

Full-day, in home validation of infant body position measurements from inertial sensors

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Abstract

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Infants’ movements facilitate and constrain how they interact with their surroundings from moment to moment. Changes in *body position*—whether infants are supine on their backs, prone on their bellies, sitting, upright, or held by a caregiver—have immediate consequences for vision, object exploration, and social interaction. When sitting and upright, infants have a better view of faces and distant objects compared to their view while in a prone position (Franchak et al., 2018; Kretch et al., 2014; Luo & Franchak, 2020). Infants struggle to manipulate objects while supine and prone, but sitting affords object exploration (Soska & Adolph, 2014). Upright walking changes how infants and caregivers interact compared with crawling in a prone position; while walking infants move farther away, share toys in different ways, and hear different language from caregivers (Chen et al., 2022; Karasik et al., 2011, 2014; West & Iverson, 2021). As infants grow older and acquire new abilities, such as independent sitting and walking, they spend more time sitting and upright and less time held, supine, and prone (Adolph & Tamis-LeMonda, 2014; Franchak et al., 2018; Franchak, 2019; Thurman & Corbetta, 2017). Thus, characterizing individual differences in the day-to-day accumulation of body position experiences informs developmental theory by revealing differential opportunities for learning.

In this paper, we present an inertial sensing method to classify infant body position from moment-to-moment across an entire day, and validate its accuracy using XX hours of video recorded across XX in-home data collection sessions. Our method takes inspiration from a more mature technology: Long-form audio recordings of infants’ language experiences using wearable audio recorders such as the LENA device. We begin by describing the impact of long-form audio recordings on research in developmental psychology, and identify the key features that should be replicated in long-form recordings of motor behavior. Next, we review the current state-of-the-art in measuring infant motor behavior—video and survey data—and their limitations in capturing real-time, full-day

behavior. Finally, we discuss the advantages of using inertial sensing to classify motor behavior. Despite promising past results in brief sessions [CITES], the current investigation takes a needed step forward by testing accuracy over long recordings.

Inspiration from Long-Form Audio Methods

Impactful findings (Hailey write this paragraph) - individual differences in experiences - distribution of experiences (burstiness) Full-day language recording synchronized with other data sources allows researchers to identify how vocal input and production interacts with other processes. Linking LENA® speech measurements to repeated, time-stamped text-message surveys about infant device use revealed that infants heard less caregiver speech during moments that they were restrained in devices such as swings, exersaucers, and car seats (Malachowski et al., 2023). A custom-built wearable ECG and audio recorder allowed Wass et al. (2022) to discover that infant arousal increases the likelihood of infant vocalization across the day. In both examples, the ability to record real-time, synchronized data is vital for making inferences about processes that happen on the timescale of minutes or even seconds within in an individual as opposed to comparisons of aggregated data between infants.

Key features - unobtrusive (Bergelson; CTL stuff) - mobile (no limits to where recording happens) - real time - long duration (capture entire day and heterogeneity in activities) - automatic classification with good-enough accuracy (scaling)

Limitations of Video and Survey Methods

Video. Only advantage is real time

Survey. Everything but real time

Promise of Inertial Sensing Methods

Wear time is not an issue. Lots of Smith and other studies with long recordings.

Classification accuracy from ML is good. older papers; Airaksinen; Frontiers

What's missing

Goals of the Current Study

Methods

Participants

Apparatus

Procedure

Body position annotation

Body position classification

Results

Goal 1: Assess the proximal accuracy of body position classification models

Goal 2: Assess the distal accuracy of body position classification models

Goal 3: Examine the data quality of full-day home recordings

Goal 4: Assess the suitability of full-day predictions for capturing age differences in body position

Discussion

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Table 1

Summary statistics for model performance metrics shown separately for group and individual models.

