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Research and Applications

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Movement patterns in women at risk for perinatal depression: use of a mood-monitoring mobile application in pregnancy

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ABSTRACT

Objectives: To examine, using a smartphone application, whether mood is related to daily movement patterns in pregnant women at risk for perinatal depression.
Materials and Methods: Thirty-six women with elevated depression symptoms (PHQ-9 $\geq$ 5) in pregnancy used the application for 8 weeks. Mood was reported using application-administered surveys daily (2 questions) and weekly (PHQ-9 and GAD-7). The application measured daily mobility (distance travelled on foot) and travel radius. Generalized linear mixed-effects regression models estimated the association between mood and movement.
Results: Women with milder depression symptoms had a larger daily radius of travel (2.7 miles) than women with more severe symptoms (1.9 miles), $P = .04$. There was no difference in mobility. A worsening of mood from the prior day was associated with a contracted radius of travel, as was being in the group with more severe symptoms. No significant relationships were found between anxiety and either mobility or radius.
Discussion: We found that the association of mood with radius of travel was more pronounced than its association with mobility. Our study also demonstrated that a change in mood from the prior day was significantly associated with radius but not mood on the same day that mobility and radius were measured.
Conclusion: This study lays the groundwork for future research on how smartphone mood-monitoring applications can combine actively and passively collected data to better understand the relationship between the symptoms of perinatal depression and physical activity that could lead to improved monitoring and novel interventions.

Key words: perinatal depression, ecologic momentary assessment, mobile application, smartphone application

BACKGROUND AND SIGNIFICANCE

In January 2016, the US Preventive Services Task Force recommended screening for depression in pregnant and postpartum women,[1] based on evidence that maternal mental illness is common (with an estimated prevalence of nearly 19%),[2] occurs during pregnancy and postpartum, and, if untreated, has multiple secondary effects on children, including cognitive delays, infant and childhood depression, and decreased attachment.[3–5] Risk factors for perinatal depression include having low income, being single or in an unhealthy relationship, having adverse childhood experiences and recent stressful events, and having poor social support.[6–8] This condition can manifest as losing interest in connecting with others, leaving one's home, and interacting with one's environment.[9] Lack of physical activity is both an exacerbating factor and a marker for worsening depression, as depressed individuals display less daytime motor activity.[9] Physical activity has been shown to alleviate depressive symptoms in a dose-response fashion[10] and is beneficial even in low doses.[11]

As both depressive symptoms and movement patterns can change moment to moment and day to day,[12] conducting ecologic momentary assessment (EMA) with mobile technology enables promising new research on mood disorders,[13] addiction,[14] eating disorders,[15] and other conditions. The high rate of mobile technology use among young, low-income populations in the United States[16] makes it an important potential tool for supporting vulnerable women in pregnancy and postpartum.[17] EMA involves repeated sampling of respondents' real-time experiences while going about their daily routines, using technologies including text messaging, smartphone applications (apps), or physiological sensors.[18] These tools can signal to health care providers that there has been a significant behavioral change, such as call or text frequency or movement pattern alterations.[19] Efforts to combine EMA with geospatial analysis to better understand "geospatial happiness"[20] are gaining momentum, as it has become increasingly recognized that real-time monitoring of individuals' visits to particular locations throughout their day, or remaining at home for extended periods, can provide important signals about mood.[21,22] To our knowledge, mobile technology–enabled EMA has not been studied in pregnant women, for whom overall physical activity (particularly outside the home) has been shown to decrease over the course of pregnancy,[23] presenting unique challenges to using EMA for mood monitoring.

OBJECTIVE

Our primary aim entailed examining the association of self-reported daily mood and passively collected data with movement patterns of pregnant women at risk for perinatal depression. Our secondary aims entailed (1) assessing the relationship between the Patient Health Questionnaire–9 (PHQ-9) and Generalized Anxiety Disorder–7 (GAD-7), validated scales for depression and anxiety, respectively,[24,25] and movement patterns, and (2) investigating the relationship between movement patterns and demographic characteristics of our sample. We hypothesized that mood and movement patterns would be associated in pregnant women at risk for perinatal depression.

