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Development of a Wearable Sensor Algorithm to Detect the Quantity and Kinematic Characteristics of Infant Arm Movement Bouts Produced across a Full Day in the Natural Environment

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Abstract: We developed a wearable sensor algorithm to determine the number of arm movement bouts an infant produces across a full day in the natural environment. Full-day infant arm movement was recorded from 33 infants (22 infants with typical development and 11 infants at risk of atypical development) across multiple days and months by placing wearable sensors on each wrist. Twenty second sections of synchronized video data were used to compare the algorithm against visual observation as the gold standard for counting the number of arm movement bouts. Overall, the algorithm counted 173 bouts and the observer identified 180, resulting in a sensitivity of 90%. For each bout produced across the day, we then calculated the following kinematic characteristics: duration, average and peak acceleration, average and peak angular velocity, and type of movement (one arm only, both arms for some portion of the bout, or both arms for the entire bout). As the first step toward developing norms, we present average values of full-day arm movement kinematic characteristics across the first months of infancy for infants with typical development. Identifying and quantifying infant arm movement characteristics produced across a full day has potential application in early identification of developmental delays and the provision of early intervention therapies to support optimal infant development.

Keywords: wearable sensors; infants; arm movement; movement system

1. Introduction

Infancy is a period of exploration and learning characterized by the development of motor skills. At least some of these skills arise from changes in synaptic connectivity that occur in response to recurring patterns of neural activity, as suggested by Hebb in the 1960s [1]. Profound behavioral changes can occur in infants as a result of both enriched [2] and deprived [3] motor experience. Extensive research demonstrates a striking relationship between the acquisition of new motor skills and subsequent cognitive development in infancy (for example [4–6]), implying that intervention to promote motor skills could be used to enhance the overall infant developmental rate. One of the biggest current challenges in this area, however, is accurately measuring the amount and type of movement practice infants are producing in order to identify relationships between movement practice and motor skill development. We do not currently know how much or what type of practice is necessary for an infant to learn a motor skill, for example reaching using their arms.

Wearable sensors record tri-axial accelerometer and/or gyroscope data at many samples per second, allowing us to record movement data unobtrusively across many continuous hours. We propose that wearable sensors should allow for the measurement of the amount and type of infant movement practice across days and months, unobtrusively across many continuous hours in the natural environment. To date, however, researchers have only recorded this type of data from infants for up to an hour, in a laboratory or clinical environment [7–13]. Another option is commercially available activity monitors such as Actigraph [14] and Actical [15], but they do not identify specific movement characteristics and only report relative intensity of physical activity. Although relative intensity of physical activity could be informative for certain research questions, their use has not been validated in infants. We are the first to validate the use of wearable sensors to identify and describe kinematic characteristics of infant arm movements from full-day data.

Our purpose here is to describe the development of an algorithm to identify and classify bouts of infant arm movement from wearable sensor data. To develop the algorithm, we included 33 infants (22 infants with typical development (TD) and 11 infants at risk of atypical development (AR)). We included infants with TD and AR in the development of the algorithm as our goal is to be able to use it in both populations. Some of the infants AR will eventually receive a diagnosis reflecting motor impairment, while others will not. They may or may not have detectable movement differences at this stage. We wanted to develop the algorithm to detect the movement of infants with a broad, representative range of movement characteristics to ensure that we could use one consistent algorithm process across both groups. Next, as the first step toward developing norms, we quantified full-day arm movement bouts and kinematic characteristics across the first months of infancy for infants with TD. Kinematic characteristics included duration, average and peak acceleration, average and peak angular velocity, and type of movement (one arm only, both arms for some portion of the bout, or both arms for the entire bout). Identifying and quantifying infant arm movement characteristics produced across a full day has potential applications in early identification of developmental delays and in the development and clinical testing of early intervention therapies.

2. Materials and Methods

2.1. Participants

Twenty-two infants with TD and eleven infants AR were included in this study. Infants with TD and AR were included in the algorithm development portion of the study in order to create an algorithm that is useful and accurate for both groups. Infants AR are not included in the presentation of average full-day values of arm movement bout characteristics. The infants AR are a small and broad group of infants with various risk levels for atypical development and a variety of developmental challenges. Their data do not lend themselves to pooling but will instead be correlated with individual future developmental outcomes. Infants with TD were from singleton, full-term (38 weeks minimum gestation) births. Infants experiencing complications during birth, or with any known visual, orthopedic, or neurologic impairment, or a score at or below the 5th percentile for their age on the Bayley Scales of Infant Development (3rd edition) [16] at the time of testing were excluded from the TD group. Infants in this group were between 38 and 203 days of age. Infants AR were born before 36 weeks of gestation or defined as at high risk for developmental delay per the definition of the state of California [17]. Infants AR were a broad group and included infants who were born small for gestational age, had congenital heart defects, or had known neurologic malformations, for example. Infants in this group were between 40 and 230 days (adjusted for prematurity). This study was approved by the Institutional Review Board of the University of Southern California. Infants were recruited at health care clinics and by word of mouth in the Los Angeles area. A parent or legal guardian signed an informed consent form for their infants' participation.

2.2. Procedures

Infants were measured once per month, from 1 to 6 visits each. We traveled to the infants' home in the morning. Continuous full day arm movement was recorded using two battery-powered wearable sensors (Opals, APDM, Inc., Portland, OR, USA), one on each wrist. Each sensor contains a tri-axial accelerometer, gyroscope, and magnetometer, and was placed inside a pocket in a custom wrist band (see Figure 1). The sensors were actively synchronized to each other, recording at 20 samples per second. Recordings began in the morning and continued until the infant was put to bed for the night. At this point, the caregiver removed the sensors, resulting in anywhere from 8 to 13 h of continuous data. Caregivers were encouraged to perform their typical daily activities.

Figure 1. Infant with typical development (104 days of age) with sensors on right and left arms. Sensors are shown in inset with a U.S. quarter for reference.

