness). Wearable sensors were placed on the infants' arms and legs (1 sensor on each ankle and each wrist) for recording tri-axial acceleration and angular velocity data at 20 Hz. We also video recorded the sessions to code for behavioral state. We removed sections of the data when the infant cried continuously for over a minute. A single video coder who completed reliability training (>90%) coded all the videos. Each infant participated in a 2-minute baseline, a 10-second demonstration of the reinforcement, 8-minute contingency and 2-minute extinction condition.

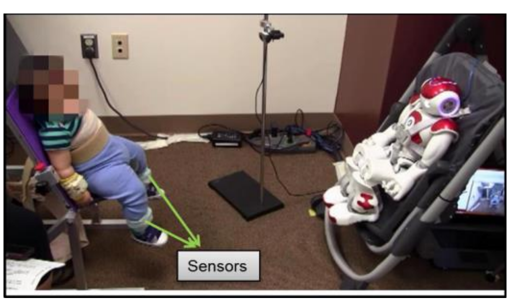


Figure 1. Study set up: Infant sitting in front of the robot with a sensor on each limb.

C. System Architecture

The system employed in this study was comprised of the NAO robot and wearable Opal sensors (consisting of a 3-axis accelerometer and a gyrometer). This system allowed for collecting real time infant leg movement acceleration and angular velocity data using the Opal sensor to trigger robot responses, as shown in Figure 2. The raw sensor data were streamed to an off-board computer with the executive component where the instantaneous resultant acceleration data were calculated using the quaternion filter. This architecture was successfully used in our prior work [23]; for this study, we updated the robot control policy to reinforce more challenging movements, in order to assess infants' selective leg control [23], as follows.

During the contingency condition, when the resultant acceleration of the infant's right leg peak acceleration was between 9 to 20 m/s^2 and the angular velocity was higher than 2 rad/s or lower than -2 rad/s, the NAO robot provided reinforcement (infant laughing sounds + flashing colorful lights + kicking both legs, 1.2 seconds in total). We chose the robot's leg kicking movement based on results from our previous project with a similar infant group showing that infants moved more after the robot kicked, while the robot's arm movements were likely to scare the infants [23]. Previous studies also showed that auditory and visual stimuli together generated more successful learning than either modality alone [23]. Based on the earlier study, the selected acceleration range estimates the 65th to 90th percentile of the distribution of infant leg accelerations. We chose this range so it would be a challenging task for our target group of infants and also prevented the unwanted robot activations caused by the high deacceleration when the infants' two legs were hitting each other. No reinforcement was provided during the baseline and extinction conditions in order to observe infant behavior in the absence of the robot's feedback.

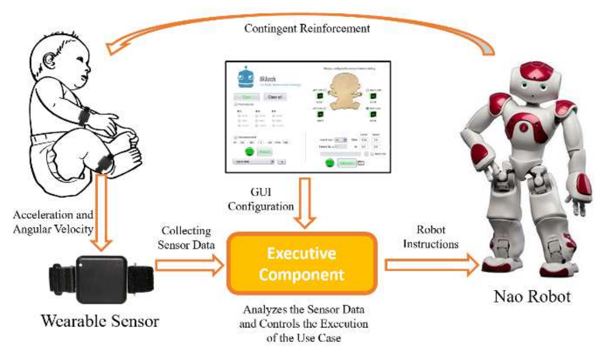


Figure 2. The socially assistive robot training system architecture integrated with wearable sensors to provide contingent reinforcement for infants.

D. Data Preparation

After data collection, we used ELAN (ELAN 4.9.1, The Language Archive) to code the infants' behavioral state as sleeping, drowsy, alert, fussy or crying [46]. Five infants cried during the last 4 minutes of data collection (2 minutes of contingency and 2 minutes of extinction conditions). To diminish the influence of emotional status across infants (e.g., faster movement when crying), we decided to remove the last 2 minutes of data for the contingency and extinction conditions for all infants. Thus, the final dataset consisted of a 2-minute baseline and a 6-minute contingency condition per infant.

E. Data Reduction

Quantity of infant leg movements: To calculate the quantity of infant leg movements, we first identified acceleration peaks between 1-3.25 m/s^2 in the baseline condition. Next, we calculated the mean ± SD for baseline acceleration data within this range to define the threshold for detecting infant movement [47]. The number of acceleration peaks above the movement threshold was used to quantify infant leg movements during both baseline and contingency conditions.

