# Network Analysis of an Infant's Motor Actions Performed in a Robot-Assisted Learning Environment

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***Abstract*— Providing infants with opportunities to engage in a variety of motor actions early in life impacts their later development. Our recent work utilizes socially assistive robots (SARs) and body weight support (BWS) technology to provide infants such opportunities. This paper examines the motor actions demonstrated by an infant with Down syndrome during their spontaneous interactions with the SARs and while using BWS assistance. The infant participated in eight 1-hour sessions over the course of four weeks. By using methodological tools from social networks, we identify and describe the complex nature of the infant's motor actions displayed during interaction with both types of technology over time. The changes in these networks informs the development of robot-assisted learning environments that can be applied at this critical life period.**

## I. INTRODUCTION

Robot-assisted learning environments have only been recently introduced in early intervention [1], [2]. With a focus on social rather than physical interaction, socially assistive robots (SARs) can provide a safe and engaging environment for infants and toddlers to move and learn [3]–[5]. Various robots have been utilized in such environments with young children; from spherical mobile robots to humanoid robots, thus, showcasing the broad spectrum of implementation of SARs with young populations [1], [2], [6], [7]. More importantly, these studies show promise for use of SARs to promote various motor actions performed by young children, ranging from kicking [1] and arm movements [8] to gross motor actions such as crawling and walking [2]. Providing experiences over a range of postural and motor actions is the key to advancing motor skill development and serves as a foundation for mobility later in life [9]–[12].

Infants learn how to adapt to their surroundings and control their movements through trial-and-error interactions with their environment [12]; an example of which is illustrated in infants actively touching surfaces to lean and push against while learning to sit [13]. As infants transition from simple to more advanced actions, each posture provides unique circumstances and restraints with which the infant must learn to orient the body [14]. These transitions through the developmental milestones afford infants opportunities to interact with their environment in new ways. For example, when in prone position, infants are unable to fully interact with the environment as their hands must be used for postural stability [15]. However, as infants transition to a sitting posture, they become capable of reorienting their body thus freeing their hands for object interaction [16], [17]. Similarly, the transition to walking affords more frequent transport of objects through the environment as compared to hands-and-knees crawling [18]. Advances in these postural and mobility milestones, which typically occur during the early years of life, are critical for environmental interactions. Developmental disorders and certain diagnoses that impact motor abilities, such as Down syndrome (DS), may affect these opportunities for object and environmental engagement.

DS affects both physical and mental development [19]. Deficits in the physical development of DS, such as lack of postural control, and poor body balance and coordination [20]–[22], result in delayed attainment of postural and motor abilities as compared to their neurotypical peers [23]–[25]. Generally, infants with DS take nearly twice as long to achieve the onset of motor milestones [26], [27]. Given that deficits in posture and mobility can have negative cascading effects on global development, early intervention is needed to aid infants with developmental delays [28]–[32]. Early intervention may involve learning environments that provide opportunities for variability of self-produced functional motor actions through the application of personal and environmental constraints [12]. This paper examines the potential of a robot-assisted learning environment to elicit various motor actions in an infant with DS (through the latter's spontaneous interaction with socially assistive robots) and showcases a novel method to analyze these actions.

There is a need for efficient methods that capture variability across movements and time scales. On a short-time scale within postural movements, non-linear analysis and frequency and time domain signal analysis of center of pressure may be used to describe postural control development [33]–[36]. On a longer time scale, behavioral variability, which refers to the different ways or positions an infant may assume within a certain skill category [33], is typically described using frequency measures. Such analyses, however, do not fully capture the complexity or describe the temporal relationship between these different actions. Recently, the use of network analysis was introduced in developmental research to assess complex behavioral patterns within infants over motor action development [37], [38]. This paper builds on the latter work and extends the use of network analysis to describe motor actions during an infant's interaction with technology in a robot-assisted environment.