Once the wearable sensors were on for each assessment, we recorded five minutes of video of the infants' spontaneous movements in the supine position. We assessed development using the Bayley Scales of Infant Development (3rd edition) [16] and the Alberta Infant Motor Scale [18]. We also measured weight, length, head circumference, and upper and lower extremity lengths and circumferences. We also collected approximately 10 min of electroencephalography data during an assessment of arm reaching skill, however those results are not presented here.

2.3. Algorithm Development

We developed a threshold-based algorithm in Matlab to identify infant arm movement bouts from the wearable sensor data for acceleration and angular velocity. The first step was to define general rejection thresholds for the acceleration and angular velocity values, which were the same for all infants. Then thresholds indicative of movement bouts were determined separately and uniquely for each infant according to a standard formula that identified local maxima within the complete sensor record. These thresholds should be computed from the data from each infant to compensate for differences in infant size and sensor placement. They assure that bouts reflect real, purposeful movements by the infant rather than background noise and small movements such as positional shifts. Movement bouts were identified as periods when both the acceleration and velocity exceeded these unique thresholds.

2.4. Acceleration Rejection Threshold Determination. Detrending and Rectification

First, we calculated resultant linear acceleration as the square root squared sum of each axis (x,y,z) as follows:

$$\mathrm{Accel_{mag}} = \sqrt{\mathrm{A_x}^2 + \mathrm{A_y}^2 + \mathrm{A_z}^2} \tag{1}$$

Next, the resultant acceleration was detrended by subtracting the median to remove the gravity component and any steady noise or offsets embedded in the signal. Then we used synchronized video and sensor data (for randomly selected infants) to empirically determine a general rejection threshold for acceleration values. The detrended acceleration signal was then rectified by applying the general rejection threshold of a = [−1.02,1.32] m/s^2 (Figure 2 top).

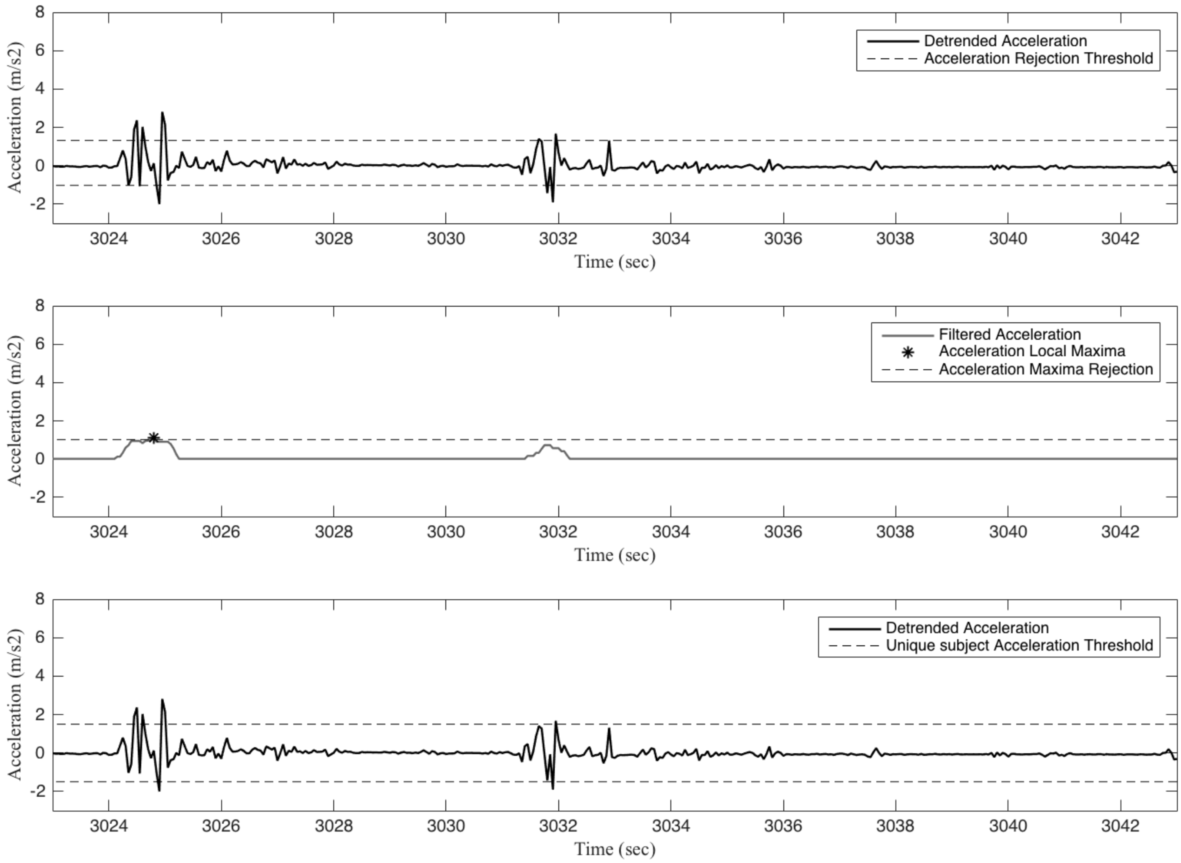

Figure 2. The top panel shows a representative detrended Accel$_{\mathrm{mag}}$ signal (solid black line) and the general rejection thresholds (black dashed lines a = [−1.02,1.32] m/s^2) for a 20 s section from the right arm of a 3-month-old infant with typical development. The middle panel shows the residual acceleration signal after full-wave rectification and smoothing (moving average with a 0.5 s window, solid black line) and the identification of local maxima (asterisk) for the filtered signal by disregarding maxima below values of 1.0 m/s^2 (dashed black line). The bottom panel shows the same representative detrended acceleration signal (solid black line) with this participant's unique acceleration threshold ±1.4972 m/s^2 (dashed black lines).