Performing criteria: Infants were classified as "performers" and "non-performers" based on the classification standard established by Rovee-Collier [31]. Infants were classified as performers when their right leg acceleration peaks fell within the acceleration band (9-20 m/s^2) $\geqslant$1.5 times baseline for any 2-minute block of the contingency condition. Infants not producing this increase in acceleration peaks were classified as non-performers. Infants who did not produce any movements within the acceleration band (9-20 m/s^2) during baseline were not classified as performers or non-performers.

Area under the curve (AUC): We computed the AUC to compare infant movement intensity of the arms and legs in order to evaluate H2. Given that arm movements have more degrees of freedom than leg movements, infants produced multiple acceleration and deceleration phases within one single bout of arm movement. To implement the AUC analysis, the resultant acceleration was low-pass filtered at 9 Hz and full-wave rectified. The AUC was calculated for each 2-minute block of baseline and contingency conditions.

Ratio of right/left leg acceleration peaks: We compared the ratio for number of acceleration peaks within 9-20 m/s^2 and all acceleration peaks above the movement threshold of the infant's right leg to that for their left leg.

F. Data Analysis

We performed all analyses for the performers and non-performers combined (10 infants) and for the performer subgroup only (6 infants). All analyses were conducted using Matlab using Wilcoxon signed rank tests with alpha level of significance at 0.05. We chose non-parametric Wilcoxon signed rank tests because results of the Shapiro-Wilk test indicated most data were not normally distributed. For analyses within infants, we chose the 2-minute block that had the greatest number of acceleration peaks within the bandwidth of 9-20 m/s^2 during the contingency condition. This block represented each infant's best performance. We selected the behavior during the contingency condition that differed the most from the baseline condition [48], presumably representing each infant's "best" performance for the analyzed metrics.

Magnitude and distribution: To investigate the change of acceleration magnitude and distribution of infants' right legs in the entire group vs. the performer subgroup, we compared the acceleration peaks' magnitude, and the proportion of acceleration peaks within 9-20 m/s^2 in all acceleration peaks above the threshold for infant leg movement, during the contingency and baseline conditions.

Selective control: To investigate whether infants adjusted the acceleration of all four limbs or only that of the legs in the entire group and the performer subgroup, the AUC values were compared between baseline and contingency conditions in infant left/right arm movements and left/right leg movements. To investigate whether infants adjusted the acceleration of both legs or only the acceleration of the right leg, we compared two variables for both legs for the entire group and the performer subgroup. First, we compared the ratio of right/left leg acceleration peaks within 9-20 m/s^2 during the baseline and contingency conditions. Second, we compared the ratio of right/left leg acceleration peaks of all peaks above the movement threshold during the baseline and contingency conditions.

TABLE II. NUMBER OF INFANT RIGHT LEG ACCELERATION PEAKS WITHIN 9-20 M/S^2.

Infant	Baseline (peaks/ min)	Performer Threshold (peaks/min)	0-2min	2-4min	4-6min	Performer (Y=Yes; N=No)
1	7	10.5	14	75	70	Y
2	7	10.5	2	2	4	N
3	39	58.5	125	47	32	Y
4	1	1.5	5	5	12	Y
5	15	22.5	4	10	5	N
6	1	1.5	2	19	13	Y
7	1	1.5	3	2	4	Y
8	19	28.5	5	1	0	N
9	7	10.5	7	7	16	Y
10	0	NA	3	6	1	NA

* Grey blocks indicate when infant demonstrated the highest number of acceleration peaks within 9-20 m/s^2 and was used for each analysis.

IV. RESULTS

Each infant's performance in each condition is shown in Table II.

A. Magnitude and Distribution

For all 10 infants (Figure 3a), the magnitude of leg peak acceleration did not differ significantly between baseline (right: 2.702 ± 1.067 m/s^2, left: 2.966 ± 0.961 m/s^2) and contingency conditions (right: 3.548 ± 1.875 m/s^2, left: 3.548 ± 1.800 m/s^2); p = 0.10 (right) and p = 0.17 (left), respectively. In comparison, for the performer subgroup (Figure 3b), we found a significant increase for the right leg (baseline: 2.687 ± 1.135 m/s^2, contingency: 4.312 ± 2.091 m/s^2, p = 0.03), but not for the left leg (baseline: 3.007 ± 1.097 m/s^2, contingency: 3.831 ± 2.167 m/s^2, p = 0.17). In summary, only the performer subgroup increased the magnitude of leg peak acceleration.