Our current understanding of infants' interaction with assistive technology in robot-assisted learning environments

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and its effects on infants' motor actions is limited. In this work, data from an infant with DS exploring a robot-assisted learning environment were utilized. The learning environment, which incorporated socially assistive robots and body weight support technology [2], was originally created to promote perceptual-motor development, by providing infants opportunities to perceive possibilities and perform new motor actions based on availability of information and robotic agents in the environment [39]–[41]. The analysis in this paper, is specifically tailored to examine the specific motor actions elicited by the infant when using body weight support (BWS) assistance and when interacting with two SARs of a different type.

## II. METHODS

### A. Data Collection

The analysis in this paper was performed on archival data collected from the single participant infant diagnosed with DS who participated in a 4-week pilot study. Throughout the study, the 24-month-old infant could sit independently and crawl, but was not yet able to stand and walk without support. As previously stated, the learning environment in this study utilized BWS technology and two SARs to promote mobility through activity-based, child-robot interaction. Each session lasted about one hour (including breaks) for a total of eight sessions.

In each session, the infant performed both goal-directed and spontaneous motor tasks in a free-play setting; the analysis in this paper focuses on the free-play task in which the infant engaged in spontaneous interactions with the robots for approximately three minutes every time. Compared to the goal-directed tasks, the free-play task provides a more ecologically-valid assessment of infant behavior and motor actions during unstructured play. In half of the trials, the infant was provided with assistance from a dynamic, open-area BWS device [42]. Providing BWS to young children in an open area (in contrast to providing over treadmills) allows for training on a variety of motor actions [43]–[46]. The order of the tasks and the conditions was respectively standardized and alternated across sessions.

Two dynamic and adaptive SARs were selected to engage with the infant in this paradigm: (1) NAO™ (Aldebaran Robotics), a 58-cm tall humanoid, and (2) Dash™ (Wonder Workshop), a small wheeled programmable toy robot. The selection of these robots was based on their capabilities to promote different actions by the infant. For instance, the wheeled robot was fast thus making it suitable for chasing games that involve gross mobility actions, while the humanoid could "mimic" human postures like sitting, standing, etc. The robots were operated within the learning environment by a researcher in the team to keep the infant engaged and increase their mobility. For example, the robots would close their distance from the infant when the latter was not engaging in the desired activity to increase the possibility for the infant to initiate an approach. During the free-play task, both robots were simultaneously present in the environment with the goal of having one robot interacting with the infant at a time. Additional information regarding the learning environment, study paradigm and robot action control can be found at [2]. The protocol for this study was approved by the Institutional Review Board (IRB). Written informed consent was provided by the parent(s) prior to participation.

### B. Data Analysis

*1) Annotation Protocol:* All sessions were video recorded for offline annotation analysis. Changes in motor actions (both postural and mobility) were annotated using the actions depicted in the Alberta Infant Motor Scale (AIMS), a valid and reliable observational assessment tool for measuring gross motor development from birth to independent walking [47]–[49]. Modifications to the AIMS were made to include actions that did not fall into an existing motor skill included in the scale (e.g., certain transitions, etc.). All of the actions annotated were then categorized as postural, mobility, or transitional. The frequency of actions for each category was computed across robots and BWS conditions. The goal was to examine if the interaction with the two robots and BWS assistance elicited different motor actions from the infant.

*2) Network Parameters:* Network analysis is a mathematical and theoretical tool to examine the structure of connections between nodes. Connections between nodes, called arcs or edges, can be bidirectional or undirected. Network analysis was utilized in an effort to identify the type of actions selected and their relationship with respect to interaction with the different robots and BWS assistance, within and across sessions. In this context, network analysis can provide insight on the (1) frequency of transitions within a session, and (2) the actions that are central to those transitions across sessions [38]. Similar to the 2020 study conducted by Thurman and Corbetta [38], the annotated actions in this work were condensed to eight broader but mutually exclusive categories (i.e. laying down, sitting, stationary on all fours, kneeling/squatting, crawling, standing, cruising, and stepping). These categories represent the nodes of the network while edges mark transitions of the infant from the posture of one category to another. To examine the complexity of these nodes within the network, the following network parameters were assessed using MATLAB 9.10 (R2021a):