MATERIALS AND METHODS

Study setting and participants

Eligible participants were women presenting for prenatal care to an urban university hospital–affiliated obstetrics practice serving predominantly racial and ethnic minority, low-income women, where patients are routinely screened for perinatal depression. Participants who met the inclusion criteria – (1) age >18 years old, (2) PHQ-9 ≥ 5 (signifying risk for perinatal depression), (3) <32 weeks gestation, and (4) possession of an Android smartphone (compatible with the study mobile app) – were consented and enrolled in a larger feasibility and acceptability study of the app's use for communicating with their prenatal health care provider. To be included in the study reported here, participants met the above criteria, were randomized to use of the app rather than routine care, and had at least 3 responses for daily mood questions, mobility, and radius measures. The feasibility and acceptability results are reported separately.

The study app

The mobile app, called Ginger.io (San Francisco, CA, USA), is HIPAA-compliant and password-protected. Participants rated their daily mood when prompted by a push notification, and the smartphone's velocimeter passively collected movement data (total distance traveled on foot per day [mobility] and farthest radius traveled by car, bicycle, or public transportation per day [radius]). The app analyzed these data, along with metadata on number and length of phone calls and text messages, to detect subtle changes in smartphone usage patterns and movement data that might indicate the need for support, then sent alerts to health care providers for personalized intervention.

Study procedures and data collection instruments

Participants downloaded the app to their smartphones, completed an enrollment interview, and used the app for 8 weeks. Every other week, they were asked to complete either the PHQ-9 or the GAD-7. Participants were prompted to respond to a daily PHQ-2 survey[26] sent through the app every morning, which included 2 questions about their mood in the past 24 hours and could be answered at any point during the day: "Have you felt little interest or pleasure in doing things?" and "Have you felt down, depressed, or hopeless?" Responses were scored on a Likert scale from 1 ("not at all") to 5 ("most of the day"). These scores were summed on a daily basis for each individual ("daily mood," range 2–10). Mobility and radius data were passively collected by the smartphone.

Statistical analyses

Demographic factors were compared between participants with mild/moderate (PHQ-9 of 5–14) vs moderately severe/severe (PHQ-9 of ≥ 15) depression at baseline, using Student t test, Wilcoxon nonparametric test, or Fisher's exact test as appropriate. Medians and interquartile ranges (IQRs) for mobility and radius measures were calculated using data across the 8 weeks of the study for all participants. Mobility and radius were log-transformed to approximate normality. Generalized linear mixed-effects regression models for repeated measures compared mobility and radius between depression groups using baseline depression category as a predictor of log-transformed mobility and radius. Variance estimates were adjusted for repeated observations.

To examine the association between demographic factors and the predictors and outcomes at baseline, we calculated the means of daily mood and log-transformed mobility and radius from week 1 for each participant. Associations were measured using t tests, analysis of variance, and linear regression. Those variables that showed a significant association ($P < .05$) with daily mood, log-transformed mobility, or log-transformed radius were included as covariates in adjusted models.

Similar generalized linear mixed-effects models were fit to test the association between mood and movement patterns. Three models were tested, using (1) all daily mood measures, (2) change in daily mood from the prior day (delta-daily mood), and (3) weekly average of daily mood, as predictors of log-transformed mobility and log-transformed radius. Models were run both unadjusted and adjusted for relevant covariates, and we calculated regression coefficients and ratios of geometric means. The latter is interpreted as the ratio of the average mobility (or radius) for every 1-unit increase in the predictor. To evaluate whether the relationship between mood scores and movement changed over the 8-week study, we tested interactions with time (day or week).

PHQ-9 and GAD-7 questionnaires were administered on alternating weeks. Hypothesizing that the participants' movement patterns on the days immediately surrounding these scales would be most closely associated with self-reported mood, the average mobility and radius for each participant during the 3-day window surrounding the questionnaire date were used in repeated-measures models. We dichotomized these variables according to clinically relevant cutoffs, with PHQ-9 scores of ≥15 and GAD-7 scores of ≥8 contrasted against lower values. As above, we considered the potential for differing associations over the study duration by including an interaction by time in the model, if found to be significant. We repeated this analysis using a 5-day window around PHQ-9 and GAD-7 as a sensitivity analysis. All available data were used in statistical modeling.