2.5. Filtering and Threshold Determination

The signal remaining after rejection was full-wave rectified and smoothed with a moving average filter (0.5 s window). We computed a unique bout threshold for each participant to distinguish potentially bout-related acceleration values from smaller movements, and we identified local maxima for the filtered signal by disregarding maxima below values of 1.0 m/s^2 (Figure 2 middle). We then set the infant's unique acceleration threshold as the mean of all such local maxima minus half standard deviation for both positive and negative values (Figure 2 bottom). Both positive and negative values of detrended acceleration that exceeded this bout threshold were used to decide when a bout had occurred. The range of unique acceleration thresholds across infants was from -2.3604 to -1.3113 m/s^2 and 1.3113 to 2.3604 m/s^2, for negative and positive thresholds, respectively.

2.6. Angular Velocity Rejection Threshold Determination. Detrending and Rectification

Similar to the acceleration signal, first, we calculated the angular velocity (ω) magnitude:

$$\text{Ang vel}_{\text{mag}} = \sqrt{{\omega_x}^2 + {\omega_y}^2 + {\omega_z}^2} \tag{2}$$

Next, the resultant angular velocity was detrended with the median to remove steady background noise embedded in the signal. We used synchronized video and sensor data (for randomly selected infants) to empirically determine a general rejection threshold for angular velocity as w = 0.32 rad/s (Figure 3 top).

Figure 3. The top panel shows a representative Ang vel$_{\text{mag}}$ signal (red solid line) and the general angular velocity rejection threshold (red dashed line at w = 0.32 rad/s) for a 20 s section of data from the right arm of a 3-month-old infant with typical development. The middle panel shows a representative filtered angular velocity signal (moving average filter with a 0.5 s window, solid red line) and angular velocity maxima rejection threshold of 0.01 rad/s (dashed red light line). The red asterisks represent the identified local maxima. The bottom panel shows the same representative detrended angular velocity signal (solid red line) and the participant's unique angular velocity threshold of 0.6200 rad/s (dashed red line).

2.7. Filtering and Bout Threshold Determination

The detrended angular velocity signal was rectified with the rejection threshold w, and then filtered with a 0.5 s window moving average filter. To determine the unique participant-based angular velocity threshold, we identified local maxima for the filtered signal by disregarding maxima below values of 0.01 rad/s (Figure 3 middle). We then set the unique angular velocity threshold for each participant as the mean of these local maxima minus half standard deviation (Figure 3 bottom). The range of unique angular velocity thresholds was from 0.4208 to 1.0515 rad/s.

2.8. Arm Movement Bout Detection

A bout was defined as the period between the start and stop of significant arm movement regardless of the position, orientation, or direction of the arm and movement. The start of a bout of movement was defined as when both detrended $Accel_{mag}$ and Ang vel_{mag} were above each signals' unique bout threshold. The end of a bout of movement was defined once the angular velocity magnitude went below its threshold (See Figure 4). To compare between visits, we normalized the number of bouts to the number of hours that the infant was awake and wearing the sensors. We visually estimated the amount of sleep time by identifying sleep time as periods of less than 3 movement bouts in 5 min. This adjusted for the different lengths of sensor wear and different amounts of nap time at each visit.

