Trends in sensor-based health metrics during and after pregnancy: descriptive data from the apple women's health study

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BACKGROUND: While it is known that vital signs and behaviors change during pregnancy, there is limited data on timing and scale of changes for sensor-derived health metrics across pregnancy and postpartum. Wearable technology provides an opportunity to understand physiologic and behavioral changes across pregnancy with greater detail, more frequent measurements, and improved accuracy. The aim of this study is to describe changes in physiologic and behavioral sensor-based health metrics during pregnancy and postpartum in the Apple Women's Health Study (AWHS) and their relationship to demographic factors.

METHODS: The Apple Women's Health Study is a digital, longitudinal, observational study that includes U.S. residents with an iPhone and Apple Watch. We evaluated changes from pre-pregnancy through delivery and postpartum for sensor-derived health metrics. Minimum required data samples per day, week and overall were data element specific, and included 12 weeks prior to pregnancy start, and 12 weeks postpartum for pregnancies lasting between 24 and 43 weeks.

FINDINGS: A total of 757 pregnancies from 733 participants were included. Resting heart rate (RHR) increased across pregnancy, peaking in the third trimester (pre-pregnancy median RHR 65.0 beats per minute [BPM], interquartile range [IQR] 60.0—70.2 B.M. third trimester median RHR 75.5 B.M. IQR 69.0—82.0 B.M., with a decrease prior to delivery and nadir postpartum (postpartum median RHR 62.0 B.M. IQR 57.0—66.0 B.M.. Heart rate variability (HRV) decreased from pre-pregnancy (39.9 milliseconds, IQR 32.6—48.3 milliseconds), reaching a nadir in the third trimester (29.9 milliseconds, IQR 25.2—36.4 milliseconds), before rebounding in the last weeks of pregnancy. Measures of activity, such as exercise minutes, stand minutes, step count and Cardio Fitness were all decreased in each trimester compared to pre-pregnancy, with their nadirs postpartum. Total sleep duration increased slightly in early pregnancy (pre-pregnancy 7.2 hours, IQR 6.7—7.7 hours; 1st trimester 7.4 hours, IQR 6.8—7.9 hours), with the lowest sleep duration postpartum (6.2 hours, IQR 5.4—6.8 hours).

INTERPRETATION: Resting heart rate increased during pregnancy, with a decrease prior to delivery, while heart rate variability decreased across pregnancy, with an upward trend before delivery. Behavioral metrics, such as exercise and sleep, showed decreasing trends during and after pregnancy. These data provide a foundation for understanding normal pregnancy physiology and can facilitate hypothesis generation related to physiology, behavior, pregnancy outcomes and disease.

Key words: Exercise, Heart rate, Postpartum, Pregnancy, Sensor, Sleep, Wearable

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Data sharing: Aggregated data that support the findings of this study may be available upon request from the corresponding author. Any request for data will be evaluated and responded to in a manner consistent with policies intended to protect participant confidentiality and language in the Study protocol and informed consent form.

Condensation: Wearable health sensors detect changes in vital signs, like heart rate, and behaviors, such as exercise and sleep, before, during and after pregnancy in the Apple Women's Health Study.

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AJOG Global Reports at a Glance

Why was this study conducted?
Vital signs and behaviors were measured with wearable sensors and compared before, during, and after pregnancy in the Apple Women's Health Study.

Key findings
In data from 757 pregnancies, resting heart rate increased during pregnancy, with a decrease prior to delivery, while heart rate variability decreased across pregnancy, with an upward trend before delivery. Behavioral metrics, such as exercise and sleep, showed decreasing trends during and after pregnancy.

What does this add to what is known?
This study describes multiple sensor-based metrics within a large cohort that is observed before, during and after pregnancy. This allows description of population level data gathered in real world conditions and their relationships to demographic factors in pregnancy.

Introduction
While it is known that vital signs and behaviors change during pregnancy, there is limited objective data on the scale and timing of changes for sensor-derived health metrics. Clinicians, researchers, and patients had become habituated to data gathered at infrequent intervals, such as at clinical visits. However, wearable technology provides an opportunity to understand physiologic and behavioral changes across pregnancy with greater detail, more frequent measurements, and accuracy. There has been work evaluating the feasibility of wearables to provide continuous monitoring of health parameters during and after pregnancy, with evidence to suggest that pregnant individuals are increasingly tracking their health, leading to richer and more detailed data.[1,2] Recent studies described changes in resting heart rate (RHR) during pregnancy, suggesting an uptrend which reverses prior to delivery, and a downtrend in heart rate variability (HRV) that follows an inverse pattern.[3,4] In other studies, deep learning models describe associations between behavioral factors, such as physical activity and sleep, and timing of delivery, or preterm birth.[5] Another analysis suggests that it is an intersection between vitals such as RHR, sleep and activity that may contribute to labor onset.[6] These individual studies tend to focus on a few variables, suggesting that there is a need for a more holistic approach to describing changes before, during and after pregnancy to understand what may be normal and expected, and also to facilitate hypothesis generation related to physiology, behavior, pregnancy outcomes and disease. As more pregnant people wear devices in their everyday lives, understanding expected changes may reduce worry when the pregnant person notes a change, and may support identification of pathology or enable disease screening or detection for clinicians and researchers.[7,8] The aim of this study is to describe changes in physiologic and behavioral sensor-based health metrics during pregnancy and postpartum in the Apple Women's Health Study (AWHS) and their relationship to demographic factors.