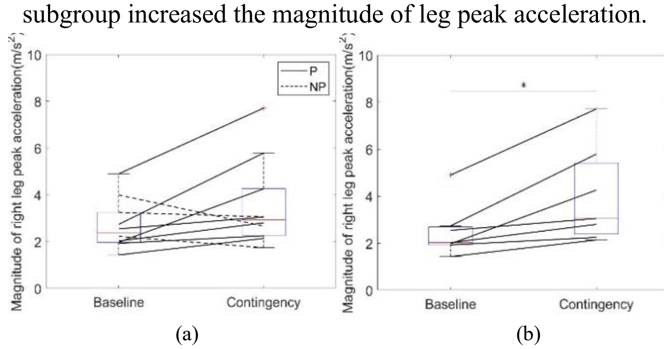


Figure 3: Magnitude of infant right leg peak acceleration during baseline and contingency conditions for (a) the entire group. (P: performers; NP: non-performers) and (b) the performer subgroup.

For the entire group (Figure 4a), the distribution of peak right leg acceleration within 9-20 m/s^2 significantly increased from baseline (7.22 ± 6.57 %) to the contingency condition

(13.55 ± 10.33 %), p = 0.047. The left leg, however, did not show a significant change from baseline (9.35 ± 7.27 %) to the contingency condition (10.69 ± 10.50 %), p = 0.67. For the performer subgroup (Figure 4b), we similarly found a significant increase in leg accelerations from baseline (6.61 ± 7.53 %) to the contingency condition (17.56 ± 11.56 %) in the right leg (p = 0.03), but not in left leg (8.08 ± 6.98% during baseline; 13.32 ± 13.05% during contingency, p = 0.35). In summary, the entire group increased the distribution of peak acceleration within 9-20 m/s^2 for movements of the right leg but not the left leg.

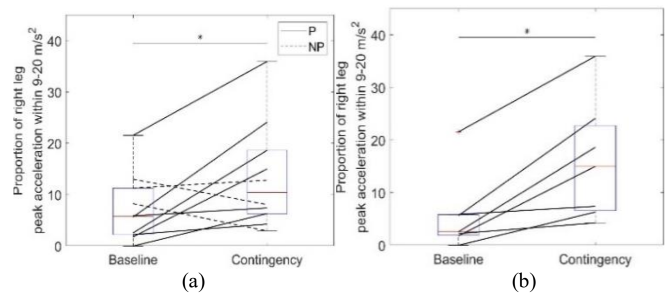


Figure 4: Proportion of infant right leg peak acceleration within 9-20 m/s^2 during baseline and contingency conditions for (a) the entire group. (P: performers; NP: non-performers) and (b) the performer subgroup.

B. *Selective Control*

For the entire group (Figure 5), no significant change of AUC was observed from the baseline (right leg: 1673.9 ± 1084.5 m/s; left leg: 1485.7 ± 922 m/s; right arm: 1169.1 ± 439.0 m/s; left arm: 1230.5 ± 632.6 m/s) to the contingency condition (right leg: 2925.6 ± 2799.9 m/s; left leg: 2390.9 ± 2231.4 m/s; right arm: 1205.8 ± 579.1 m/s; left arm: 1144.1 ± 627.5 m/s), with p = 0.11, 0.09, 0.65, 0.72 respectively. For the performer subgroup, the AUC of both legs (Figure 6) changed significantly (right leg: p = 0.02; left leg: p = 0.03) from the baseline (right leg: 1587.0 ± 1286.9 m/s; left leg: 1343.8 ± 1024.8 m/s) to the contingency condition (right leg: 3636.3 ± 3124.4 m/s; left leg: 2854.5 ± 2560.2 m/s). However, no significant change of AUC for infant arm movements (Figure 6) was observed from the baseline (right arm: 1128.7 ± 419.5 m/s; left arm: 1102.2 ± 461.6 m/s) to the contingency condition (right arm: 1364.5 ± 557.1 m/s; left arm: 1288.1 ± 651.4 m/s), p = 0.18 and 0.74 respectively. In summary, an increase in AUC measures was limited to leg acceleration in the performer subgroup.

