Validating a System to Monitor Motor Development of At-Risk Infants in Black Communities: A Case Study

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Abstract— Infants born prematurely are at an increased risk of motor development delays. Demographic measures such as race, level of maternal education, and access to prenatal care are additional indicators for elevated risk. It is thus especially important to provide widespread and easily accessible tools to monitor infant motor development in higher-risk groups to mitigate delays as early as possible. This is especially true for communities that have traditionally been neglected due to the racial disparities found with respect to healthcare access. In this paper, we introduce an automated system to gather infant kicking data and determine the developmental maturity of an infant's kicking using identified kinematic features. Infant kicking behavior has been found to be a valid pre-marker that is useful for identifying potential developmental delays in at-risk infants. Using this system, designed for pervasive use in underserved communities, we then analyze the developmental maturity of a preterm African-American infant, clinically identified as at-risk, by identifying kinematic markers that might indicate delay as compared to normative infant kicking data. Results show that the system can readily be deployed in the home setting to identify developmental maturity for at-risk underserved infants.

I. Introduction

Our research aims to develop a system to monitor infant motor development and detect delays through the extended observation of infant kicking. In this work, we first describe our system for the observation of infant motor development and determination of normative values. We then discuss our pilot study in which the system was deployed to the home of a preterm, at-risk African American infant.

In the United States, approximately 10% of births are considered premature according to the Center for Disease Control and Prevention (CDC). Preterm infants, especially those with very low birthweight (VLBW), are more likely to develop neuro-developmental disorders and experience motor development delays than their term counterparts [1,2]. In addition to known risk factors like premature birth and VLBW, various demographic measures serve as indicators for elevated risk of motor development delays. Race, socioeconomic status, and level of maternal education have been associated with elevated risk [4]. For example, the rate of preterm birth is almost 50% higher for Black women than for all other women in the United States [26]. As a result, preterm birth is the leading cause of motor disability, developmental delay, and infant death among Black infants [27]. Furthermore, infants born to women who did not have prenatal care are also at elevated risk [5].

Intervention therapy may be used to improve the overall quality of life for preterm infants with developmental delays if these delays can be reliably detected early in life [3]. However, it is oftentimes difficult for diagnostic tests to encompass all patients due to the variability between individuals [2]. As such, various efforts have been made to automate the diagnosis process using artificial intelligence [9-21]. However, many similar efforts in other healthcare applications, such as [23-25, 29], have neglected certain segments of the population and resulted in disparate healthcare outcomes. To help mitigate racial disparities in healthcare outcomes for preterm infants, an affordable and accessible option for monitoring infant motor development is needed. Having said access can provide improved care for preterm infants in communities associated with higher risk to maximize their overall quality of life. Our research aims to develop a system to monitor infant motor development and to detect delays through the extended observation of infant spontaneous kicking. We aim to make this system accessible and low in cost when compared to in-clinic human observations.

In this work, we first describe our system for the observation of infant motor development in these underserved communities. This system is low cost, easy to use with minimal training, and robust to environmental uncertainties such as found in the home environment. This system has previously been used to develop a set of features to describe normative kicking behavior in typically developing infants. Secondly, we discuss our pilot study in which, on three separate occasions, the system was deployed to the home of a preterm, at-risk African American infant (see Figure 1). The parents used the system to gather kicking data from which kinematic markers were calculated. These markers were then compared to normative data to determine developmental maturity for the preterm infant.

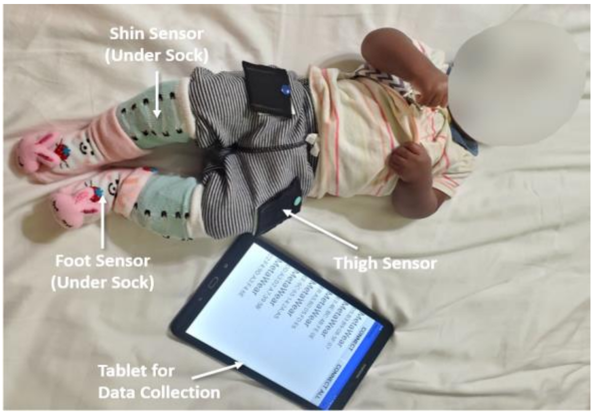

Figure 1. Set up of our system deployed to the home of a preterm, at-risk African American infant. Photo was taken during the third data collection session (38 weeks).

II. Related Work

Numerous technologies have been developed to automate the observation of and analyze various aspects of infant motor development. Multiple approaches make use of specialized equipment like depth cameras and motion tracking systems to gather infant movement data. In [9-11], depth cameras are used to gather 3D movement data to analyze infant kinematic motion and for infant pose estimation. Other approaches use motion capture to gather infant pose data and track infant movement [12]. Furthermore, electromagnetic tracking is used in [13, 14] to examine infant upper and lower limb motion and to track fidgety movements in 3D space. The use specialized equipment (as in these methods) allows for precise spatial tracking of infant spontaneous movement. However, these systems are oftentimes expensive and require a controlled environment. Methods that use these systems are unsuitable for use outside of a laboratory or clinical setting for these reasons.