Materials and methods
Study design
AWHS is a digital, longitudinal study of menstrual health, conducted using the Apple Research app.[9] Enrollment began in November 2019 and is ongoing; methods have been described previously, consent is obtained at the time of enrollment.[10] Objectives of the AWHS include advancing the understanding of the menstrual cycle, and informing screening and risk assessment of gynecologic health conditions using menstrual, reproductive, health factors and sensor data. AWHS inclusion criteria includes having menstruated at least once. The study was approved by the Institutional Review Board at Advarra (CIRB PRO00037562) and registered to ClinicalTrials.gov (ClinicalTrials.gov Identifier: NCT04196595).

Sample and participants
For this analysis, pregnancy was reported by participants using monthly surveys. Inclusion criteria for this report include twelve weeks prior to pregnancy, pregnancy start (last menstrual period, LMP), end (delivery), and 12 weeks postpartum all occurring between November 2019 and November 2023. LMP, which was used to calculate estimated gestational age, was reported during the monthly menstrual survey, and delivery date was reported via the monthly pregnancy survey administered after delivery. Exclusion criteria were pregnancies of <24 weeks or >43 weeks gestational age. Demographic and medical history were reported using an annual survey.

Measures
HealthKit provides a central repository for health and fitness data on iPhone and Apple Watch, and is viewable to participants using the Apple Health app.[11] Included health metrics from Apple Watch are resting heart rate (RHR) in beats per minute (BPM), heart rate variability (HRV) in milliseconds (ms), walking heart rate (WHR) in BPM, respiratory rate (RR) in breaths per minute (BrPM), Cardio Fitness which is an estimate of VO2max based upon heart rate and motion during pedestrian activity, as well as biometrics and related medications, in mL/kg/min. Additionally, we evaluated blood oxygen saturation in percentage (%) saturation, step count, active energy burned in calories, exercise time in minutes, standing time in minutes, and sleep duration in hours.[12−22] Spearman correlation between each pair of health metrics evaluated correlations between sensor-derived health metrics. Repeated measures correlation between each pair of metrics was used to represent within participant correlation. (Supplemental Figure 2) Apple Watch is not provided to study participants. A detailed description of each data type and the

minimum required data to be included in the analysis is described in Supplemental Table 1.

At enrollment, participants report race/ethnicity and sociodemographic information. Survey content has been previously published.[10] Race/ethnicity is self-reported and used a single 'select all that apply' question from the NIH-sponsored All of Us Study.[23] Participant age was calculated by subtracting self-reported birth year of participant from the year of pregnancy start. Age groups for comparison are <30 years, 30-34 years and ≥35 years. All medical conditions were self-reported at enrollment and updated annually. Pregnancy complications were reported via survey after delivery.

Data collection and analysis

Sensor data was filtered to include samples generated by Apple Watch and exclude any from iPhone or third-party sources. The operating system was restricted to watchOS 7 or later to ensure consistency in metrics. Data were aligned by LMP and included 12 weeks prior to the first day of the LMP. LMP was used as pregnancy start. First trimester was from LMP through 13 weeks 6 days, second trimester was 14 weeks through 27 weeks and 6 days, and third trimester was 28 weeks through 42 weeks 6 days, and postpartum was 12 weeks after delivery. To account for physiology that may be related to the end of pregnancy rather than the gestational age, data were also aligned by delivery date with the number of weeks prior to delivery represented as negative numbers, and 12 weeks after delivery representing postpartum. Additional comparison groups included evaluation based on estimated gestational age at delivery for preterm (<37 weeks) and term (37 weeks−42 weeks), and based on primiparity versus multiparity.

Daily (24 hour) means were calculated for RHR, WHR, RR, blood oxygen and Cardio Fitness; daily median was calculated for HRV; daily sum was calculated for step count, active energy burned, stand time, and exercise time. Sleep duration was extracted nightly during participant selected sleep schedule and was assigned to the day the sleep period ended. After aligning with either LMP or delivery date of the pregnancy, daily metrics that satisfied the availability criteria in Supplemental Table 1 were aggregated weekly or by trimester for each participant using median. Trimester medians and weekly medians were summarized using median, 95% CI of median and IQR across population. (Table 2, Supplemental Tables 2, 3) Changes in median health metrics across trimesters, before and after pregnancy were summarized using median and IQR. Wilcoxon signed-rank test was used to assess these changes across the matched samples. Weekly z-score values and differences relative to participant's baseline median were summarized using median, 5th, 25th, 75th and 95th percentiles across the population. Z-score of metrics were calculated by subtracting the participant's baseline mean and dividing by participant's baseline standard deviation. The baseline statistics were calculated using daily values over the 12 weeks prior to start of pregnancy when aligning with LMP and the 12 weeks postpartum when aligning with delivery date.

Results

Study population description

A total of 4296 pregnancies from 3797 participants were evaluated, 2450 pregnancies were excluded due to missing start and/or end dates of pregnancy, 95 pregnancies were excluded due to pregnancy < 24 weeks or > 43 weeks, and 993 pregnancies were excluded due to not meeting minimum sensor data requirements (Supplemental Table 1); 757 pregnancies from 733 participants were included. (Supplemental Figure 1) Demographic data from these 733 participants is presented in Table 1. The median age at pregnancy start was 32 years (IQR 29−35), and the median BMI at study start was 26.3 (IQR 23−31.8). The median pregnancy duration was 39 weeks 1 day (IQR 38 weeks 1 day−40 weeks, 10−90 percentiles 36 weeks 5 days−41 weeks).(Supplemental Table 5)

Health metrics aligned by pregnancy start

Alignment of data by LMP allows for evaluation of events based on estimated gestational age.