Metric	Group			Individual		
	Median	Mean	SD	Median	Mean	SD
Overall Accuracy	0.908	0.848	0.143	0.936	0.919	0.071
Balanced Accuracy	0.909	0.897	0.074	0.916	0.907	0.072
F1	0.813	0.827	0.101	0.873	0.870	0.089
Sensitivity	0.840	0.836	0.123	0.848	0.840	0.121
Pos Pred Value	0.822	0.815	0.125	0.915	0.899	0.108
Kappa	0.769	0.757	0.160	0.846	0.820	0.141

Table 2

Model performance metrics for each body position category, shown separately for group and individual models.

Metric	Position	Group			Individual		
		Median	Mean	SD	Median	Mean	SD
Balanced Accuracy	Supine	0.977	0.935	0.099	0.995	0.957	0.090
	Prone	0.997	0.950	0.110	0.983	0.921	0.132
	Sitting	0.932	0.861	0.151	0.973	0.943	0.071
	Upright	0.930	0.867	0.146	0.937	0.877	0.123
	Held	0.907	0.872	0.111	0.892	0.854	0.153
F1	Supine	0.952	0.873	0.173	0.987	0.937	0.130
	Prone	0.965	0.923	0.124	0.958	0.889	0.186
	Sitting	0.897	0.805	0.247	0.963	0.927	0.101
	Upright	0.781	0.748	0.235	0.868	0.769	0.227
	Held	0.813	0.783	0.163	0.862	0.786	0.240
Sensitivity	Supine	1.000	0.945	0.125	1.000	0.948	0.141
	Prone	1.000	0.907	0.216	0.988	0.856	0.266
	Sitting	0.901	0.787	0.291	0.977	0.917	0.136
	Upright	0.878	0.767	0.275	0.893	0.790	0.255
	Held	0.867	0.774	0.229	0.817	0.722	0.309
Pos Pred Value	Supine	0.973	0.802	0.300	1.000	0.939	0.131
	Prone	0.991	0.896	0.196	0.993	0.901	0.197
	Sitting	0.910	0.840	0.238	0.967	0.947	0.078
	Upright	0.848	0.743	0.285	0.875	0.817	0.205
	Held	0.917	0.803	0.247	0.949	0.872	0.232
Kappa	Supine	0.932	0.770	0.307	0.984	0.913	0.169
	Prone	0.951	0.887	0.208	0.948	0.851	0.242
	Sitting	0.836	0.712	0.308	0.946	0.889	0.134
	Upright	0.729	0.700	0.277	0.829	0.744	0.232
	Held	0.786	0.733	0.219	0.845	0.744	0.280

Table 3

Correlations between human-coded and model-predicted body position durations across the entire long delay period. Correlations are provided within each posture and overall, and computed separately using group and individual models with and without outlier participants.

Position	With Outliers		Without Outliers	
	Group	Individual	Group	Individual
Held	-0.03	0.12	0.55	0.58
Prone	0.97	0.85	0.97	0.84
Sitting	0.73	0.93	0.91	0.97
Supine	0.84	0.94	0.94	0.97
Upright	0.84	0.93	0.99	0.94
Overall	0.80	0.91	0.95	0.96

Table 4

Correlations between human-coded and model-predicted body position durations using 10-minute bins during the distal comparison. Correlations are provided within each posture and overall, and computed separately using group and individual models with and without outlier participants.

Position	With Outliers		Without Outliers	
	Group	Individual	Group	Individual
Held	0.45	0.43	0.57	0.55
Prone	0.96	0.89	0.96	0.88
Sitting	0.72	0.92	0.91	0.93
Supine	0.75	0.95	0.90	0.94
Upright	0.93	0.95	0.97	0.95
Overall	0.80	0.94	0.93	0.94

Table 5

Summary of age differences in full-day body position for younger (4- to 7-month) and older (11- to 14-month) infants. Values shown are the mean percent of time for each body position averaged across infants in each group. Standard deviations are shown in parentheses. Descriptive statistics are shown separately for group and individual models.