Other approaches utilize optical devices such as video cameras to analyze infant motion data. Oftentimes, markers are placed on the infant to aid in tracking the infant's movements [15]. Other approaches attempt to track infant motion and identify at risk infants using markerless video data [16-19]. These methods often rely on assumptions about joint positions/measurements and require a specific configuration between the camera and the infant being filmed. Additionally, these methods are oftentimes not robust to occlusions, making these approaches non-ideal for usage outside of a controlled environment.

To our knowledge, none of the systems described thus far have been deployed in the home setting for use by the parents or guardians of the infant. Additionally, these technologies are unsuitable for deployment in under-resourced communities due to their high cost and need for specialized training. In response to these concerns, there has been a push towards using wearable sensing technology like clothing embedded with sensors to gather infant movement data. In [21], Smith et al. embedded determined the daily quantity of infant leg movement from infant kicking data gathered over the course of a full day to determine the daily kicking sequence. Accelerometer data was used in [20] to identify motor milestones in infants and identify at risk infants. To our knowledge, these systems have not yet been deployed in the home setting nor have they been used to monitor the motor development of a preterm infant in an underserved community. As such, it is unclear whether these systems would be viable for use by the parents or guardians of the infants for extended observation.

As of this work, our system has been deployed to the home of an infant from an underserved community for

Table 1. Calculation of Kinematic Features

Metric	Variables	Equation
Frequency of Activity	n_{Act}: number of active samples N: total number of samples	$FA_i = {n_{Act}}/{N}$
Avg. Duration of Activity	K: total number of movements in a one-minute segment $(t_{start})_k$: start time of the kth movement $(t_{end})_k$: end time of the kth movement	$AvgKDur_i = \frac{1}{K}\sum_{k=1}^{K}(t_{end})_k - (t_{start})_k$
Avg. Duration of Rest	R: total number of rests in a one-minute segment $(t_{start})_r$: start time of the rth period of rest $(t_{end})_r$: end time of the rth period of rest	$AvgRDur_i = \frac{1}{R}\sum_{r=1}^{R}(t_{end})_r - (t_{start})_r$
Peak Acceleration	$GAct_i(s)$: vector identifying activity for data segment i $GAct_i(s) \neq 0$ for an active sample $\boldsymbol{a}_s$: 3D vector of acceleration for sample s	$PeakAccel_i = \max(\lvert\boldsymbol{a}_s\rvert, \forall\, s = 1 \dots N \mid GAct_i(s) \neq 0)$

data collection. The initial analysis of this infant's data collected by the parents over three sessions will be presented in this work.

III. System Description

Our system couples a Bluetooth-connected infant sensor suit with a data collection app, resident on a mobile device. The infant sensor suit incorporates three 6-axis IMU sensors (MbientLab's MetawearC) per leg, placed on each limb segment [6]. When the infant is placed supine, 3-axis acceleration and angular rate data for each limb segment is gathered at a sampling rate of 100 Hz. Parents of the infant are provided with infant clothing, 8 IMU sensors and batteries, and a tablet with the data collection app installed. Prior to the first data collection session, parents are instructed via remote video call on outfitting the infant, proper placement of the IMU sensors, and use of the data collection app. This training session was designed to take approximately 15 to 30 minutes of interaction time, including Q&A. Finally, during infant testing, while the parents administer the data collection using the sensor suit, a researcher is available to answer any questions the parents may have while ensuring proper setup and adherence to the data collection protocol. The parent of the infant may also record video data of the infant kicking using a cell-phone or tablet camera to provide a visual aid to compare to data from the sensors. Following data collection, the data collected by the system is parsed through various algorithms to calculate key kinematic features of spontaneous kicking: frequency of activity, average duration of movement and rest, and peak acceleration (PA) of the dominant leg. The calculation of these measures for a one-minute data segment *i* is given in Table 1.

The *frequency of activity* (FA_i) is a measure of how often a baby is actively kicking during a period. For a one-minute duration, the number of samples where an infant is actively kicking, regardless of coordination pattern, is recorded. This value, divided by the total number of samples within the segment of data, gives the frequency of activity. In clinical works, this feature was shown to decrease with age, especially as infants approach crawling and walking age [21]. However, for infants with very low birthweight (VLBW) and low gestation age (GA), an increase in kicking frequency was observed [11].