RHR, WHR, and RR are significantly higher during pregnancy as compared to pre-pregnancy, and decrease postpartum (Table 2, Table 3). In early pregnancy, there is a brief increase in RHR (12 weeks pre-pregnancy RHR: median 64.8, IQR 60.0−70.6 B.M. pregnancy week 6 RHR: median 69.0, IQR 63.2−74.5 B.M. and WHR (12 weeks pre-pregnancy WHR: median 100.7, IQR 93.5−108.8 B.M. pregnancy week 5 WHR: median 105.5, IQR 97.0−112.8 B.M.. (Figure 1, Supplemental Table 2) After a brief downtrend, both RHR and WHR demonstrate a more sustained increase with a peak in the third trimester (pregnancy week 32 RHR: median 76.9, IQR 70.0−84.0 B.M. pregnancy week 31 WHR: median 109.9, IQR 102.5−116.1 B.M.. (Figure 1, Supplemental Table 2) HRV shows a brief decrease (12 weeks pre-pregnancy HRV: median 39.5, IQR 31.9-49.7 milliseconds, pregnancy week 5 HRV: median 35.1, IQR 28.4−44.8 milliseconds), followed by a more sustained drop (nadir pregnancy week 30, HRV median 28.2, IQR 23.8−35.9 milliseconds). (Figure 1, Supplemental Table 2). These changes are also apparent when evaluating changes relative to each participant's baseline. (Supplemental Figures 3,4, Supplemental Tables 6, 8) When separating based on gestational age at delivery, overall trends were similar in pregnancies that delivered preterm (<37 weeks) as compared to those which delivered at term, and based on parity. (Supplemental Tables 12, 14, Supplemental Figures 5, 6)

First trimester step count decreased significantly (median decrease 614, IQR -1304 to 37 steps) compared to pre-pregnancy, and continued to decrease across the three trimesters. (Tables 2, 3) Similarly, exercise time before pregnancy was median of 17.5 minutes per day (IQR 9−40 min) with the lowest value in pregnancy in the third trimester (median 10.5, IQR 6.0−23 min). (Table 2) Total sleep duration increased

TABLE 1
Demographics

Demographic Variable	Median (IQR) or n (%)
Participant count	733
Pregnancy count	757
Age at pregnancy start in years, n=712 (by participant)	32.0 (29.0-35.0)
BMI at study start in kg/m2, n=729 (by participant)	26.3 (23.0-31.8)
Ethnicity (by participant)	
White, non-Hispanic	588 (80.2%)
Hispanic, Latina, Spanish and/or other Hispanic	38 (5.2%)
Black or African American or African	18 (2.5%)
Asian	18 (2.5%)
Other	8 (1.1%)
More than 1 race	63 (8.6%)
Education (by participant)	
Not college educated	161 (22.0%)
College educated	266 (36.3%)
Graduate school degree	304 (41.5%)
Missing	2 (0.3%)
Employment (by participant)	
Employed for pay (part-time, full-time, self-employed)	635 (86.6%)
Unemployed	8 (1.1%)
Unable to work (i.e., disability, illness, other circumstances)	4 (0.5%)
In school	11 (1.5%)
Taking care of house or family	72 (9.8%)
In retirement	1 (0.14%)
Missing	2 (0.3%)
Gestational age in weeks	39w1d (38w1d-40w)
Gravidity (by participant)	
1	260 (34.3%)
2	208 (27.5%)
3	154 (20.3%)
>3	127 (16.8%)
Missing	8 (1.1%)
Parity (by pregnancy)	
1	399 (52.7%)
2	227 (30.0%)
3	87 (11.5%)
>3	36 (4.8%)
Missing	8 (1.1%)
Mode of delivery (by pregnancy)	
Vaginal	454 (60.0%)
Cesarean	242 (32.0%)
Missing	61 (8.1%)

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in the first trimester (pre-pregnancy: median 7.2 hour, IQR 6.7−7.7 hour, 1st trimester: median 7.4 hour, IQR 6.8−7.9 hour), with the least nightly sleep postpartum (median 6.2 hour, IQR 5.4−6.8 hours). (Tables 2, 3, Supplemental Table 2)