Written consent was provided, and the University of Pennsylvania's Institutional Review Board approved the study. Study data were collected and managed using Research Electronic Data Capture, (REDCap), a secure, web-based application for electronic data capture hosted at the University of Pennsylvania. Analyses were performed in SAS (SAS Institute, Cary, NC, USA).

RESULTS

Characteristics of the sample

Of the 36 women in our cohort, 27 (75%) met the PHQ-9 criteria for mild to moderate depression on enrollment and 9 (25%) were classified as moderately severe to severely depressed (Table 1).[24]

The mean age was 25.7 years, 88.6% of the participants were African-American, 11.4% were married, 40% were employed, and 13.9% had private insurance. The percentages of women with alcohol use during pregnancy, tobacco use during pregnancy, and past or current cocaine, crack, or heroin use were 24.1, 36.7, and 20.0%, respectively. Average gestational age at enrollment was 20.9 weeks. On average, women in the more depressed group were older than those in the less depressed group (29.7 vs 24.3, respectively, $P = .017$). There were no other statistically significant differences in demographic characteristics by depression severity (Table 1).

Similarly, there was no difference in median daily mobility over the 8-week study in women with less severe depression vs more severe depression at baseline (1.2 miles [IQR: 0.4–2.3 miles] vs 1.0

Table 1. Demographic/clinical characteristics of the cohort,[a] and mobility and radius,[b] by depression severity

Characteristic	Overall N = 36	Mild/moderate depression N = 27 (75%)	Moderately severe/severe depression N = 9 (25%)	P value[c]
	Mean (SD)	Mean (SD)	Mean (SD)	
Age	25.7 (5.9)	24.3 (5.2)	29.7 (6.2)	**0.017**
	n (%)	n (%)	n (%)	
African-American/black	31 (89)	23 (89)	8 (89)	1.00
Hispanic ethnicity	4 (11)	2 (8)	2 (22)	0.27
Married	4 (11)	2 (8)	2 (22)	0.27
Employed	14 (40)	12 (46)	2 (22)	0.26
Postsecondary education	17 (49)	12 (46)	5 (56)	0.71
Private insurance	5 (14)	3 (11)	2 (22)	0.58
Ever diagnosed with a mental health condition	26 (72)	18 (67)	8 (89)	0.39
Number of children (parity)				0.43
None	21 (58)	17 (63)	4 (44)	
1	8 (22)	6 (22)	2 (22)	
2 or more	7 (19)	4 (15)	3 (33)	
Prenatal care during first trimester	27 (75)	21 (78)	6 (67)	0.66
Alcohol use (current)	7 (24)	6 (27)	1 (14)	0.65
Tobacco use (current)	11 (37)	7 (32)	4 (50)	0.42
Cocaine/crack/heroin use (past/current)	7 (20)	6 (22)	1 (13)	1.00
	Mean (SE)	Mean (SE)	Mean (SE)	
Gestational age at baseline in weeks	20.9 (1.13)	21.1 (1.25)	20.2 (2.43)	0.75
Mobility (miles/day)	−0.16 (0.14)	−0.08 (0.17)	−0.38 (0.29)	0.40
Geometric mean	0.85	0.92	0.68	
Average replicates per woman	45.0	46.4	40.8	
Radius (miles/day)	0.32 (0.15)	0.49 (0.17)	−0.21 (0.29)	**0.037**
Geometric mean	1.38	1.63	0.81	
Average replicates per woman	45.0	46.4	40.8	
Daily mood (QSum)	4.32 (0.25)	1.60 (0.51)	3.92 (0.26)	**0.002**
Average replicates per woman	40.8	40.4	42.0	
	Median (IQR)	Median (IQR)	Median (IQR)	
Average PHQ-9 score at baseline	9 (7.5–14.5)	8 (6–10)	18 (17–19)	**<0.001**

[a]Characteristics reported at enrollment.

[b]Calculated across the 8-week study period.

[c]Significant $P < .05$ in bold and calculated with following tests: *t* test (age, gestational age); Wilcoxon 2-sample test (average PHQ-9); Fisher's exact test (all categorical variables; repeated measures models with baseline depression category predicting log-transformed mobility and radius.

miles [IQR: 0.4–2.1 miles], respectively; $P = .40$). There was a statistically significant difference between groups in median daily radius (less severe depression: 2.7 miles [IQR: 0.6–5.9 miles] vs more severe depression: 1.9 miles [IQR: 0.1–3.5 miles], $P = .04$) (Table 1).