The *average duration of activity* ($AvgKDur_i$) and *the average duration of rest* ($AvgRDur_i$) are measures of how long an infant is typically moving or resting during a period. For a one-minute segment, the duration for each period of continuous activity and continuous rest is taken. The average value for each of these metrics is then taken. The duration of overall activity has not been studied extensively in clinical works but is used to evaluate the efficacy of systems used to stimulate infant kicking activity [7].

Finally, the *peak acceleration* ($PeakAccel_i$) is an indirect measure of how quickly the infant is moving their legs. The magnitude of the foot's acceleration is taken for each movement within a one-minute data segment. The peak magnitude for the infant's dominant leg, the leg the infant moves more often, is then computed. Trujillo-Priego et. al. found no relationship between this metric and age [22]. However, this study limited its analysis to specific movement sequences. To our knowledge, no studies have examined accelerations of general leg motions as we do here.

In [8], our system is used to determine normative values of these kinematic features at various ages using data from term infants. Once the kinematic features of an infant are computed, their features are compared to normative values at the same age to determine if the infant is developmentally delayed (i.e. the developmental maturity). Given the inclusion criteria and focus on at-risk infants for deployment of the system, we anticipate that any preterm infants evaluated with this system will be at-risk for being developmentally delayed. Furthermore, we expect that the features of a preterm infant's kicking will more closely align with normative values at their adjusted age (their birth age minus how early they were born) than with their birth age. Finally, we anticipate that a preterm infant's features will more closely align with normative values at their birth age as the infant ages.

Table 2. Term Infants Observed for Normative Metrics

Identifier	Sex	Gestational Age [weeks]	Age at Observations [weeks]
B	F	38	12, 18
D	F	38	8, 20, 32
E	F	39	8, 14
H	F	39	4, 20, 34
J	M	39	8, 16, 18
K	F	37	8, 14, 26
L	M	37	8, 18, 26
M	M	39	12, 22
O	M	38	12
P	M	40	12, 22
Q	F	39	6
R	F	40	12, 18
S	F	40	12
T	M	40	12

IV. Analysis of Preterm Infant Data

Three sessions of data were gathered from a very low birthweight (VLBW), premature (28 weeks gestational age (GA)) infant. This infant was identified at additional risk due to her gender (female), race (black), and mother's lack of prenatal care. These sessions occurred in the afternoon during a period when the parents indicated the infant was typically well rested and active. Data collection occurred over a 15-week time and was administered by the parents in the common living space, where play typically occurred. The parents were encouraged to interact with their child as they normally would, including introducing toys and a pacifier as needed. The parents were instructed to not physically manipulate the infant's legs, or to move the infant during data collection. Finally, the parents were informed that they could halt data collection at any time and for any reason. All sessions with the preterm infant discussed here were completed without interruption.

Kinematic features of the infant's kicking were calculated at each visit and compared to term, typically developing infants of similar age as in [8]. These normative metrics were calculated from infants aged 2 to 8.5 months, 6 male and 8 female for a total of 30 sessions of data (see Table 2). For each feature, a model (linear or quadratic) was fit to each metric to determine a trend with respect to age. The preterm infant's developmental maturity was then determined by comparing their kinematic features with respect to each model. While the model could predict an exact estimation of age, we report a window of predictions to account for variability and uncertainty between data segments. Tables 3 through 5 show the developmental maturity of the preterm infant's kicking for specific kinematic features. If the predicted developmental maturity is computed as lower than the age of the preterm infant (as indicated in the table header), then for that metric, the individual is considered developmentally delayed.

Table 3. Preterm Infant's Kicking Metrics (at 26 Weeks)

Kinematic Feature	Value	Developmental Maturity
Frequency of Activity	48.89%	25-30 weeks
Avg. Duration of Activity	0.72 s	*5-10 weeks
Avg. Duration of Rest	0.76 s	*5-10 weeks
PA of Dominant Leg	0.82 g	*5-10 weeks

*delayed based on kinematic feature

Table 4. Preterm Infant's Kicking Metrics (at 35 Weeks)

Kinematic Feature	Value	Developmental Maturity
Frequency of Activity	23.24%	35-40 weeks
Avg. Duration of Activity	0.93 s	*10-15 weeks
Avg. Duration of Rest	2.82 s	40+ weeks
PA of Dominant Leg	1.03 g	*10-15 weeks

*delayed based on kinematic feature

Table 5. Preterm Infant's Kicking Metrics (at 41 Weeks)

Kinematic Feature	Value	Developmental Maturity
Frequency of Activity	50.28%	*20-25 weeks
Avg. Duration of Activity	1.58 s	40+ weeks
Avg. Duration of Rest	1.76 s	35-40 weeks
PA of Dominant Leg	2.78 g	40+ weeks

*delayed based on kinematic feature

For this infant at 26 weeks, the average duration of activity and rest as well as the peak acceleration of the dominant leg were significantly delayed when compared to the normative values for the infant's birth age (see Table 3). These features more closely resembled normative values associated with the infant's adjusted age rather than their birth age, though they would still be considered slightly delayed. Interestingly, the frequency of activity for the infant kinematic feature was the only feature that did not show delay when compared to the normative values associated with the infant's birth age. One possible explanation is that the preterm infant is engaging in the same exploratory behavior that term infants exhibit early in life resulting in a high movement frequency. In the preterm infant's case, while the frequency of kicking is comparable to term infants of the same birth age, the speed and duration of these movements are reduced due to weaker, underdeveloped muscles. As a result, a preterm infant would have frequency measures like term infants of the same age while duration and acceleration measures lag.