Health metrics aligned by delivery

Aligning data based on the day of delivery allows for events preceding delivery to be grouped, regardless of estimated gestational age of delivery. There is a peak in RHR (median 77.0, IQR 70.0−84.0 B.M. and WHR (median 109.5, IQR 103.0−116.6 B.M. eight weeks before delivery which downtrends prior to delivery. (Figure 1, Supplemental Table 3) The RHR and WHR are significantly lower postpartum than pre-pregnancy (RHR median 3.0 BPM lower, IQR -6 to 0) BPM, WHR median 2.2 BPM lower, IQR -6.8 to 2.5 B.M.. (Table 3) The pattern of HRV demonstrates a nadir 10 weeks before delivery (median 28.5, IQR 24.3−35 milliseconds) and subsequent rise prior to delivery, and is higher postpartum than pre-pregnancy (HRV median 2.0 milliseconds higher, IQR -1.9 to 6.9 milliseconds). (Table 3) This pattern of peak RHR and WHR prior to pregnancy end, as well as HRV nadir is preserved in pregnancies which delivered preterm (<37 weeks) compared to those that delivered at term and in primiparous compared to multiparous participants. (Supplemental Tables 5, 13, 15, Supplemental Figures 5, 6) These changes are also apparent when evaluating changes relative to each participant's baseline. (Supplemental Figures 3,4, Supplemental Tables 7, 9) Cardio Fitness values were lowest 4 weeks postpartum (median 29.1, IQR 26.0−32.8 mL/kg/min), and subsequently began to uptrend, without returning to pre-pregnancy values twelve weeks after delivery. (Supplemental Table 3) Total step count (median 4056, IQR 2792−5270 steps), active energy burned (median 387, IQR 303−535 kcal), exercise time (median 4, IQR 2.5−8.0 min) and stand time (median 61.0, IQR 46.0−77.6 min) all had their lowest values in the first week postpartum, and were significantly

TABLE 1
Demographics *(continued)*

Demographic Variable	Median (IQR) or n (%)
Complications count (% by pregnancy)	
Single complication	259 (34.2%)
More than 1 complication	128 (16.9%)
No complications	370 (48.9%)
Complications (by pregnancy, conditions can overlap, self-report)	
Anemia	141 (18.6%)
Gestational diabetes	88 (11.6%)
Gestational hypertension	87 (11.5%)
Heart problems	4 (0.5%)
Hysterectomy	2 (0.3%)
Intrauterine growth restriction	25 (3.3%)
Perinatal depression	54 (7.1%)
Placenta previa	18 (2.4%)
Placental abruption	7 (0.9%)
Postpartum hemorrhage	45 (5.9%)
Preeclampsia or eclampsia	85 (11.2%)
Seizure disorder	0 (0.0%)
Severe infection or sepsis	7 (0.9%)
Pre-existing health conditions (by subject)	
Hypertension	
Yes	52 (7.1%)
No	660 (90.0%)
Missing	21 (2.9%)
Diabetes Type 1 or Type 2	
Yes	4 (0.5%)
No	707 (96.5%)
Missing	22 (3.0%)
Hyperthyroidism or Hypothyroidism	
Yes	80 (10.9%)
No	633 (86.4%)
Missing	20 (2.7%)

BMI: Body Mass Index. IQR: Interquartile Range.

Summary of demographic characteristics and pregnancy details for all participants included in analysis. Data is presented as count, median (IQR) or count (percentage). Gestational age is shown in terms of total weeks and days, for example, 39w1d is to be read as 39 weeks and 1 day. The para being reported includes the pregnancy and delivery included in this analysis.

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lower than pre-pregnancy (Table 3, Supplemental Table 3). Similarly, total sleep duration decreased shortly after delivery (week 1, median 4.8, IQR 4.0−5.6 hours), and postpartum sleep was significantly less than sleep before pregnancy (median decrease 0.9 hours, IQR -1.5 to -0.4 hours) (Table 3)

Age and health metrics

To understand if participant age led to differing patterns of change across health metrics, we examined the same sensor-derived health metrics and found similar increases in RHR and WHR in all age groups. (Figure 2, Supplemental Tables 4, 10, 11) Those 35 and older had the lowest HRV pre-pregnancy (median 37.9 milliseconds, IQR 31.1−46.1) and postpartum (median 38.5 milliseconds, IQR 33.1−47.6) as well as during all three trimesters of pregnancy. (Supplemental Table 4) Step count and exercise time was typically lowest for those under 30 years of age. (Figure 2, Supplemental Table 4)

Comment

Principal findings

This study describes trends in sensor-derived health metrics across a large cohort of pregnant individuals under real-world conditions, highlighting that for physiologic and behavioral parameters there are measurable differences across pregnancy. Quantifying the degree and direction of these trends is a first step in enabling disease screening or detection.

Results in the context of what is known

While it has been observed in obstetrics practice that vital signs change during and after pregnancy, only recently have wearables provided a more granular view into the scale and generalizability of changes.[24] RHR and HRV are metrics of interest, and here we reinforce and expand previous findings. We found that RHR increased from pre-pregnancy to the third trimester, peaking about eight weeks before delivery, with a decrease postpartum to a lower value than pre-pregnancy. This agrees with two previous studies that reported increasing RHR from the first to third trimesters.[3,25] This also aligns with a study of 58 participants who began monitoring in the second trimester; similarly RHR up-trended until week 35, then began to decrease.[4]

There have been several evaluations of HRV during pregnancy, which are expanded with our results. Wearing Holter monitors, 8 pregnant individuals had up to 5, 24-hour electrocardiographic recordings during