Position	Group		Individual	
	Younger	Older	Younger	Older
Upright	7.6% (8.9)	18.6% (7.4)	9.9% (13.1)	18.7% (8.4)
Sitting	26.3% (12.1)	44.4% (10.1)	20.2% (16.3)	46.9% (13.3)
Prone	13.8% (13.5)	14.4% (6.0)	11.9% (9.9)	16.9% (10.6)
Supine	37.9% (23.2)	14.0% (8.4)	39.4% (30.3)	10.0% (9.5)
Held	12.7% (6.9)	8.5% (5.4)	17.6% (19.9)	7.4% (7.6)

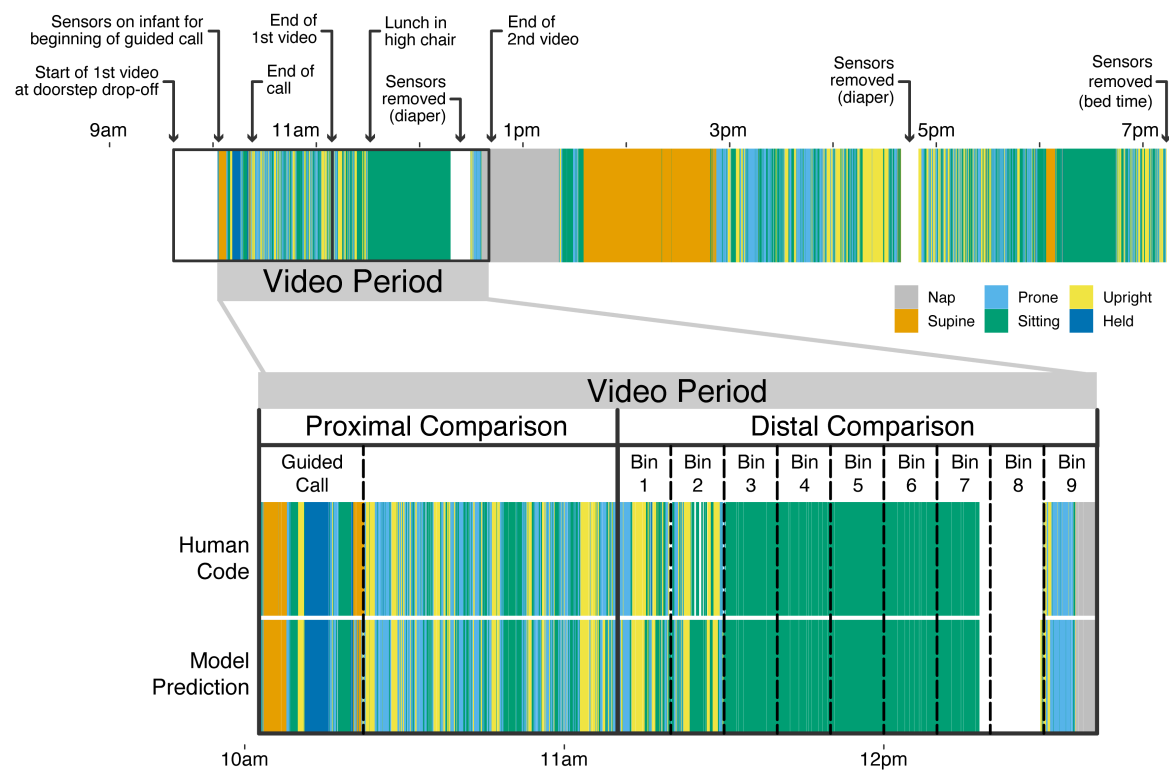


Figure 1. Example Timeline Caption.