Most variables had little missing data. However, 19.6% of the observations were missing for mobility/radius and 27.1% were missing for daily mood.

Association between demographic characteristics and baseline movement patterns and mood

We examined unadjusted associations between demographic characteristics at study enrollment and baseline mobility and radius data (averaged over the first week of the study). There were no significant associations between average daily mobility or radius during study week 1 and the following demographic covariates: gestational age, parity, alcohol use, race, ethnicity, education, employment, insurance type, marital status, tobacco use, or prenatal care in the first trimester. Older participants had a smaller radius of travel in week 1 than younger participants ($P = .02$) (Table 1). Women who reported use of cocaine, crack, or heroin had significantly more average daily mobility ($P = .02$).

We then compared these demographic characteristics to baseline mood (daily mood averaged over study week 1). While there was no significant difference in the percentage of women employed in each depression group, overall, participants who were employed (full- or part-time) had a significantly lower daily mood score (mean 3.9, standard deviation [SD] 1.1) than those who were unemployed (mean [SD] 5.1 [1.4]), indicating a positive association between employment and improved mood ($P = 0.013$). Week 1 daily mood averages were also significantly associated with the depression group as defined by baseline PHQ-9 scores ($P = .023$).

Association between mood and movement patterns over the study period

Table 2 summarizes the associations between self-reported daily mood and movement patterns (log-transformed mobility and radius).

Models were adjusted for baseline depression group, age at enrollment, drug use, and employment status. There were no significant relationships between daily mood, delta-daily mood, or weekly average of daily mood and mobility. However, both delta-daily mood and the weekly average of daily mood were negatively associated with radius in the adjusted model ($P = .028$, $P = .039$, respectively) (Table 2). For example, the geometric mean ratio of 0.87 in the model of the association between weekly average of daily mood and weekly average of radius indicates that for every 1-point increase on the daily mood scale from one week to the next (with higher scores signifying worse mood), the participant's radius of travel that week was contracted by an average of 13% from the prior week. A similar relationship existed with delta-daily mood (Table 2). For every 1-unit increase in delta-daily mood, the radius was contracted by an average of 5%. No interactions between time and mood were found to be significant. Figure 1 shows a representative participant's daily delta-daily mood and log-transformed radius for the 8-week study period.

In analyzing movement patterns during the 3-day windows around PHQ-9 and GAD-7 reports, we found a significant association between depression severity and mobility, and an interaction with time was present (Tables 3 and 4).

These models were adjusted for time and drug use (Table 3) and drug use only (Table 4). Unlike the models with daily self-reported mood, employment status was not associated with PHQ-9 or GAD-7, nor was it a confounder of the association between these outcomes and mobility or radius. Women with more severe depression in a given week had twice the average daily mobility at the beginning of the study than women with milder depression (mobility ratio = 2.27, 95% CI, 1.11–4.65, $P = .025$) but by week 5, they had 78% lower mobility than women with milder depression (mobility ratio = 0.22, 95% CI, 0.052–0.893, $P = .036$) (Table 4), a relationship that continued through week 8 of the study.

Finally, there was a significant association between depression severity and radius in the 3-day window around the reported PHQ-9 ($P = .003$) (Table 3), and no interaction with study week was present (data not shown). When depression symptoms were worse, the radius of travel was contracted over the 3-day window around PHQ-9. The ratio of geometric means of 0.362 indicates that for every 1-point increase on the PHQ-9, the radius was, on average, 64% smaller.

No relationship was found between GAD-7 and mobility over the course of the study, or between GAD-7 and radius (Table 3). The sensitivity analysis with a 5-day window showed similar but slightly attenuated findings (data not shown).