TABLE 2
Sensor-derived health metrics by trimester

Variable	Pre-pregnancy	1st Trimester	2nd Trimester	3rd Trimester	Postpartum
Resting heart rate (BPM), n=612	65.0 (60.0-70.2)	67.0 (62.0-72.0)	72.0 (67.0-79.0)	75.5 (69.0-82.0)	62.0 (57.0-66.0)
Heart rate variability (ms), n=614	39.9 (32.6-48.3)	37.6 (30.3-46.2)	32.4 (26.5-38.8)	29.9 (25.2-36.4)	41.4 (34.7-51.4)
Walking heart rate (BPM), n=607	101.0 (94.6-108.1)	102.2 (96.0-109.0)	106.0 (99.0-113.0)	109.0 (102.1-115.2)	99.0 (93.0-104.5)
Respiratory rate (BrPM), n=326	17.4 (16.0-18.7)	18.0 (16.3-19.3)	17.9 (16.0-19.5)	17.8 (15.7-19.5)	16.3 (14.7-17.7)
Blood Oxygen (%), n=399	96.6 (95.6-97.2)	97.0 (96.1-97.6)	97.0 (96.0-97.6)	96.5 (95.3-97.4)	96.0 (94.9-96.6)
Cardio fitness (mL/kg/min), n=88	37.7 (33.1-40.7)	36.7 (33.0-40.5)	34.4 (31.3-38.1)	32.0 (28.3-35.3)	31.8 (28.6-34.2)
Steps (count), n=533	6745 (5089-9005)	6030 (4627-8141)	5745 (4364-7587)	5352 (3989-6957)	5284 (4209-6866)
Active energy burned (kcal), n=530	586 (433-814)	523 (388-704)	497 (379-666)	480 (378-630)	454 (348-601)
Exercise time (minutes), n=509	17.5 (9.0-40.0)	13.5 (7.0-29.5)	12.0 (7.0-25.0)	10.5 (6.0-23.0)	9.0 (5.0-19.0)
Stand time (minutes), n=531	99.0 (77.6-123.0)	88.0 (69.0-112.0)	89.0 (66.0-109.0)	85.0 (68.0-105.0)	74.5 (58.0-95.8)
Total sleep duration (hours), n=233	7.2 (6.7-7.7)	7.4 (6.8-7.9)	7.4 (6.7-7.9)	7.0 (6.4-7.6)	6.2 (5.4-6.8)

BPM: beats per minute. ms: milliseconds. BrPM: breaths per minute. mL: milliliters. Kg: kilograms. Min: minute. kcal: kilocalories. IQR: interquartile range. IQR: interquartile range. LMP: last menstrual period.

Table shows median (IQR) across population for each pregnancy interval. Individual data points themselves are the medians of sensor values by participant during the same interval. Intervals are defined as: Pre-pregnancy: 12 weeks to 1 day prior to LMP, 1st Trimester: LMP to 13 weeks 6 days after LMP, 2nd Trimester: 14 weeks to 27 weeks 6 days after LMP, 3rd Trimester: 28 weeks after LMP to end of pregnancy, Postpartum: 1 day to 12 weeks after end of pregnancy. The n on each row represents the total count of pregnancies used in that row.

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pregnancy, and found a decrease in HRV, though the infrequency of readings and small sample size prevented generalizations of trends.[26] HRV from a wrist wearable, in a cohort of 23 pregnant individuals, presented a U-shaped pattern, declining during two-thirds of the pregnancy then starting to rise approaching baseline.[25] Similarly, in a study of 18 individuals wearing a sensor strap, there was a steady decrease in HRV during pregnancy, with a reversal in this trend around 49 days prior to birth.[3] Our findings with respect to RHR and HRV agree with and extend

TABLE 3
Differences in sensor-derived health metrics

Variable	1st Trimester - Pre-pregnancy Median (IQR)	2nd Trimester - Pre-pregnancy Median (IQR)	3rd Trimester - Pre-pregnancy Median (IQR)	Postpartum - 3rd Trimester Median (IQR)	Postpartum - Pre-pregnancy Median (IQR)
Resting heart rate (BPM), n=612	2.2 (0.0, 4.2)*	7.5 (4.0, 10.2)*	10.3 (6.2, 14.8)*	−13.0 (−18.0, −9.0)*	−3.0 (−6.0, 0.0)*
Heart rate variability (ms), n=614	−1.7 (−4.6, 0.7)*	−6.7 (−10.6, −2.9)*	−8.7 (−15.4, −3.8)*	10.7 (6.1, 18.3)*	2.0 (−1.9, 6.9)*
Walking heart rate (BPM), n=607	1.5 (−1.0, 4.0)*	5.0 (1.0, 9.2)*	7.6 (2.8, 12.1)*	−10.0 (−14.5, −4.8)*	−2.2 (−6.8, 2.5)*
Respiratory rate (BrPM), n=326	0.5 (0.1, 1.0)*	0.3 (−0.3, 1.1)*	0.2 (−0.7, 1.4)	−1.1 (−2.1, −0.2)*	−0.9 (−1.7, −0.3)*
Blood Oxygen (%), n=399	0.4 (0.1, 0.7)*	0.4 (−0.2, 0.9)*	0.0 (−0.7, 0.6)	−0.7 (−1.3, 0.0)*	−0.6 (−1.1, −0.1)*
Cardio fitness (mL/kg/min), n=88	−0.8 (−1.7, 0.3)*	−2.7 (−4.0, −1.2)*	−5.2 (−7.7, −3.8)*	0.0 (−0.9, 1.3)	−5.5 (−7.5, −3.3)*
Steps (count), n=533	−614 (−1304, 37)*	−945 (−1953, −80)*	−1284 (−2570, −346)*	158 (−870, 1047)	−1365 (−2707, −112)*
Active energy burned (kcal), n=530	−48 (−102, −4)*	−66 (−146, −8)*	−77 (−172, −11)*	−31 (−99, 24)*	−105 (−243, −33)*
Exercise time (minutes), n=509	−2.0 (−7.1, 1.0)*	−3.0 (−13.6, 1.0)*	−4.5 (−18.0, 0.0)*	0.0 (−4.5, 3.0)	−5.5 (−19.5, 0.0)*
Stand time (minutes), n=531	−8.2 (−17.5, 1.4)*	−9.5 (−24.0, 2.0)*	−12.0 (−27.5, 2.0)*	−10.5 (−25.0, 4.5)*	−22.8 (−44.0, −2.9)*
Total sleep duration (hours), n=233	0.2 (−0.1, 0.4)*	0.1 (−0.2, 0.4)	−0.2 (−0.6, 0.2)*	−0.8 (−1.3, −0.3)*	−0.9 (−1.5, −0.4)*