- Node degree: measures the number of connections of a node; provides information about the existence of highly connected nodes in the postural network.
- Degree centrality: measures the posture(s) most often used to transition to other postures.
- Betweenness centrality: measures the posture(s) that may have served as bridges to other postures (i.e. it is like a bridge connecting postures in the network).
- Eigenvector centrality: measures the relative influence of certain posture(s) in the network; captures a given posture's frequency of connections to other postures and the relative importance of the postures from which those transitions are sourced, indicating which posture has wide-reaching influence in the network.

- Network density: measures the complexity of the network; expressed as a ratio of actual node connections in the network to the possible node connections.

## III. RESULTS

Overall, the infant displayed a variety of motor actions in the robot-assisted learning environment over the sessions. As the data utilized here are based on a single participant, descriptive results are provided.

### A. *Proportions of Engagement Across Action Categories*

About half of the infant's actions performed during the sessions were postural actions, followed by transitions, and mobility actions (Fig. 1).

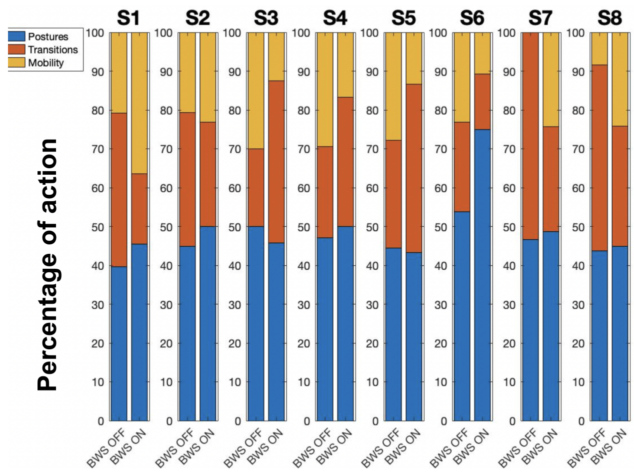


Fig. 1. Percentage of the infant's postural, transitional and mobility actions across sessions with and without BWS.

Looking at the proportions of these actions with and without BWS separately, we see similar results for postural actions ($M_{w/}$=46.27%, $SD_{w/}$=4.29%; $M_{w/o}$=50.39%, $SD_{w/o}$=10.25%), transitions ($M_{w/}$=29.47%, $SD_{w/}$=10.20%; $M_{w/o}$=33.71%, $SD_{w/o}$=12.32%), and mobility actions ($M_{w/}$=20.14%, $SD_{w/}$=8.54%; $M_{w/o}$=20.02%, $SD_{w/o}$=10.66%).

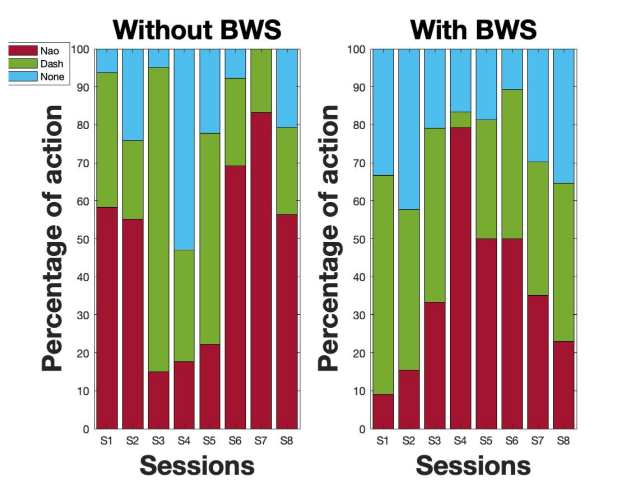


Fig. 2. Percentage of the infant's actions with each robot across sessions.