DISCUSSION

To our knowledge, this study is the first to examine, using a smartphone application, the association between self-reported mood and passively measured movement data in pregnant women at risk for perinatal depression. We found that the association of mood with radius of travel is more pronounced than its association with mobility. Our study also demonstrated that a change in mood from the

Table 2. Self-reported daily mood, change in mood from prior day, and weekly average of self-reported mood predicting mobility and radius[a]

Outcome	Predictor	Beta estimate (95% CI)[b]	Ratio of geometric means (95% CI)	*P* value[c]
Mobility[d]	Daily mood	−0.0152 (−0.0615, 0.031)	0.985 (0.940, 1.031)	.52
	Delta-daily mood	−0.0055 (−0.0339, 0.0229)	0.995 (0.967, 1.023)	.70
	Weekly average of daily mood	−0.0497 (−0.1081, 0.0087)	0.952 (0.898, 1.009)	.095
Radius[d]	Daily mood	−0.0616 (−0.1326, 0.0095)	0.940 (0.876, 1.010)	.089
	Delta-daily mood	−0.052 (−0.099, −0.006)	0.949 (0.906, 0.994)	**.028**
	Weekly average of daily mood	−0.142 (−0.276, −0.007)	0.868 (0.759, 0.993)	**.039**

[a]Models adjusted for baseline depression group, age at enrollment, drug use, and employment status.
[b]CI = confidence interval.
[c]Significant *P* values (<.05) in bold.
[d]Mobility and radius are log-transformed and, for the model with weekly average of daily mood as the predictor, averaged over the week.

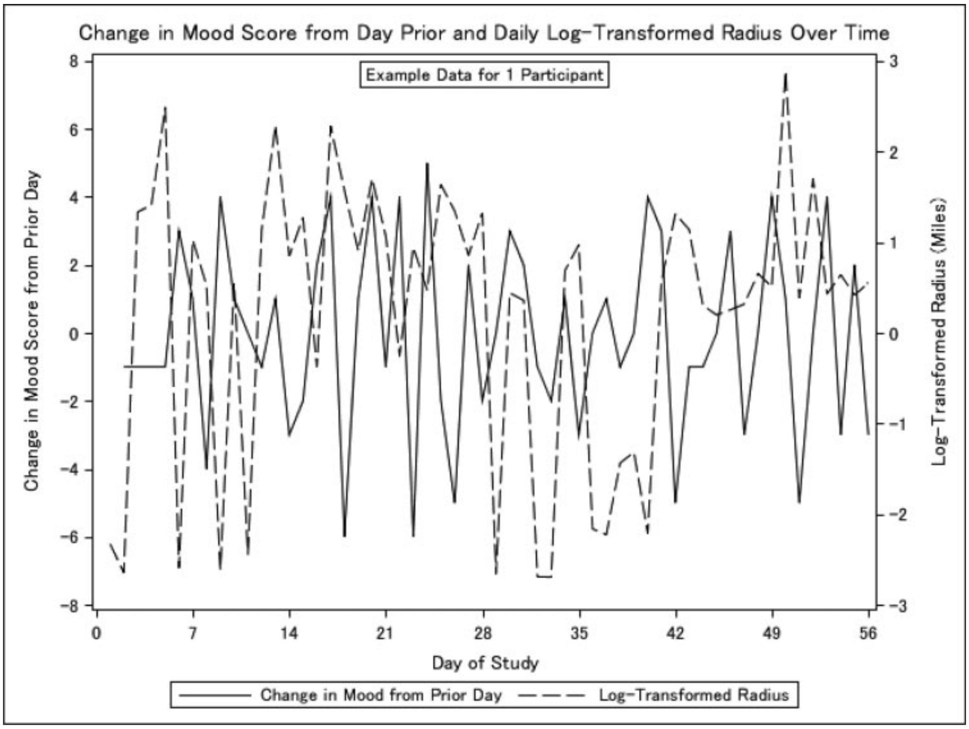

Figure 1. Example of longitudinal data on mood and mobility for 1 study participant over the 8-week study period.

prior day was significantly associated with radius but not mood on the same day that mobility and radius were measured.

Overall, women with milder depression had a larger radius of travel than women with more severe depression. The mileage difference (0.8 miles) represents approximately 8 city blocks in the urban location of this study, meaning that the woman could have traveled to a completely different part of the city. Additionally, when examining the 3-day window around the PHQ-9, there was a significant inverse relationship between depression severity and radius. Our results are consistent with past findings that people with depression, regardless of pregnancy status, spend more time at home and visit fewer locations throughout their daily activities due to the loss of motivation, decreased activity, and social withdrawal that characterize this mood disorder.[27] Our results also support the findings of a study showing that spending time outside the home or work environment had a positive effect on stress level.[28] Interestingly, another study found that staying close to home in deprived neighborhoods was a risk factor for depression, but it was protective for people in advantaged neighborhoods.[29] As our study was conducted in a population of women of almost universally low socioeconomic status, likely residing in deprived neighborhoods, our finding of an association between worsening depressive symptoms and a contracted radius of travel supports those results.