For the entire group (Figure 7), the ratio of right/left leg acceleration peaks within the 9-20 m/s^2 bandwidth significantly increased from baseline (0.85 ± 0.54) to the contingency condition (2.04 ± 1.70), p = 0.01. However, the ratio of right/left leg acceleration peaks for all peaks above the movement threshold did not change significantly from baseline (1.89 ± 2.51) to the contingency condition (1.84 ± 2.40), p = 0.26. Similarly, in the performer subgroup (Figure 8), the ratio of right/left leg acceleration peaks within 9-20 m/s^2 bandwidth significantly increased from baseline (0.87 ± 0.52) to the contingency condition (2.32 ± 1.88), p = 0.04. The ratio of right/left leg acceleration peaks above the movement threshold, on the contrary, did not change significantly from baseline (2.41 ± 3.24) to the contingency condition (2.31 ± 3.06), p = 0.40. In summary, only the ratio of right/left leg acceleration peaks within the target acceleration range increased from baseline to the contingency condition.

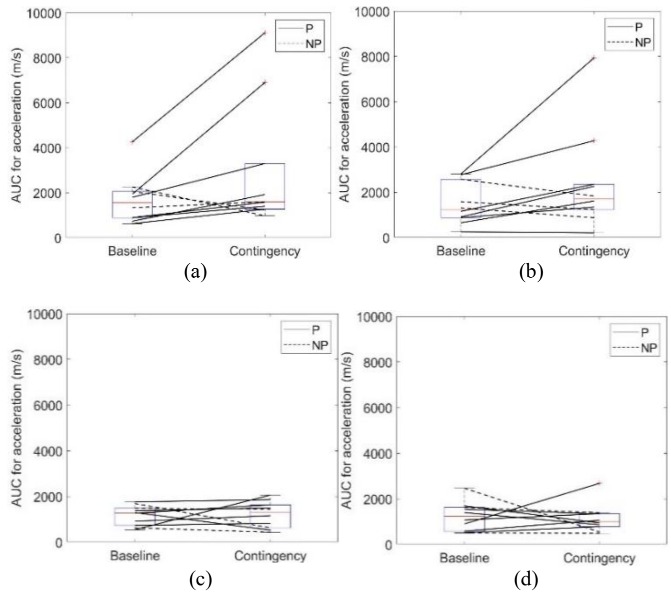


Figure 5: The area under the curve for the infant (a) right leg, (b) left leg, (c) right arm, and (d) left arm acceleration during baseline and contingency conditions for the entire group (P: performers; NP: non-performers).

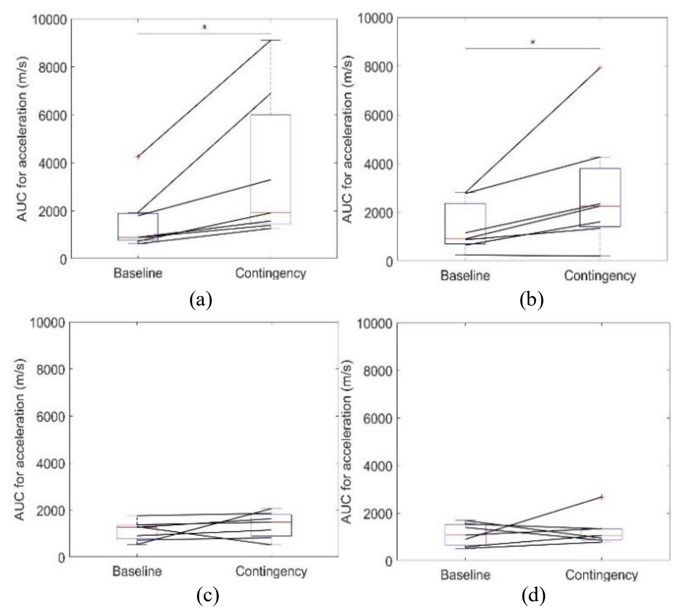


Figure 6: The area under the curve for the infant (a) right leg, (b) left leg, (c) right arm and (d) left arm acceleration during baseline and contingency conditions for the performer subgroup.