BPM: beats per minute. ms: milliseconds. BrPM: breaths per minute. mL: milliliters. Kg: kilograms. Min: minute. kcal: kilocalories. IQR: interquartile range.

Median (IQR) of differences in sensor-derived health metrics compared between pre-pregnancy and each trimester, between 3rd trimester and postpartum, and between pre-pregnancy and postpartum. (*) indicates a p-value of <0.001 in a Wilcoxon signed-rank test. The n on each row represents the total count of pregnancies used in that row. The column name '1st Trimester - Pre-pregnancy' corresponds to 1st trimester median minus pre-pregnancy median.

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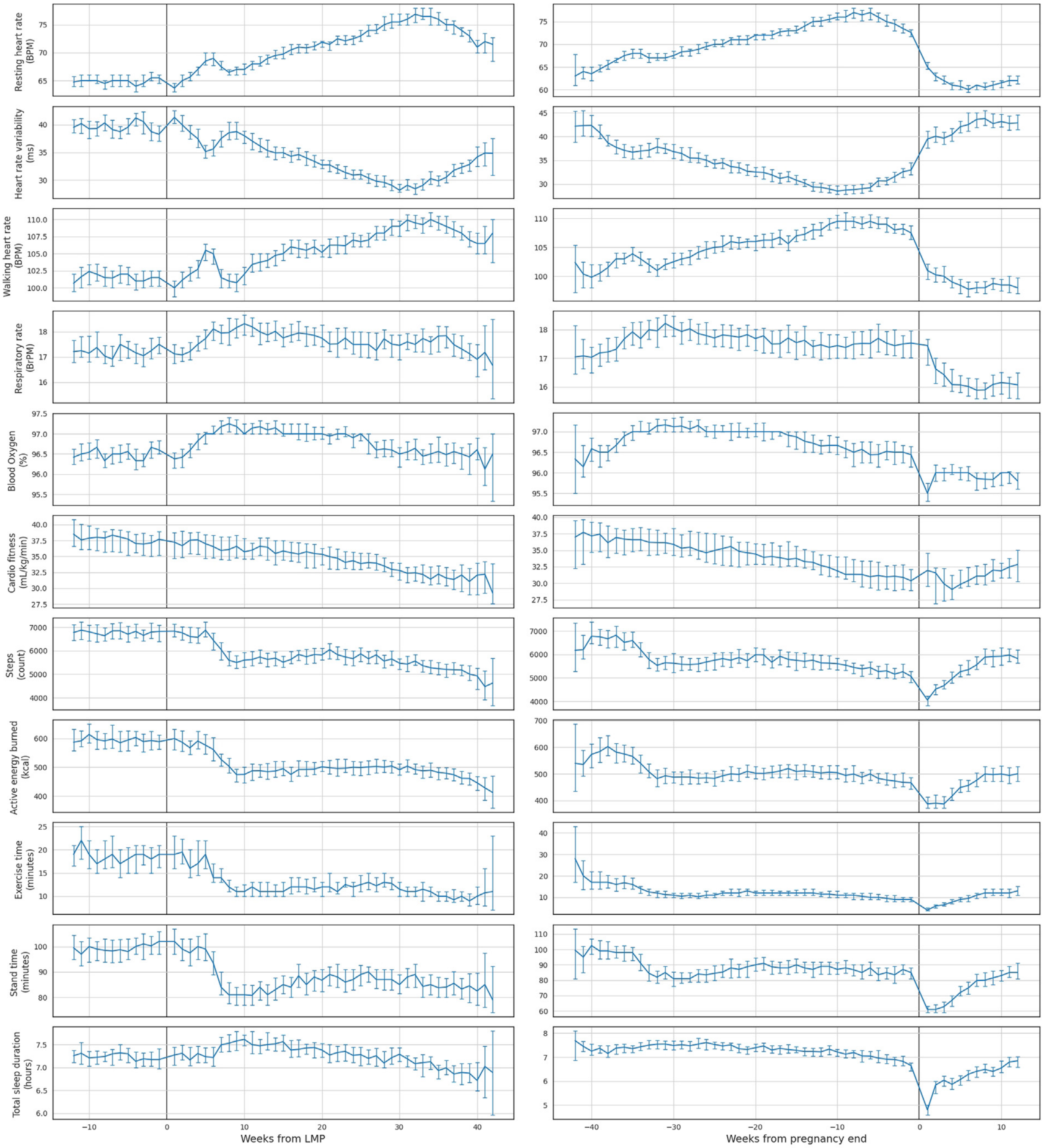
FIGURE 1
Longitudinal trends in sensor-derived health metrics during pregnancy