We also found that daily mood was not associated with same-day mobility or radius. However, we found a significant relationship between *change* in mood from the prior day and radius, with worsened mood associated with contracted radius. Perhaps the change in mood, rather than absolute symptom severity, is perceived more acutely and is therefore associated with a change in distance travelled from home that day. The underlying physiology that makes certain women more susceptible to perinatal depression, including hormonal dysregulation, hypothalamic-pituitary-adrenal axis abnormalities, genetics, and epigenetics,[30] could potentially heighten their sensitivity to improved or worsened mood from the prior day. In these analyses, we controlled for employment status, which confounded the relationship between mood and radius, likely because employment generally requires leaving home on a regular basis.

We found no significant association between *daily* mood and mobility, in contrast to a study of postpartum women where those with lower activity levels reported more depressive symptoms.[31] The limited duration of our study, and perhaps the documented secular trend of decreased physical activity over time during pregnancy,[23] may have contributed to this negative result. Yet surprisingly, when examining the 3-day window around the biweekly PHQ-9, the relationship between depressive symptoms and mobility changed over time, depending on depression severity. For women with mild/moderate depression, average daily mobility increased over the study period, but the opposite was true for those with more severe depression. Perhaps women with milder depression benefited from the behavioral activation prompts and/or increased contact with their health care providers, leading to improvement in depressive symptoms and thus more physical activity over time. In contrast, the association between mood and mobility may be stronger in those with more severe depression, such that the self-reinforcing cycle of worse mood and less physical activity progresses over time.

Finally, anxiety was associated with neither mobility nor radius of travel during the 3-day window around the GAD-7. Less is known about the relationship between anxiety symptoms and

Table 3. Association between depression and anxiety symptom severity and mobility and radius[a]

Depression or anxiety severity	Mobility[b]		Radius[b]	
	Ratio of geometric means (95% CI)	*P* value[c]	Ratio of geometric means (95% CI)	*P* value[c]
More vs less severe depression[d]	See Table 4 for results of model with time interaction		0.362 (0.185, 0.706)	**.003**
More vs less severe anxiety[d]	0.918 (0.549, 1.535)	.7454	0.593 (0.302, 1.165)	.13

[a]Models controlled for time and drug use.
[b]Values were averaged over the 3-day window around the date the PHQ-9 or GAD-7 was reported.
[c]Significant *P* values (<0.05) in bold.
[d]Clinically relevant PHQ-9 scores of ≥15 and GAD-7 scores of ≥8 contrasted against lower values.

Table 4. Interaction between depression severity and time as predictors of mobility[a]

More vs less severe depression	Ratio of geometric means (95% CI)	*P* value[b]
Weeks 1 and 2	2.269 (1.107–4.652)	**.025**
Weeks 3 and 4	0.920 (0.407–2.079)	.84
Weeks 5 and 6	0.216 (0.052–0.893)	**.034**
Weeks 7 and 8	0.321 (0.232–0.443)	**<.001**

[a]Model controlled for drug use.
[b]Significant *P* values (<.05) in bold.

physical activity, as interventions tend to focus on mindfulness-based stress reduction, cognitive restructuring and reframing, and relaxation techniques.[32] Furthermore, the GAD-7 is sensitive for a range of anxiety disorders, but other scales might be better at detecting small variations in a person's anxiety symptoms over time.[33]

These findings should be interpreted in the context of a study design that examined an *association* between predictor (mood) and outcome (movement patterns). Therefore, we cannot disentangle the complex temporal dynamics of this relationship: does a contracted radius of travel worsen the depression symptoms due to lack of physical activity or contact with social support networks, and/or does worsening depression lead to a smaller radius that can be detected by a smartphone app's pattern-sensing technology? We hypothesized that the latter would be the case, and our analysis of a change in mood from the prior day supports the directionality we chose to model. This hypothesis is further supported by recent studies among third-trimester pregnant women[34] and nonpregnant adults[35] suggesting that depressive symptoms are more likely to contribute to disruptions in daily physical and social activity rather than the reverse, although the relationship is likely bidirectional.[12,36] Overall, our study suggests that a smaller radius of travel might be a more sensitive warning signal for the smartphone application to detect worsening perinatal depression than a decrease in mobility. Perhaps normal fluctuations in both physical discomfort and energy level in pregnancy make mobility a less sensitive metric for detecting mood changes.