With reference to Fig. 2, when there is no BWS assistance we observed that the majority of the infant's lumped actions were performed during their interaction with the humanoid robot (M=47.14%, SD=25.62%) rather than the wheeled robot (M=35.48%, SD=21.73%). On the other hand, enabling BWS assistance appears to introduce a balance between the infant's overall interaction with the humanoid robot (M=36.88%, SD=22.61%) and the wheeled robot (M=37.16%, SD=15.44%).

We then move on to assess the infant's actions for each of the three categories of interest separately (Fig. 3 and Fig. 4). The infant demonstrated more mobility actions with the BWS while interacting with the wheeled robot (Fig. 3). However, without the BWS, the infant displayed more postural actions while interacting with the humanoid robot (Fig. 4).

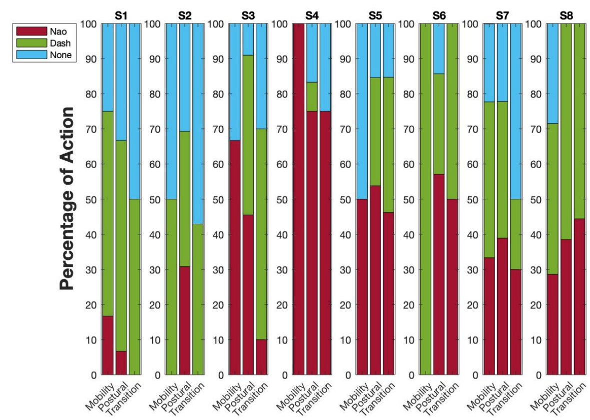


Fig. 3. Percentage of the infant's postural, transitional and mobility actions across sessions with BWS for each robot.

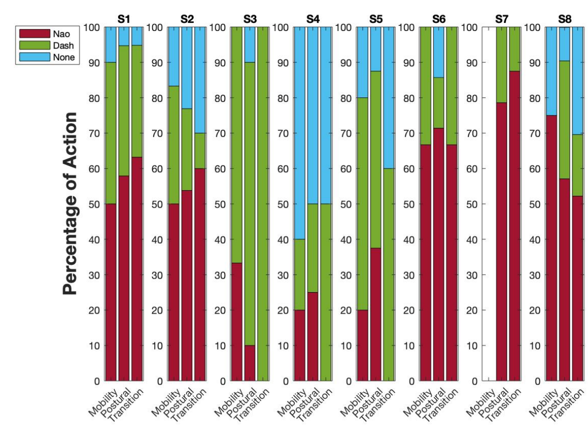


Fig. 4. Percentage of the infant's postural, transitional and mobility actions across sessions without BWS for each robot.

### B. *Type of Actions from Network Analysis*

The postural networks became more complex over time. Looking at Sessions 1 and 8, there was an increase in number as well as thickness of arcs. Thickness of an arc in the network represents more frequent occurrence of that arc in the network. Therefore, these results suggest an increase in connected actions performed by the infant (Fig. 5). Furthermore, in both BWS conditions, network density increased from session 1 to session 8 (Table I).

TABLE I
NETWORK DENSITY OF THE POSTURAL NETWORK WITHOUT AND WITH BODY WEIGHT SUPPORT (BWS)

| Session | Without BWS | | With BWS | |
|---|---|---|---|---|
| | Active Edges | Network Density | Active Edges | Network Density |
| S1 | 6 | 0.1071 | 6 | 0.1071 |
| S2 | 6 | 0.1071 | 6 | 0.1071 |
| S3 | 6 | 0.1071 | 4 | 0.0741 |
| S4 | 6 | 0.1071 | 6 | 0.1071 |
| S5 | 6 | 0.1071 | 6 | 0.1071 |
| S6 | 6 | 0.1071 | 6 | 0.1071 |
| S7 | 2 | 0.0357 | 6 | 0.1071 |
| S8 | 12 | 0.2143 | 12 | 0.2143 |