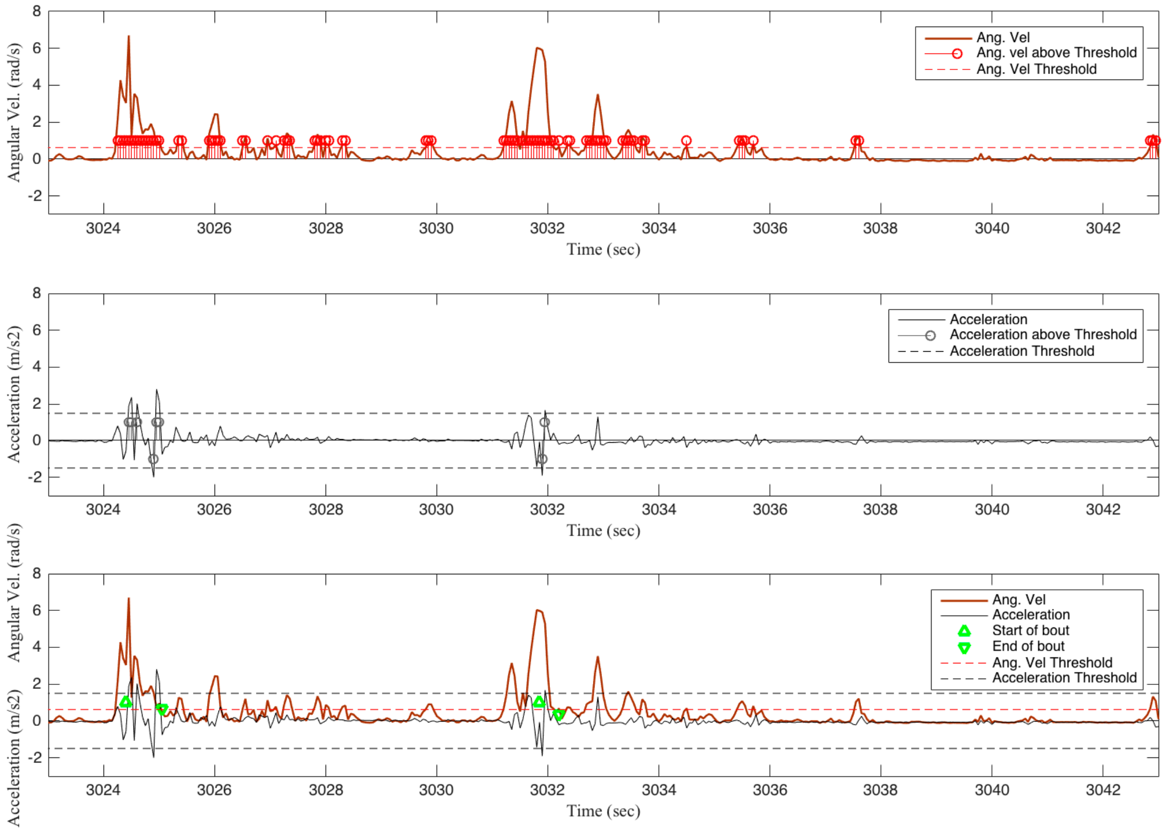

Figure 4. Top panel shows 20 s of the angular velocity detrended signal (rad/s solid dark red line), and the identification of values above the angular velocity threshold (light red circles; threshold dashed red line). Middle panel shows 20 s of the detrended acceleration signal (m/s^2 solid black line), and the identification of values above the acceleration threshold (light black circles; acceleration thresholds dashed black lines). Bottom panel shows the arm movement bout count from 20 s of representative acceleration (m/s^2; solid black line) and angular velocity (rad/s; solid red line) data. There are two arm movement bouts identified by the algorithm. The start of each bout is identified by a green triangle pointing up in the figure when the acceleration and angular velocity each went above their unique thresholds (dashed lines). Green triangles pointing down represent the end of an arm movement bout, when the angular velocity magnitude went below its threshold. All figures are from data of the right arm of a 3-month-old infant with typical development.

2.9. Algorithm Performance: Counting Number of Bouts of Arm Movement

The algorithm was compared to visual observation as the gold standard. For 10 visits from 10 different infants in each group, an interval of 20 s of infant arm movement was selected. We compared the number of bouts counted by the algorithm to the number identified by one expert observer (Beth A. Smith). Frame-by-frame video coding software (ELAN, The Language Archive, Nijmegen, The Netherlands) was used for the counting of movements, however for a new bout of movement to be counted each time the arm paused, the pause had to be observed in real time.

2.10. Type of Movement

For each arm separately, we compared the start and stop samples of each bout to those of the other arm to determine if only one arm was moving, both arms were moving for some portion of the bout, or both arms were moving for the entire bout.

2.11. Kinematic Characteristics

Duration (s), was determined by counting the number of samples for each bout and dividing that number by 20, as data were collected at 20 samples per second. Average Acceleration (m/s^2) was calculated as the sum of the absolute values of acceleration divided by the number of samples of the bout. *Peak Acceleration* (m/s^2) was calculated as the maximum absolute value of acceleration within a bout.

2.12. Acceleration Area

As a general calculation of overall arm "activity", we also calculated the area under the absolute value of the resultant acceleration curve (Acceleration Area) across the time period that the sensors were worn by the infant. To compare between visits, we normalized the area to the number of hours that the infant was awake and wearing the sensors, rounded to the nearest five minutes. A larger normalized acceleration area value indicates that the infant was moving the arm more frequently and/or faster than a smaller value.

2.13. Statistical Analyses

To examine the characteristics of full-day arm movement bouts across the first months of infancy for infants with TD, trends were developed using longitudinal linear effects modeling centered at mean age. Random differences in level were estimated. There was insufficient data to allow for the estimation of individual differences in slopes, so average slopes were estimated. Models were compared using measures of fit (BIC, -2Ln Likelihood difference) in order to determine if a linear or quadratic model fit better for any given variable.

3. Results

3.1. Algorithm Performance

The algorithm was compared to visual observation as the gold standard from 20 video segments of 20 s each, as described previously in Section 2.9. Overall, the algorithm counted 173 bouts and the observer identified 180, resulting in a sensitivity of 90% (sensitivity = true positive/(true positive + false negative)). For the infants with TD, the algorithm counted 93 bouts of arm movement and the observer identified 90. The algorithm undercounted (did not identify a movement the observer did) by 10 and overcounted (identified a movement the observer did not) by 13 bouts. For infants AR, the algorithm counted 80 bouts of arm movement and the observer identified 90. The algorithm undercounted by 11 and overcounted by 1 bout. Algorithm overcounting most often occurs because the algorithm is able to identify pauses in arm motion that can be as short as 1/20 of a second, so the algorithm identifies 2 bouts when an observer only sees 1. Algorithm undercounting most often happens when an infant produces a very long, slow arm movement (e.g., lowering one arm very slowly while focusing attention on the other arm). We did not actively identify periods of no movement, we assumed the infant was not moving if no active movement was identified by the algorithm, and therefore only report the ability of our algorithm to count movements and not its ability to count non-movement.

3.2. Number of Bouts

Table 1 shows the total number of bouts for the right and left arms across a full day at each visit for infants with TD. A full day ranged from 8 to 13 h, and included variable amounts of nap time, therefore each infants' hours of awake time at each visit is also provided. To allow for the comparison of movement rates between infants and across visits, Figure 5 shows the average number of bouts per hour of awake time for the right and left arms, by age, for infants with TD. For the number of bouts per hour of awake time, infants generally move their arms more as they get older. For each arm a linear trend fit best.

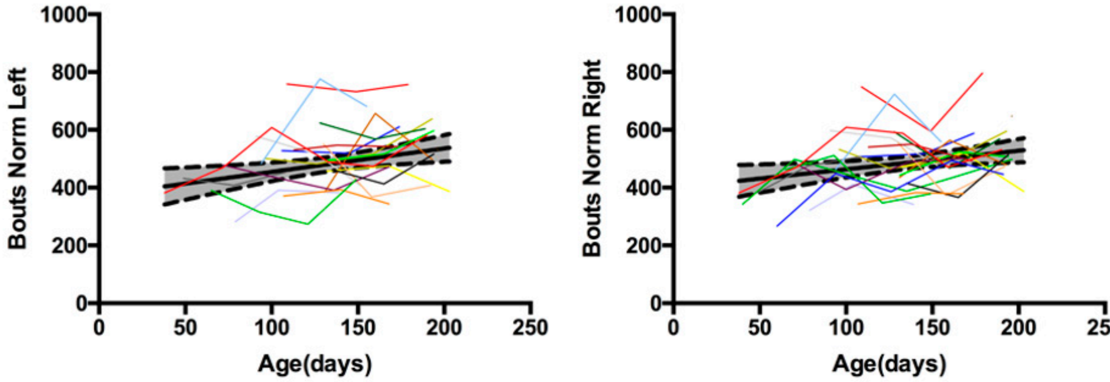

Figure 5. Average number of bouts per hour of awake time for the left and right arms, by age, for infants with typical development. Each colored line represents a different infant across 3 to 6 visits. Two single assessments are represented by dots. Thick black line is the mean and shaded area bordered by dashed black line is one standard deviation. For each arm, a linear trend across time best fit the data.