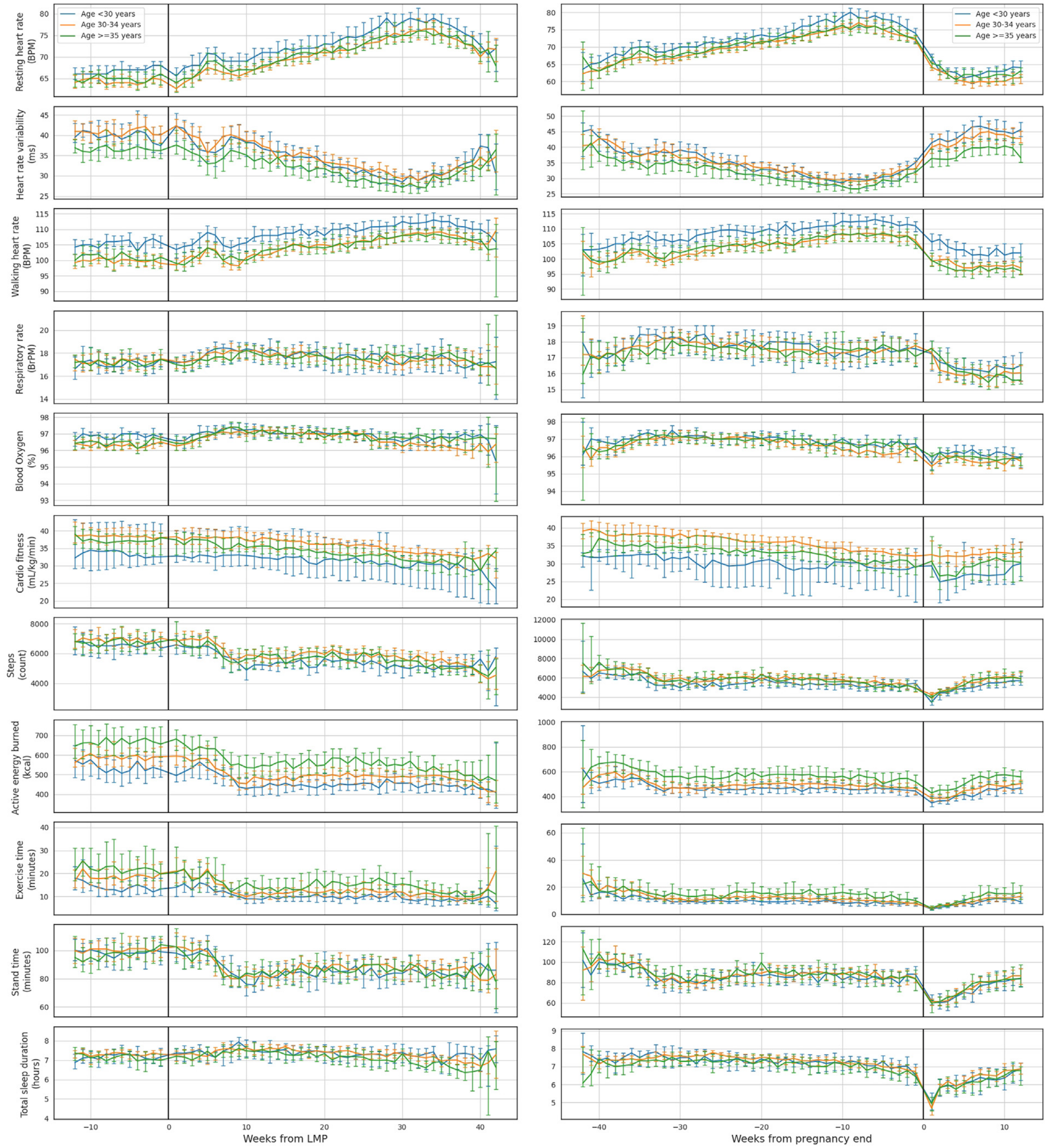


Plots show median and 95% CI of median for each health metric. The plots on left column are graphed with data aligned by the start of pregnancy, LMP. The plots on right are aligned on delivery date. Aligned data is median aggregated weekly for each participant, which is then median aggregated across population.

BPM: Beats Per Minute. ms: milliseconds. BrPM: Breaths Per Minute. mL: Milliliters. Kg: Kilograms. Min: Minute. kcal: kilocalories. LMP: Last Menstrual Period.

Curry. Trends in sensor-based health metrics during and after pregnancy. AJOG Glob Rep 2024.

FIGURE 2
Longitudinal trends in sensor-derived health metrics during pregnancy by age



Median and 95% CI of median plotted for each sensor-derived metric, separated based on age at pregnancy start, LMP. The left-most images are graphed with the data aligned by the start of pregnancy. The right-most images are aligned on delivery date.

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the observation that there is a pattern of RHR peak and HRV nadir prior to pregnancy end. Additionally, we add the observation that at the estimated gestational age of 5 to 6 weeks, there is a brief increase in RHR, WHR, and decrease in HRV.