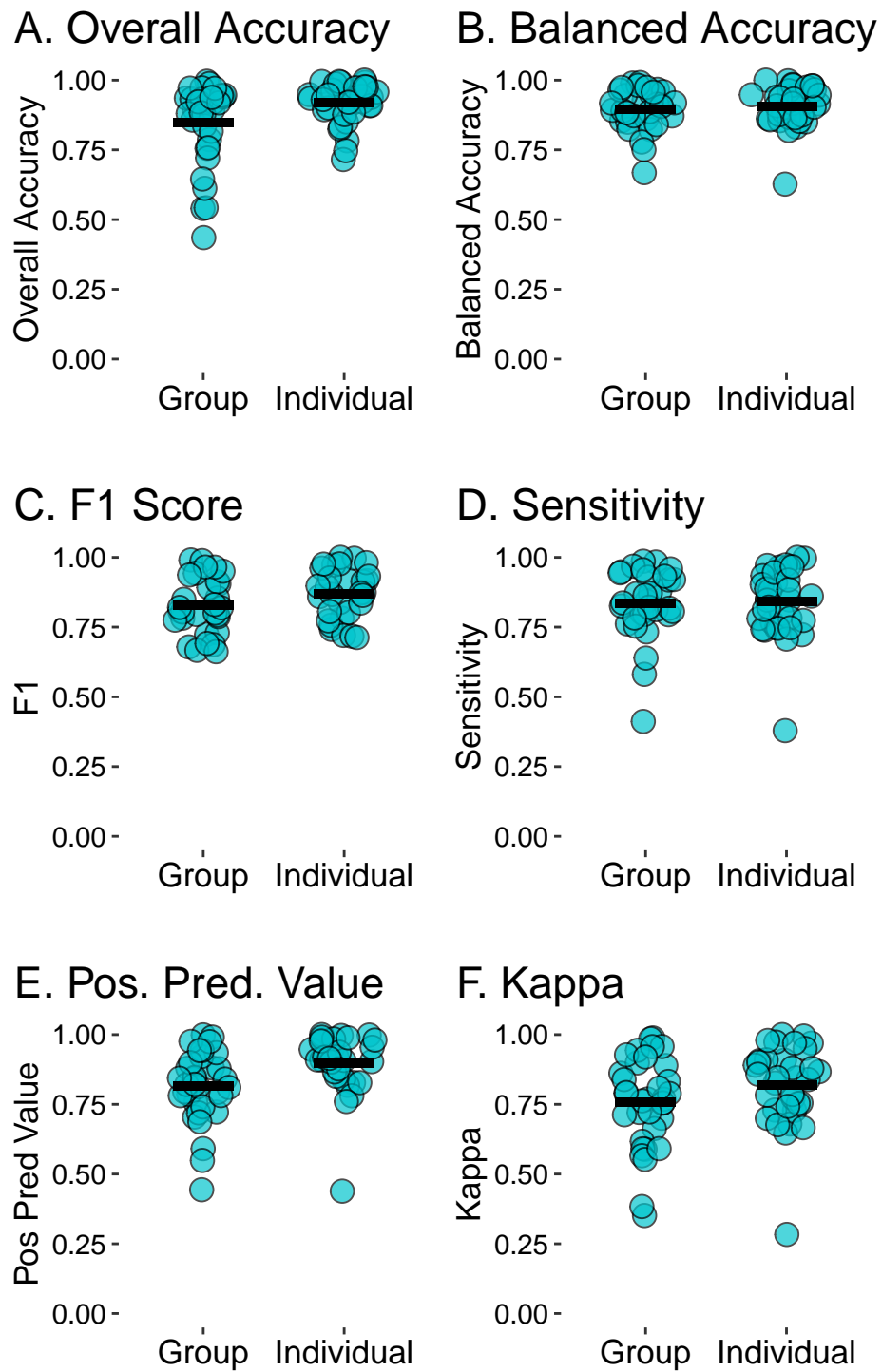


Figure 2. Metrics

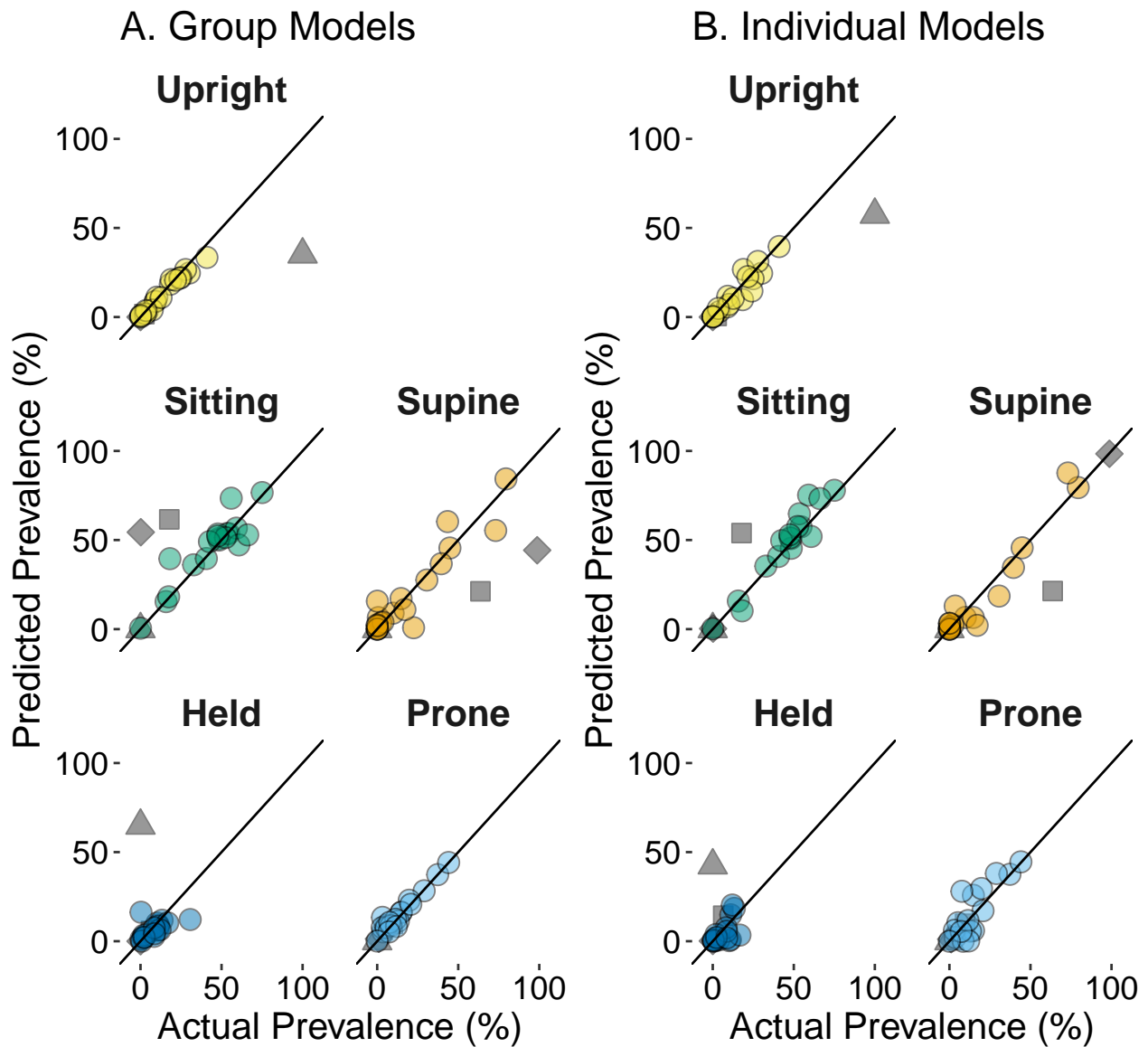


Figure 3. Overall agreement between human-coded body position and model-predicted body position in the distal comparison. Agreement for group models is shown in (A) and agreement for individual models is shown in (B). Plots are shown separately for each body position with a reference line that indicates perfect agreement; each point in a plot represent data for a single participant. The three outlier participants are plotted in dark gray, with a different shape marking each individual.