At 35 weeks, the average duration of activity and the peak acceleration of the dominant leg were still significantly delayed when compared to values associated with the birth age and slightly delayed when compared to values associated with the adjusted age (see Table 4). The average duration of rest though converged to normative values associated with the infant's birth age indicating potential improvement in overall kicking behavior. The frequency of activity continued to be comparable to normative values associated with the infant's birth age.

Finally, at 41 weeks, the average duration of activity and the peak acceleration of the dominant leg have converged to normative values (see Table 5). The average duration of rest for this session slightly decreased compared to values at 35 weeks, resulting in values that were indicative of a slightly younger infant. Additionally, the frequency of activity was significantly higher than in previous sessions. As higher frequencies generally are associated with younger infants, this metric seems to indicate a delay with respect to normative values. Given the infant's improvement in all other metrics, it is unclear why this metric seems to indicate delay. A potential explanation for this difference is that premature infants may display a different pattern in kicking frequency as compared to typical infants. In the early stages of development, premature infants tend to have less muscle development as compared to their term counterparts. The decreased muscle development results in decreased durations of continuous activity and peak accelerations. During this stage, less frequent activity may be the result of fatigue rather than evidence of more mature kicking (as with term infants). Once preterm infants have grown stronger, as evidenced by longer durations of continuous activity and larger magnitudes of acceleration, their kicking frequency may increase as they are less prone to fatigue.

V. Discussion

Developmentally, a preterm infant is oftentimes evaluated with respect to their adjusted age, determined as the age the infant would be if they had been born on their due date. In this case, the preterm infant was born 12 weeks early (i.e. at 28 weeks gestation out of a 40 week term). So, her adjusted age would be calculated at each testing date by subtracting 12 weeks from her indicated age at testing. As expected, the developmental maturity of the infant's kicking was considered delayed for most of the metrics we examined and more closely resembled the normative features at her adjusted. As the infant aged, the durations of activity and rest as well as the peak acceleration of the dominant leg converged to normative values.

Interestingly, the frequency of activity for the infant's kicking did not indicate developmental delay and more closely indicated normative values associated with the infant's birth age at younger ages. However, once the other metrics converged to normative values, the frequency of activity increased, indicating values associated with younger infants. A potential explanation for these differences is due to the decreased muscle development of premature infants as compared to their term counterparts early in life. The decreased muscle development results in decreased durations of continuous activity and peak accelerations. In this case, less frequent activity may be the result of fatigue rather than evidence of more mature kicking as is the trend for term infants. Once preterm infants have grown stronger, as evidenced by longer durations of continuous activity and larger magnitudes of acceleration, their kicking frequency may increase as they are less prone to fatigue.

Though an infant may be delayed in one or more individual features, further analysis is needed to quantify the overall maturity associated with an infant's kicking movements. Additionally, ongoing observation for this preterm individual is needed to determine how the observed delays change over time, most notably if the delays completely go away. Finally, further work is needed to determine when observed delays are expected versus when they become problematic and in need of potential intervention therapy.

VI. Conclusion

Our research aims to provide an accessible and robust means to observe infant motor development in the home setting. In this study, we showed how this system complied with this goal and could be deployed to the homes of underserved and under-resourced infants as a more cost effective and accessible option to traditional clinical observation. We presented an analysis of data collected by the parents of a preterm infant from an underserved community. This data was collected by the parents across multiple sessions in the infant's home after minimal training. From this data, developmental delays were detected in the preterm infant's kicking.

Additionally, though not presented in this work, the goal of this research is to provide an estimate of infant developmental age to determine whether an infant is developmentally delayed. Using the features presented in this work, a model to estimate developmental age will be created. An infant would be considered developmentally delayed if the estimate from this model indicated a developmental age younger than the birth age for a term infant or the adjusted age for a preterm infant. This estimate will be compared a clinician's estimate of developmental age using current clinical evaluation techniques.

Following the detection of these delays, intervention therapy could be provided as needed, resulting in better outcomes for the infant and improving their overall quality of life. Due to its low cost and ease of use, our system could be one avenue available to address and hopefully mitigate racial disparities found in healthcare outcomes for at-risk infants in Black communities.

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