Table 1. Overall arm movement activity, number of bouts, and type of bouts, by infant and visit.

Infant	Visit	Age (Days)	Awake Time (Hours)	Acceleration Area Left	Acceleration Area Right	Total Bouts Left (Number)	Bout Type: Left Only (Number)	Bout Type: Left with Right for Portion of Bout (Number)	Bout Type: Left with Right for Entire Bout (Number)	Total Bouts Right (Number)	Bout Type: Right Only (Number)	Bout Type: Right with Left for Portion of Bout (Number)	Bout Type: Right with Left for Entire Bout (Number)
1	1	60	9.3	55,715	55,419	2326	1126	790	410	2491	1288	781	422
	2	94	6.1	109,295	101,822	2783	1195	987	601	2758	1216	1034	508
	3	126	9.3	102,163	110,379	3242	1443	1169	630	3591	1774	1201	616
	4	161	8.4	243,714	154,263	4019	1584	1695	740	4140	1568	1595	977
	5	191	9.0	204,974	176,775	4001	1662	1512	827	4002	1656	1555	791
2	1	113	8.0	194,156	172,301	4224	1648	1750	826	4308	1654	1597	1057
	2	138	7.2	164,813	185,299	3919	1358	1596	965	3939	1482	1617	840
	3	173	7.2	194,881	151,906	3904	1674	1314	916	3558	1389	1438	731
3	1	128	8.6	296,547	310,820	5382	1887	2113	1382	5112	1753	2290	1069
	2	160	8.2	296,786	280,371	4636	1870	1860	906	3820	1133	1778	909
	3	189	8.1	332,616	297,343	4885	2147	1832	906	4604	1866	1754	984
4	1	130	8.0	216,062	255,311	4372	1712	1698	962	4410	1799	1726	885
	2	158	5.9	122,224	102,956	2166	874	877	415	2196	811	858	527
	3	192	5.0	139,128	97,527	2030	775	857	398	2355	1066	803	486
5	1	131	8.0	152,452	164,041	3944	1555	1379	1010	3537	1396	1490	651
	2	165	5.9	184,351	132,371	3051	1114	1279	658	3099	1165	1242	692
	3	194	8.4	233,834	167,870	5020	2201	1666	1153	4266	1664	1802	800
6	1	94	8.1	214,226	162,435	3917	1444	1632	841	3746	1314	1596	836
	2	128	8.1	373,701	240,609	6320	2393	2674	1253	5902	1965	2483	1454
	3	155	8.7	329,202	344,689	5921	2740	1909	1272	4860	1874	2029	957
7	1	79	6.4	259,136	224,860	1790	588	697	505	2050	868	805	377
	2	104	5.5	145,214	95,116	2148	828	849	471	2260	986	886	388
	3	139	7.0	132,645	117,248	2672	1099	950	623	2382	915	1052	415
8	1	49	7.3	212,830	146,430	3138	1628	928	582	2794	1299	930	565
	2	78	7.9	175,388	166,622	3229	1527	1169	533	3762	1943	1186	633
	3	108	8.6	316,156	315,490	3913	1694	1417	802	4377	2137	1477	763
9	1	132	5.7	207,620	181,761	2618	1004	1128	486	2704	965	1021	718
	2	168	9.3	301,681	381,848	4439	1697	1658	1084	4867	1966	1694	1207
	3	203	7.0	157,550	125,030	2723	1300	820	603	2727	1345	928	454
10	1	40	8.1	144,204	154,457	2963	1302	1001	660	2769	1141	1003	625
	2	70	8.8	281,301	326,961	4204	1659	1604	941	4397	1895	1638	864
	3	97	8.1	257,067	274,005	3676	1397	1420	859	3677	1403	1432	842
	4	135	7.5	137,842	166,236	2734	956	1094	684	2899	1138	1128	633
	5	162	7.5	194,881	225,728	2842	1187	957	698	3262	1652	1118	492
	6	196	8.5	368,220	311,846	4006	1635	1503	868	4220	1813	1604	803
11	1	131	8.4	223,325	153,311	3267	1188	1426	653	3658	1487	1396	775
	2	160	8.9	350,880	319,955	5857	2871	1948	1038	5025	2063	1936	1026
	3	193	8.8	202,446	185,489	4376	2102	1429	845	4207	2004	1548	655