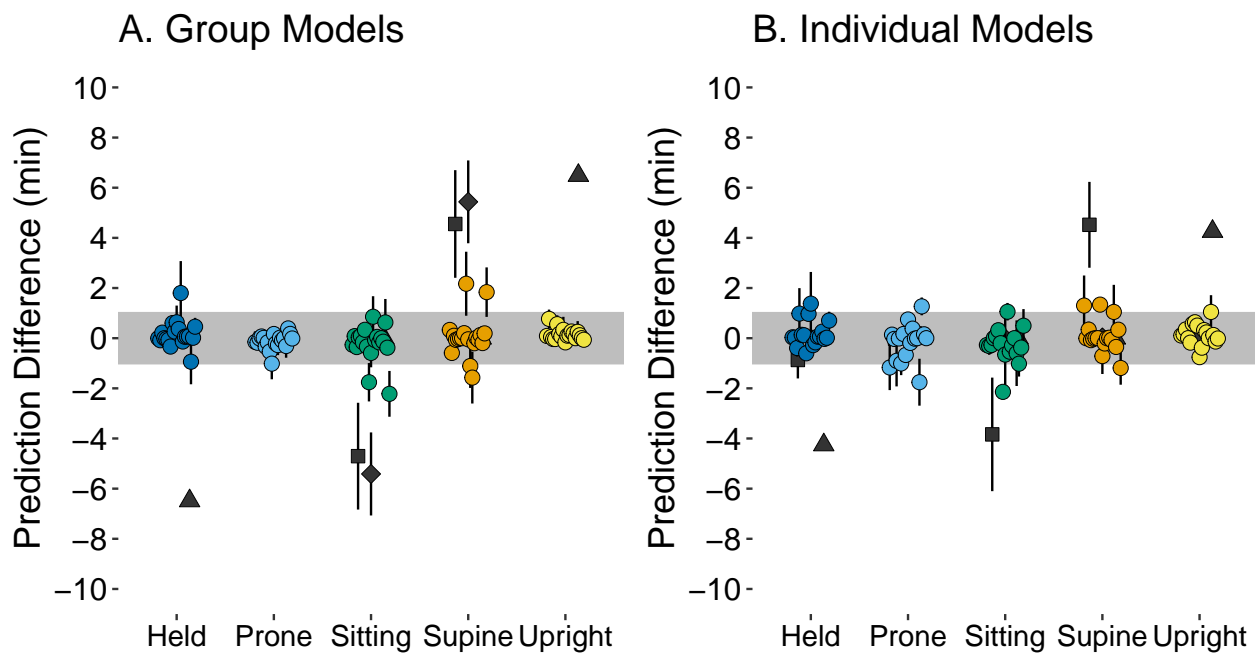
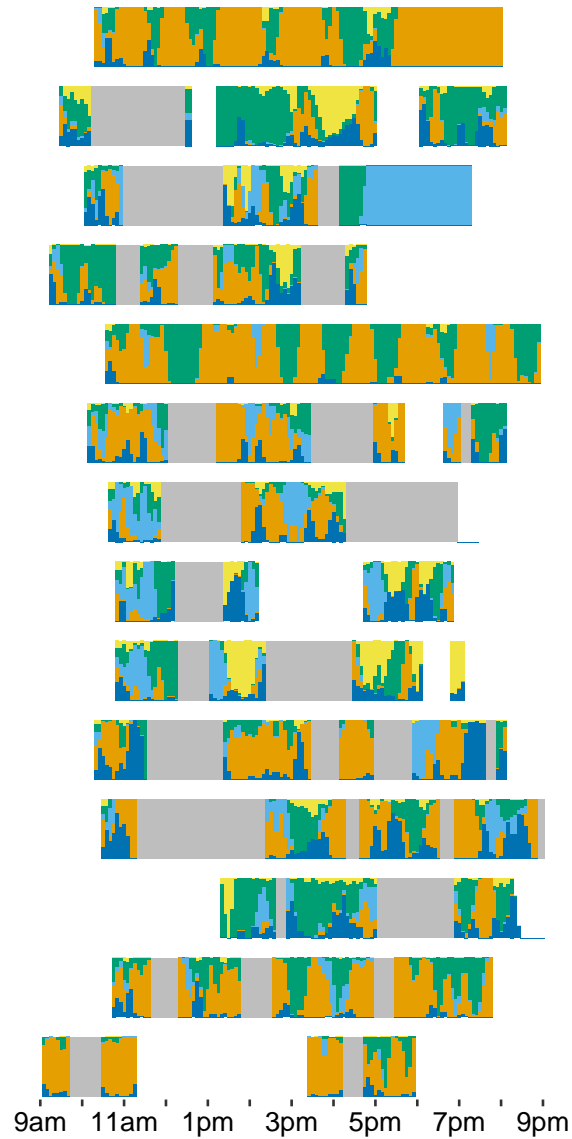