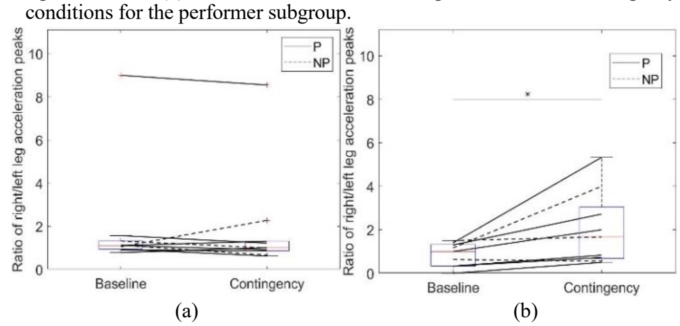
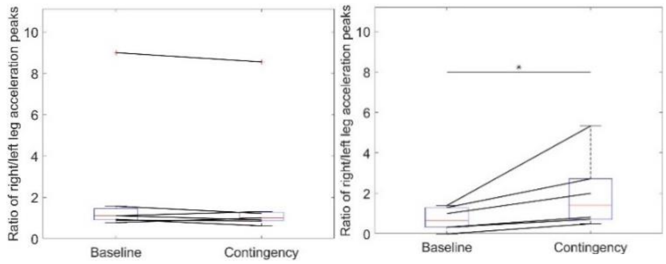


Figure 7: (a) Ratio of infant right/left leg acceleration peaks of all peaks above the movement threshold during baseline and contingency conditions for the entire group and (b) Ratio of right/left leg acceleration peaks within

9-20 m/s^2 during baseline and contingency conditions for the entire group. (P: performers; NP: non-performers)



(a) (b)

Figure 8: (a) Ratio of infant right/left leg acceleration peaks of all peaks above the movement threshold during baseline and contingency conditions for the performer subgroup and (b) Ratio of right/left leg acceleration peaks within 9-20 m/s^2 during baseline and contingency conditions for the performer subgroup.

V. Discussion

The goal of this work was to investigate whether the SAR is effective in encouraging infants to selectively adjust their leg acceleration within a single-session contingent learning paradigm.

A. Magnitude and Distribution

Magnitude: The ability of infants to adjust their leg movements (H1) was not supported by the data from the entire group (10 participants) but was supported by the data from the performer subgroup (6 participants). The change of leg peak acceleration magnitude from baseline to contingency was not significant when considering the performance of the entire group. This is likely because the group of 10 infants was nearly equally composed of infants that met our *a priori* criteria for "performer" (6) and those who did not (4). This limited our ability to tease out the "learning effect" within the entire group considering the substantial difference of performance between the performers and non-performers. However, the performer subgroup demonstrated a significant increase in right leg peak acceleration, thereby meeting the task requirements. Specifically, 6 of the 10 infants who performed the task selectively shifted the peak acceleration magnitude of right leg movement towards the pre-defined acceleration range (9-20 m/s^2).

Distribution: H1 was supported both by the entire group and the performer subgroup: infants changed the distribution of leg accelerations so that they produced relatively more accelerations in the reinforced acceleration range during the contingency condition compared to the baseline condition. The increased proportion of targeted acceleration implies the infants were actively choosing to initiate higher accelerations for right leg movements instead of simply moving more to receive more reinforcement. The entire group shifted their behavior although only 6 of the 10 infants were considered performers according to the movement rate definition (1.5 times of qualified movement in contingency than baseline). This highlights a limitation of the dichotomous performer/non-performer classification based on movement rate alone for this study: to accurately assess infant learning, we should also consider how the infant's overall behavior changes.

Our finding that infants at 6 to 8 months of age can adjust their leg movement acceleration patterns in response to robot feedback is consistent with previous studies that infants have been learning to modify their movement acceleration patterns before they were born to 3 years old [5], [34]–[38]. In contrast to previous studies that involved an endpoint-goal-directed task, the robot-provided reinforcement requirement in our study did not have a clear endpoint-goal yet the infants still managed to change the leg acceleration distribution.

B. Selective Control

Arms vs. Legs: The ability of infants to selectively control a single limb (H2) was not supported by the data from the entire group but was supported by the data from the performer subgroup. When comparing the movement intensity of the arms and legs, the entire group did not show a significant change from the baseline to the contingency condition. However, the performer subgroup increased significantly in both legs but not arms from the baseline to the contingency condition. Across the first couple months, infant gradually increased the ability to differentiate arms and legs [40], [41], [43]. Our results showed that some infants 6 to 8 months old were able to specifically adjust their arms and legs acceleration patterns in an episodic contingency paradigm (reinforcement is given with a delay after qualified behavior happens) provided by a SAR within a brief training interval (less than 6 minutes).