In light of the likely bidirectional relationship between mood and radius of travel, our study has implications for enhancing the well-being of women at risk for perinatal depression beyond just detecting worsening symptoms using movement patterns. In addition to psychotherapy and pharmacotherapy, interventions such as pre- and postnatal home visits and peer support groups have been developed to address perinatal depression, and more recently, virtual home visits and support groups have been created by leveraging social media and telemedicine.[37–39] The most promising preventive interventions include professionally-based home visits, telephone-based peer support, and interpersonal psychotherapy.[40] Many of these interventions aim to meet women "where they are" (eg, at home). Despite evidence of their success, our study suggests that innovative strategies could go further in combating social isolation and encouraging physical activity, given that only about 25% of pregnant women engage in levels of physical activity recommended by the American College of Obstetrics and Gynecology.[23] For instance, home-visiting programs and telehealth could be built upon to include social gatherings of pregnant and postpartum women in convenient, community-based locations for professionally-guided peer support and shared childcare. Interventions should be individualized based on a woman's need to include, for example, "supportive outings:" a visiting nurse or community health worker could encourage a socially-isolated pregnant woman to reengage with her community by running errands, visiting friends or family, or joining prenatal, lactation, or parenting support groups. Special attention should be paid to the barriers to joining group physical activities during pregnancy (eg, childcare logistics, fluctuations in energy level and pregnancy-related discomfort) and to stated preferences for variety and choice of activity (eg, walking, yoga, etc.).[41] Finally, given the positive relationship between mood and employment in the overall sample, it is also likely that job assistance might be another promising intervention to combat perinatal depression, if tailored to the woman's preferences, skills, family situation, and postpartum plans. Each of these potential interventions should be rigorously studied to evaluate their effectiveness in this unique population.

This study had certain limitations, including missing data and small sample size. As in other studies of app usage, missing data could be attributable to cultural or age-related variation, the reliance on participants to turn on the phone and carry it with them, or a decline in use if the mood assessments were perceived to be burdensome or if the app consumed too much battery power.[19] Also, we studied patients with elevated depression symptomatology and cannot address differences in movement patterns among asymptomatic women (the majority of pregnant women). Finally, the focus on women from low-income and racial/ethnic minority backgrounds limits generalizability. These limitations were balanced by the granular data at the individual level and participants reporting their mood using the same measures on a daily and biweekly basis for 8 weeks.

CONCLUSION

In this cohort of pregnant women, we found a relationship between mood and radius of travel, despite day-to-day variability in mood for each participant, variability in daily movement patterns, and the restriction of mobility and radius to a fairly narrow mileage range. Thus, EMA, with frequent sampling of a person's internal state and environmental interactions, is able to capture fluctuations in both mood and movement patterns throughout the course of a woman's day, week, and entire pregnancy. This study lays the groundwork for future research on how smartphone mood-monitoring applications can combine actively and passively collected data to better understand the relationship between the symptoms of perinatal depression and physical activity that could lead to novel, real-time, location-specific, person-centered interventions. Future studies should further elucidate the directionality of this relationship, explore the relationship at different points during pregnancy, and examine optimal ways of incorporating these data into the workflow of health service delivery in both the health care setting and the community.

CONTRIBUTORS

LJF: conceptualized the study, developed data analysis plan, drafted the manuscript.

LH: supervised acquisition of study data, participated in data analysis and interpretation, critically revised the manuscript for intellectual content.

DA: analyzed the data and revised the manuscript for intellectual content.

MDS: analyzed the data and revised the manuscript for intellectual content.

IMB: conceptualized the study, supervised acquisition of study data, critically revised the manuscript for intellectual content.

DJW: conceptualized the study, contributed to data analysis and interpretation, critically revised the manuscript for intellectual content.

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COMPETING INTERESTS

The authors have no competing interests to declare.

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