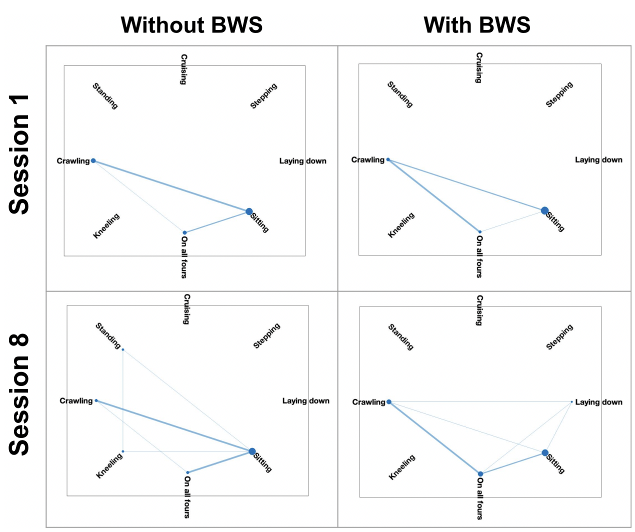

Fig. 5. Networks in the first and last session.

Regardless of BWS assistance, the sitting posture had the highest degree centrality (both conditions: M=1, SD=0; Fig. 6). This suggests that the infant most frequently shifted to a sitting posture. On all fours and crawling were also important postures when examining degree centrality, that differed across BWS conditions. The degree centrality for on all fours was higher with BWS (M=0.44, SD=0.19) than without BWS (M=0.38, SD=0.11), whereas for crawling, it was similar between conditions (without BWS: M=0.38, SD=0.24; with BWS: M=0.37, SD=0.21). This suggests that the infant shifted to a more demanding posture (on all fours demands higher motor control compared to sitting) and trained in this posture more often with BWS assistance. Lastly, looking at eigenvector centrality, sitting also scored the highest (without BWS: M=0.19, SD=0.05; with BWS: M=0.19, SD=0.04).

## IV. CONCLUSIONS

This paper describes the motor actions demonstrated by an infant diagnosed with DS while exploring a robot-assisted learning environment. Network analysis was utilized to examine the relationship of these actions. The use of such an analysis is novel to describe motor actions elicited in an infant-robot interaction paradigm.

The preliminary data in this work suggest that SARs may be used to elicit various motor actions within the same session and paradigm. Although the infant in our paradigm primarily engaged in postural actions (followed by transitions and mobility actions), this may be due to the developmental stage of the infant which was mainly characterized by pre-standing and pre-walking abilities [38]. Nevertheless, the infant demonstrated an increase in the connections between actions and node density over time suggesting a greater postural network complexity by the end of the participation in our paradigm. Although we expected to see a more gradual increase in complexity over time, the infant demonstrated a drastic increase in network complexity in both BWS and without BWS conditions in the last session. It is difficult to draw any conclusions regarding these findings since the analyses were only completed on one participant with DS; however, these results do suggest that other factors, such as the time required for familiarization with the learning environment and changes in developmental skills that simultaneously occur, may also impact network complexity [38].

There are a number of factors that warrant consideration. First, the analysis in this paper was performed on a single infant with DS during a a free-play task. Involving more participants and various motor tasks may produce different motor actions and networks. Second, although the study from which the data were utilized spanned a handful of sessions, the term period of four weeks may be too short to allow for conclusions on developmental changes. Further research is needed that includes a larger sample size, more diverse demographics (e.g., additional developmental disabilities, etc.), and a longer time frame in order to fully understand how motor variability changes over time in robot-assisted learning environments. Despite these limitations, this paper is the first to describe the variability of motor actions and use of network analysis in an infant-robot interaction paradigm.

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Fig. 6. Degree centrality (panels in top two rows; grey background) and Eigen centrality (panels in bottom two rows, white background) measures of the postural network of the infant.

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