Table 1. *Cont.*

Infant	Visit	Age (Days)	Awake Time (Hours)	Acceleration Area Left	Acceleration Area Right	Total Bouts Left (Number)	Bout Type: Left Only (Number)	Bout Type: Left with Right for Portion of Bout (Number)	Bout Type: Left with Right for Entire Bout (Number)	Total Bouts Right (Number)	Bout Type: Right Only (Number)	Bout Type: Right with Left for Portion of Bout (Number)	Bout Type: Right with Left for Entire Bout (Number)
12	1	91	6.5	164,559	133,873	3767	1159	1518	1090	3894	1193	1627	1074
	2	126	6.7	190,355	147,707	3435	1117	1490	828	3807	1441	1553	813
	3	153	8.3	266,442	274,558	3325	1202	1433	690	3962	1816	1485	661
13	1	96	8.3	205,658	181,497	4170	1420	1772	978	4424	1698	1820	906
	2	126	4.1	121,324	71,953	1964	672	819	473	1901	629	824	448
	3	159	3.3	259,972	122,373	1693	498	607	588	1613	596	711	306
	4	193	3.6	141,730	129,298	2278	746	889	643	2125	652	978	495
14	1	106	7.6	171,517	123,718	3983	1464	1533	986	3821	1474	1697	650
	2	145	10.0	307,196	257,059	5210	1903	2111	1196	5193	1917	2155	1121
	3	174	8.6	294,043	234,330	5255	2066	2109	1080	5063	1914	2180	969
15	1	109	7.6	293,670	281,731	5743	2102	2281	1360	5671	2125	2271	1275
	2	149	9.2	336,525	208,733	6774	3140	2409	1225	5499	1945	2263	1291
	3	179	8.9	330,367	333,966	6769	2645	2827	1297	7113	2893	2733	1487
16	1	65	10.1	154,081	120,320	3958	2104	1295	559	4680	2781	1231	668
	2	93	7.5	82,914	129,435	2353	951	971	431	3826	2240	938	648
	3	121	8.4	170,686	129,842	2309	846	990	473	2923	1363	1041	519
	4	149	9.2	222,313	338,706	3953	2124	1225	604	3497	1584	1114	799
17	1	38	10.4	186,933	204,148	3987	1595	1576	816	3989	1520	1482	987
	2	72	10.4	327,534	269,737	4910	1832	1960	1118	4937	1785	1982	1170
	3	100	9.9	338,695	320,021	6006	2242	2594	1170	6017	2145	2406	1466
	4	133	8.3	238,994	219,733	4068	1385	1832	851	4894	2031	1829	1034
	5	159	9.8	319,265	362,508	4659	1735	1788	1136	4634	1803	1768	1063
	6	190	9.4	328,468	314,207	5478	2402	2028	1048	4995	1939	1995	1061
18	1	107	10.3	158,525	173,526	3828	1916	1139	773	3548	1716	1336	496
	2	140	7.6	149,758	119,284	3002	1482	1015	505	2922	1351	1048	523
	3	168	9.6	231,146	188,059	3287	1543	1213	531	3622	1833	1133	656
19	1	135	11.5	259,696	202,839	5313	2675	1607	1031	4768	2175	1687	906
	2	165	9.7	220,708	153,669	4602	1931	1379	677	4580	1457	1307	767
	3	194	8.9	207,079	199,449	3987	2188	1544	870	3531	2201	1616	763
20	1	72	9.0	174,939	163,847	4287	1908	1563	816	4296	1918	1546	832
	2	100	9.0	158,163	147,436	3960	2012	1264	684	3567	1655	1292	620
	3	136	8.7	142,320	146,028	3386	1215	1471	700	4241	1980	1515	746
	4	168	7.9	174,443	164,425	3721	1783	1368	570	3956	1964	1341	651
21	1	196	8.4	289,408	294,277	4467	1852	1830	785	5430	2607	1749	1074
22	1	203	10.0	211,167	188,905	4903	2054	1896	953	5288	2274	1876	1138

3.3. Type of Movement

Table 1 shows the total number of each type of bout produced across the full day. To compare between infants and across visits, Figure 6 shows the average percentage of each type of bout produced across the full day for the right and left arms, by age, for infants with TD. In general, it appears that infants show a "U"-shaped developmental trajectory for one arm only bouts, an inverted "U"-shaped developmental trajectory for both arms moving for some portion of the bout, and no change across time for both arms moving for the entire bout. Quadratic trends were the best fit for one arm only and both arms moving for some portion of the bout for the right and left arms, while a linear trend best fit both arms moving for the entire bout for the right and left arms.

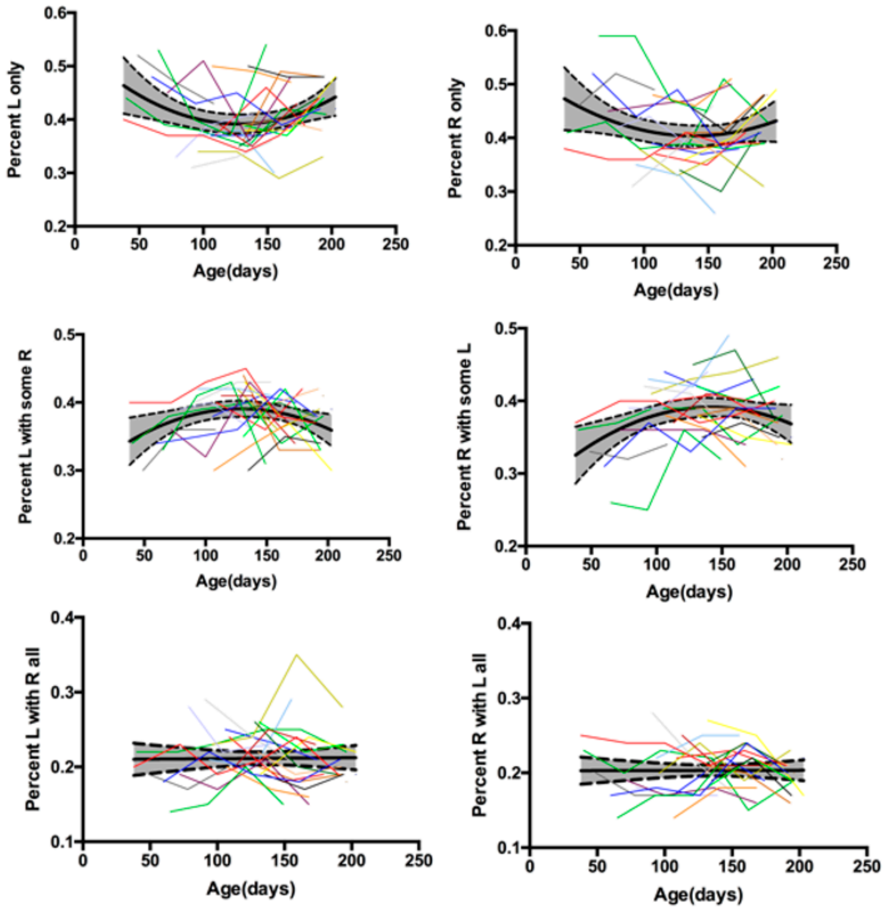

Figure 6. Average percentage of each type of bout (only one arm moving, both arms moving for some portion of the bout, or both arms moving for all of the bout) produced across the full day for the left and right arms, by age, for infants with typical development. Each colored line represents a different infant across 3 to 6 visits. Two single assessments are represented by dots. Thick black line is the mean and shaded area bordered by dashed black line is one standard deviation. Quadratic trends were the best fit for the right and left arms for only one arm moving and both arms moving for some portion of the bout. Linear trends were the best fit for both arms moving for all of the bout.