Secondly, behavioral elements measured by wearables, such as exercise minutes or stand minutes, give insight into real world activity. Often the addition or modification of exercise is suggested to pregnant individuals to impact disease risk. Clinicians typically recommend that those without contraindications participate in exercise throughout pregnancy with resumption when deemed appropriate after delivery.[27,28] Exercise during pregnancy can influence pregnancy outcomes, such as sleep duration, rates of gestational diabetes, and cesarean risk.[29,30,31] Trends within this cohort demonstrate step count and exercise time decrease across the pregnancy and remain lower than pre-pregnancy in the initial postpartum weeks. There appear to be differences in exercise and activity in different age groups. These findings have implications for clinicians and researchers who may be designing interventions or treatment modalities that rely on participant activity or exercise, and may need to account for overall decrease in activity in the third trimester and postpartum.[32,33]

Thirdly, many studies of sleep during pregnancy rely on self-report of sleep patterns, which may misrepresent associations with disease risk. Findings related to sleep from this cohort reinforce the lived experience of pregnant individuals around sleep length during pregnancy and after delivery and expand the preceding studies.[34] A study of 20 pregnant participants wearing a finger-based sensor presented a trend of sleep duration being longest in the second trimester and decreasing in later pregnancy.[35] A number of adverse outcomes are linked to sleep timing or quality, making understanding typical patterns important as a point of comparison. In a study of 51 individuals with previous depression, late start of sleep was associated with symptoms of depression.[36] When separating 1125 pregnant participants into groups based on self-reported sleep duration, shorter sleep duration was associated with the highest report of gestation diabetes; 31.3% with short (<7 hours) sleep duration, 25.2% with normal (7−9 hours) sleep duration, and 14% for those with prolonged (>9 hours) sleep duration. Evaluating objective, real world sleep data before and during pregnancy, in addition to survey based qualitative assessments may improve future understandings of sleep-related pregnancy outcomes.

Clinical and research implications

There are several potential research implications. Notably, the observation that RHR and HRV begin to return to baseline before delivery suggests an ability to leverage physiologic sensor data to better understand changes leading up to, or potentially being related to, labor onset, particularly given that similar trends in RHR, WHR and HRV were seen prior premature deliveries as compared term deliveries. Additionally, we describe here a number of behavioral trends that can be used to understand population level behavior. This can be of use in clinical conversations, such as providing trends in total exercise minutes or sleep duration during and after pregnancy to a patient during motivational interviewing as a way to help set goals and expectations.

Strengths and limitations

This analysis provides longitudinal data among participants in a large and diverse cohort, observed in a free-living conditions.[7] The rates of pregnancy outcomes, such as cesarean rates, postpartum hemorrhage, and preeclampsia, are similar to those reported by other US-based studies, suggesting generalizability of this cohort in terms of medical comorbidities.[37,38,39] Similarly, the age at pregnancy start in this cohort is similar to the mean age of childbirth in the US of age 30 years.[40] Unlike preceding studies, collection of data prior to pregnancy start, as well as after delivery, permits comparison between these physiologically and behaviorally different times. The size of this cohort also permits evaluation based on different ages.

This work has several limitations. The ability to generalize to other populations may be limited as the AWHS cohort is restricted to iPhone users, and demographic characteristics such as race/ethnicity may not be representative of the US or other populations. Gestational ages are estimated based on last menstrual period, which may lead to errors in estimation. Medical history and complications are self-reported, which may lead to miscategorization of participants. Additionally, context around delivery such as if delivery was spontaneous or induced, is not available. The physiology preceding spontaneous labor cannot be differentiated from that leading up to a scheduled cesarean, and it doesn't account for other pathology, such as if a participant had hypertensive complications. There is also bias introduced in that pregnancies that were ongoing at the end of window of analysis would not have been included, which may lead to decreased representation in longer gestational aged pregnancies. Sleep metrics are only extracted during the participant-set sleep window, therefore not accounting for naps if there is sleep that occurs during the day. Exercise minutes may be underestimated, as they only include minutes of exercise when a participant manually initiates a workout on their Watch. Limitations are also notable for data that requires that a participant has the sensor in place for a significant fraction of their day. For several of the metrics, there is less data availability, such as for Cardio Fitness, respiratory rate and total sleep duration, which may be related to the versions of hardware or software that any given participant was using. Though we have tried to minimize the effect of intermittent watch wear using our availability criteria, it is possible that estimates of behavioral elements, such as step count or exercise time, may be underestimated if the wearable was not on during times the participant was active.

Conclusion

There are significant differences in vital signs and behavioral trends in sensor-derived health metrics during and after pregnancy as compared to pre-pregnancy. These data provide a foundation for understanding normal pregnancy physiology and can facilitate hypothesis generation related to physiology, behavior, pregnancy outcomes and disease. ■

CRediT authorship contribution statement

Anshuman Mishra: Formal analysis, Data curation, Conceptualization. **Jihyun Park:** Data curation, Conceptualization. **Ian Shapiro:** Methodology, Data curation. **Tyler Fisher-Colbrie:** Software, Project administration, Funding acquisition. **Donna D. Baird:** Writing – review & editing, Methodology, Conceptualization. **Sanaa Suharwardy:** Writing – review & editing, Conceptualization. **Shunan Zhang:** Supervision, Resources, Project administration, Methodology. **Anne Marie Z. Jukic:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Christine L. Curry:** Writing – original draft, Supervision, Methodology, Conceptualization.

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Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.xagr.2024.100388.

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