Figure 4. Prediction performance (difference in minutes between human-coded and model-predicted body position) for 10-minute bins in the distal comparison. Each point shows the mean and SE for a single participant for each body position, summarizing the prediction difference for each of their 10-minute bins. Points falling within the gray shaded region indicate that average prediction errors were less than 1 minute. Performance is plotted separately for (A) group models and (B) individual models. The three outlier participants are plotted in dark gray, with a different shape marking each individual.

A. 4–7 Months



B. 11–14 Months

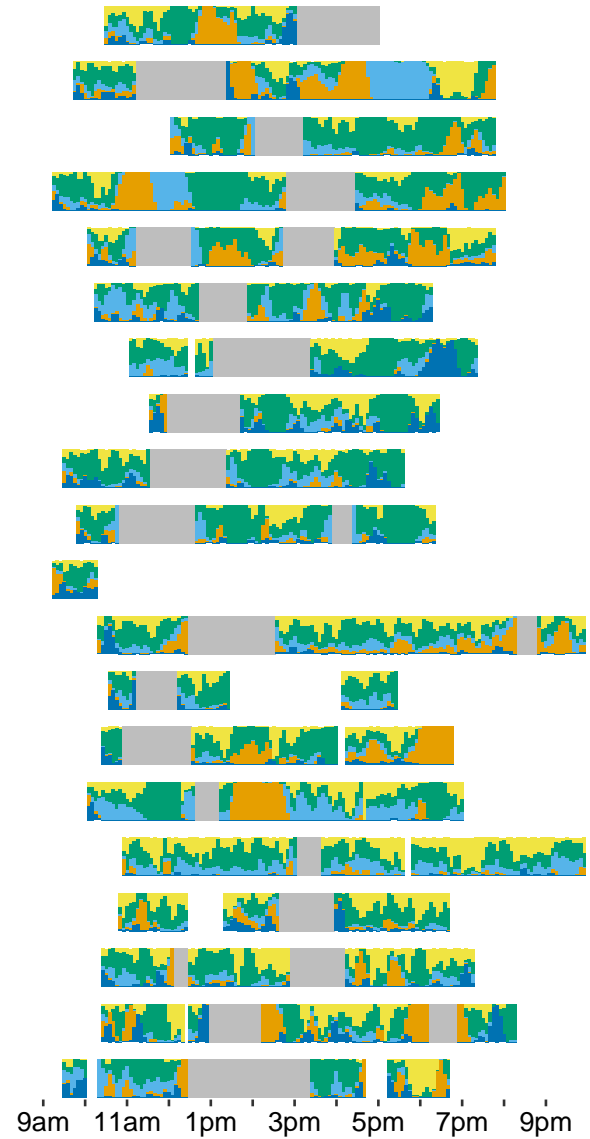


Figure 5. Timelines

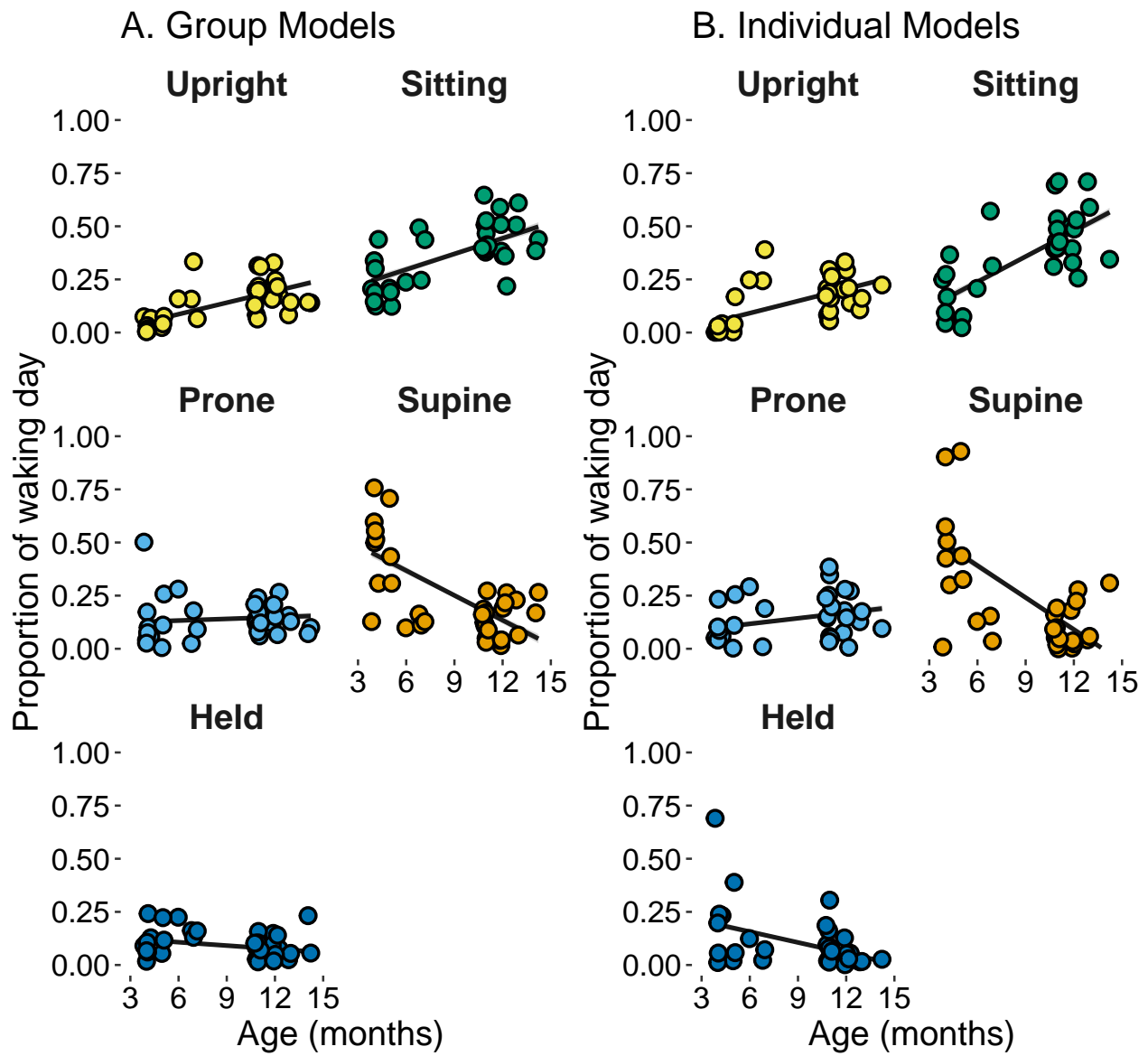


Figure 6. Age trends