3.4. Kinematic Characteristics

Figure 7 shows the average bout duration (s) at each visit, by age, for infants with TD. A linear trend fit the left and right arm data best, indicating that movement bouts get shorter as infants get older. Figure 8 shows the average acceleration (m/s^2) and average peak acceleration (m/s^2) at each visit, by age, for infants with TD. For average acceleration, a linear trend fit the left arm data best and a quadratic trend fit the right arm best. For peak acceleration, data for both arms were best fit by a linear trend. Taken together, duration and acceleration data indicate that infants move with shorter duration and faster acceleration arm movements as they get older, and the rate of change may not be constant between arms. Table 1 provides the acceleration area values for each arm, at each visit. To compare between infants and across visits, Figure 9 shows the normalized acceleration area for the right and left arms per hour of awake time, by age, for infants with TD. A linear trend fits the right and left arm data best, indicating normalized acceleration area increases as infants get older.

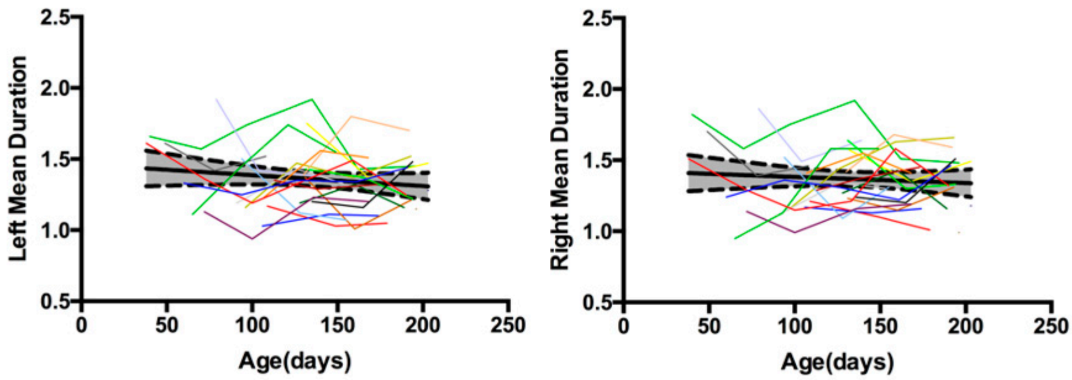

Figure 7. Average bout duration(s) for the left and right arms, by age, for infants with typical development at each visit. Each colored line represents a different infant across 3 to 6 visits. Two single assessments are represented by dots. Thick black line is the mean and shaded area bordered by dashed black line is one standard deviation. A linear trend fit the left and right arm data best.

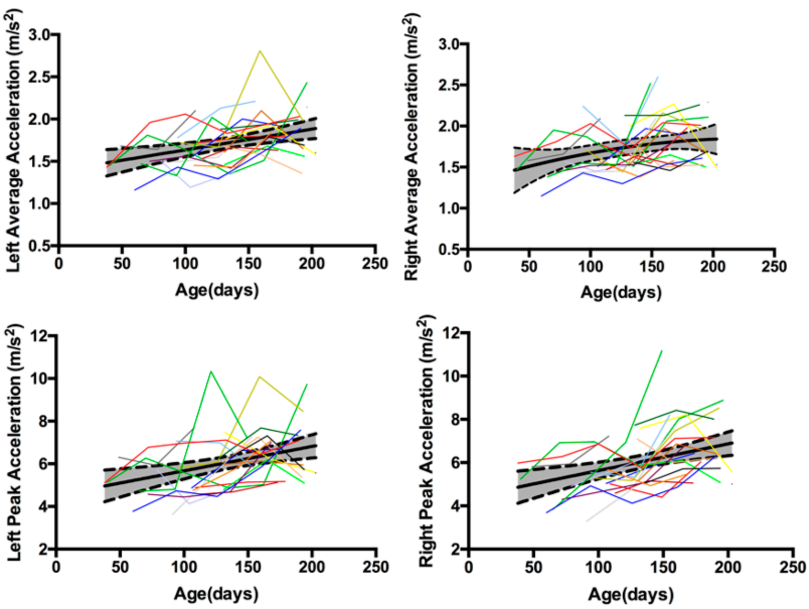

Figure 8. Average acceleration (m/s^2) and average peak acceleration (m/s^2) for the left and right arms, by age, for infants with typical development at each visit. Each colored line represents a different infant across 3 to 6 visits. Two single assessments are represented by dots. Thick black line is the mean and shaded area bordered by dashed black line is one standard deviation. For left average acceleration, a linear trend fit the data best. For right average acceleration, a quadratic trend fit the data best. Peak acceleration data were best fit by a linear trend.

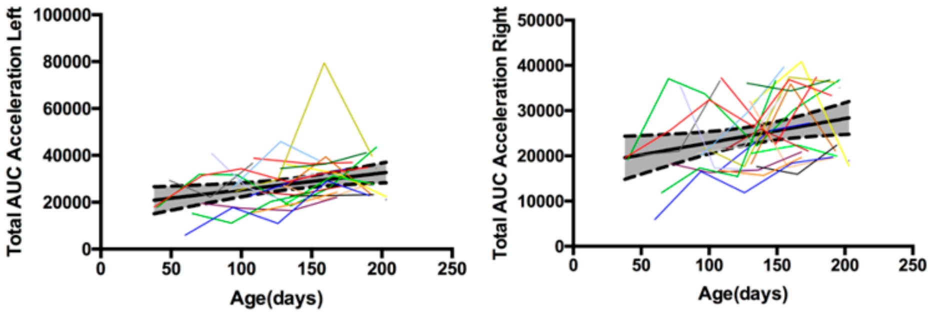

Figure 9. Normalized acceleration area (AUC = area under the curve) for the left and right arms (per hour of awake time), by age, for infants with typical development at each visit. Each colored line represents a different infant across 3 to 6 visits. Two single assessments are represented by dot. Thick black line is the mean and shaded area bordered by dashed black line is one standard deviation. Linear trends fit the right and left arm data best.