Laterality: H2 was supported by the data: robot-provided reinforcement increased infant leg movements within the acceleration band only in the leg targeted by the reinforcement in the performer subgroup. Although the AUC shows that the performer subgroup increased their left and right legs' movement intensity concurrently, the increased ratio of right/left leg acceleration peaks indicated those infants chose to generate more of the movements within the targeted acceleration band on the right leg than the left leg. This shows that performer subgroup was able to appropriately change their leg movement acceleration patterns based on the task requirements, as the right leg was the one activating the reinforcement.

Our finding that infants selectively modified the acceleration in one leg when reinforced by a robot is consistent with previous research on infant movement frequency. Infants were able to specifically increase the relative kicking frequency of the leg that was connected to a moving mobile in a contingency learning paradigm around 3 months of age [40], [41], [43], [44]. Interestingly, our results showed the ratio of right/left leg acceleration peaks above the movement threshold did not change significantly from the baseline to the contingency condition for the entire group and the performer subgroup. This suggests that these infants did not simply generate more limb-specific leg movements with various acceleration randomly, but that they specifically generated more movements within the targeted acceleration range. Further, our findings indicate that a SAR can encourage infants to specifically refine their movement strategy within a short motor learning session.

C. Behavior of non-performers

There were differences in how the infants responded to the contingency between the entire group and the performer subgroup. This is likely due to the variability within the participating infants. Some non-performers had an opposite trend compared to the performers: some non-performers appeared to show a decrease in magnitude of peak acceleration or movement intensity in the contingency compared to baseline condition. We hypothesize that these non-performers did not move "enough", so they did not have the chance to discover the relationship between their leg movements and the activation of the SAR. Another possibility is that they were moving "enough" but their typical leg movement accelerations were too low to go above our threshold, so they were not capable of activating the reinforcement repetitively. However, it is not known what amount of reinforcement is "enough" for infants to learn or if that amount is consistent across infants.

D. Future work

We acknowledge the sample size in this study is small and unbalanced between females and males, especially in the analysis of the performer subgroup. However, our small sample shows that infants were able to specifically adjust their leg movement acceleration in response to robot feedback, a key first step in studying infant leg acceleration control. A larger sample size in a future study will allow us to compare the difference between performers and non-performers' behavior and help explain the reasons underlying the learning outcome. A major challenge for infant research lies in the high variability of infant behavior. The data we analyzed varied from the first to the third block during the contingency session. We chose the block with the best performance in order to compare across the whole group. Based on our observations, the differences in infants' best performance block times are likely due to infants' attention and baseline behavior. Infants who moved more at the baseline and/or attended to the robot more were more likely to reach the best performance block faster. Further studies are needed to confirm these observations. We also excluded the data from the extinction condition as 5 of the infants were crying. As a result, we were unable to interpret infant behavior during the extinction condition. Data from the extinction condition could potentially reveal more of the learning progress of acceleration control in terms of whether the learning effect would last without reinforcement and for how long. Similarly, additional outcome variables (i.e., visual anticipation) and testing conditions (i.e., retention condition) may help to reveal the learning processes involved with contingency learning. Using a retention condition instead of an extinction condition may be more effective for this age group in order to reduce crying-related drop outs. Our work shows that a SAR can increase infant movement and encourage selection of specific movement strategies. Future studies may consider designing individualized threshold and rewards to increase an infant's ability to explore and successfully discover the contingent relationship between their movement and the effect their movement has on the robot's feedback.

VI. Conclusion

Through a contingency learning paradigm, we found that a SAR that leverages a selective contingency policy can encourage infants to adjust their leg movement acceleration based on the task requirement and to generate limb-specific task-oriented behavior. In dividing the infants into performers and non-performers, within-group comparisons suggested that performer subgroup produced more pronounced changes in leg movement from the baseline in the contingency condition. In the long term, we aim to understand how to utilize human-robot interaction to provide personalized, real-time adaptive robot-reinforced learning tasks and how to optimize the robot's action selection policy in order to provide effective interventions. Infants at risk for developmental disabilities have distinct motor challenges, and using a personalized robot-delivered reinforcement policy could be the key to providing the 'just-right challenge' and improve the quality, rather than quantity, of an intervention.

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