4. Discussion

Full day infant arm movement monitoring is necessary in order to advance our understanding of how much and what type of movement practice is necessary to learn functional skills. Laboratory based studies are limited to short periods of data collection and do not inform us about how much or how infants are moving across the course of the day in their natural environments. Despite the great knowledge gathered from these studies, it has recently been argued that to further advance the field we now must sample development for a minimum of 24 h in order to overcome the effects of circadian rhythms, behavioral context, environmental stimuli, mood and motivation, and other factors [19]. In this paper, we move from being able to assess only a few minutes of arm movement data to being able to assess a full day through the use of wearable sensors.

Our purpose was to describe the development of a wearable sensor data algorithm for identifying bouts of infant arm movement in infants with TD and AR. We found an overall performance of the algorithm of 90% sensitivity. The algorithm does not make systematic errors (consistent over- or under-counting). It is not able to distinguish between the infant moving his or her arms and the caregiver moving the infant's arms (for example, when putting on a shirt), however this type of occurrence is expected to be low among the thousands of bouts of arm movement an infant produces across a day. We feel this amount of non-systematic error is acceptable to move forward with studying how full day movement patterns relate to infant development and the acquisition of functional skills.

Our report here of the number and kinematic characteristics of arm movement bouts from 22 infants with TD is the first step toward developing norms for full-day arm movement behavior. We have provided the values obtained from 8 to 13 h of arm movement data, as well as normalized to hours of awake time or as a percentage of movements made, in order to allow the comparison between infants and across time. These data are the first step in measuring mean values and variability in a small sample of infants with TD, and will allow us to power future studies to look for relationships between changes in full-day arm movements and functional skill acquisition and to look for early differences in arm movement patterns in infants AR. We have presented data here by chronological age as a first step, however it will be as important to explore movement variables in relation to the developmental trajectory. Two infants of the same chronological age are not expected to be at the same point in their developmental trajectory of motor, cognitive, and/or social development. We believe this method has potential, due to its quantitative assessment and multiple continuous hours of measurement, to embrace the high variability that is a hallmark of typical development and use this information to accurately identify infants who fall outside of the norms of TD very early in development.

Our results for the duration of arm movement bouts averaged around 1.3 s per bout. Previous literature has focused on the duration of reaches, which are discrete movements of the arm to a target. Infant reach durations have been observed to be approximately 0.6–0.9 s in 3-month-old infants [20], around 0.8 s in infants from 100 days through 200 days of age and beyond [21], 1.6 s in 4-month-old infants and 1.2 s in 6-month-old infants [22], 0.5–0.7 s for 5-month-old infants [23], 1.1 s for the left arm and 1.3 s for the right arm in 6-month-old infants [24], and around 1 s for 7 month-old infants [25]. Given that our arm movement data included both reaching and non-reaching activity, we feel that our results are consistent with the previous data from shorter periods of laboratory-based infant reaching assessments.

There are two studies that include arm acceleration values, each from a single infant. Average arm accelerations across a full day from one infant between 51 to beyond 200 days of age ranged from around 1.2–1.4 m/s^2 [26]. These data included periods of no movement occurring across the day, whereas our data are only during arm movement bouts. As a result of this methodological difference, our average acceleration values are higher (around 1.7 m/s^2), but we believe this is reasonable given the different methodology. The other study reported arm peak acceleration of around 6000 mm/s^2 in a 6-month-old boy [24], consistent with our findings of mean peak accelerations around 6 m/s^2.

Across these first months, the majority of the bouts infants made were with one arm only, compared to both arms moving for some or all of the bout. Within that stable preference, however, there appears to be an interesting shift in the relative preference for one arm only moving vs. both arms moving for some portion of the bout. The trajectories indicate that infants start lower but then shift to increase their preference for arm bouts when both arms are moving for some portion of the bout, followed by a decrease. Future work will allow us to explore whether this is related to the development of reaching skill.

Our data are consistent with the previous data, showing that there is not an overwhelming preference across infancy for right or left arm movement; infants with TD employ many different strategies for reaching or otherwise moving their arms. Corbetta and Thelen collected kinematic arm movement data for 4 infants longitudinally from 3 to 52 weeks of age (weekly from 3 to 30 weeks and bi-weekly from 30 to 52 weeks). They identified both reaching and non-reaching interlimb activity. For reaching, preference was attributed to the hand that made initial contact with the target. For laterality in non-reaching movements, the hand with the faster average velocity over a 1-s window was identified as the preferred hand. A right or left preference for each category of movement was determined overall for each visit. The infants produced unstable and fluctuating lateral preferences for reaching and non-reaching movements across the 1st year. Furthermore, when a preference was detected in reaching, it was also observed in non-reaching movements [27]. In another study, 17 infants at 6 months of age did not show a significant difference between right, left, or bimanual reaches, they performed all three types of reaching equally [24].

5. Conclusions

We created an algorithm that can be used to quantify kinematic characteristics of infant arm movement bouts produced across a full day in the natural environment. We chose these specific metrics as a first step as they are commonly assessed kinematic measures. In future work, we will explore more advanced computational techniques, such as non-linear analysis measures and machine learning approaches to describe other aspects of our movement data. Furthermore, we will relate the amount and type of arm movement practice across days and months to the development of functional arm reaching skills. Finally, we will determine if early differences in arm movement patterns are predictive of later neuromotor outcomes in infants AR. These results will inform the development of early intervention therapies to support optimal neuromotor development.

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