The Pennsylvania State University

The Graduate School

UNDERSTANDING THE ROLE OF RESTING ENERGY EXPENDITURE IN GESTATIONAL WEIGHT GAIN IN PREGNANT WOMEN WITH OVERWEIGHT OR OBESITY

A Dissertation in

Kinesiology

by

Krista S. Leonard

Submitted in Partial Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

December 2020

The dissertation of Krista S. Leonard was reviewed and approved by the following:

Danielle Symons Downs
Professor of Kinesiology and Obstetrics & Gynecology
Dissertation Advisor, Chair of Committee

Joshua M. Smyth
Professor of Biobehavioral Health and Medicine

Michael Blair Evans
Assistant Professor of Kinesiology

Zita Oravecz
Assistant Professor of Human Development and Family Studies

Jonathan Dingwell
Professor of Kinesiology
Graduate Program Director, Kinesiology

ABSTRACT

Pregnant women with overweight or obesity (PW-OW/OB) and/or excessive gestational weight gain (GWG) are at increased risk for maternal and infant morbidity and mortality. Most randomized controlled trials aiming to regulate GWG in PW-OW/OB have focused on the effects of moderating energy intake and improving physical activity. However, most have shown either no effect or a modest effect on GWG due to the difficulties with promoting these behaviors. While moderating energy intake and promoting physical activity remain important, there is a need to identify useful ways to promote these behaviors and/or find other "achievable" targets to effectively regulate GWG in PW-OW/OB. Resting energy expenditure (REE) is used to create energy intake and physical activity goals in non-pregnant individuals to manage weight given that it accounts for 60-70% of total energy expenditure. Yet, little attention has been given to REE as a determinant of gestational weight gain (GWG).

Thus, the overall objective of this dissertation was to examine REE in relation to energy intake, physical activity, and GWG in PW-OW/OB in an effort to understand the extent to which REE can be used in future interventions to inform energy intake and physical activity goals as a strategy for effective GWG regulation and improve maternal and infant well-being. Three studies were conducted to achieve this goal. These studies capitalized on the existing infrastructure of the Healthy Mom Zone Study and conducted secondary data analyses using a sample of PW-OW/OB (N = 27; mean age = 30.6 years; mean body mass index [BMI] = 32.0 kg/m^2) randomized to an intervention (Healthy Mom Zone) or usual care control group from ~8 to 36 weeks gestation. The dissertation studies aimed to understand: (1) correspondence between objective (mobile metabolism device) and estimated (equation) measures of REE to understand agreement between these methods and utilize REE assessments with both methods to better examine variability in REE and its influence on GWG, (2) the extent to which REE predicted second trimester GWG after considering the contributions of energy intake and physical activity, and (3)

weekly point estimates of REE and its time-varying association with weekly GWG in relation to energy intake and physical activity patterns during the second trimester.

There are three major findings that emerged from this research. First, objective (mobile metabolism device) and estimated (valid equation) measures of REE were positively associated from 8 to 36 weeks gestation. However, proportional bias was detected at gestational weeks 11, 23, 32, 33, and 35, suggesting that the difference between the mobile metabolism device and the equation to estimate REE varied by study assignment (i.e., randomized to intervention vs. control groups) and participant characteristics: pre-pregnancy BMI (overweight vs. obese), fat-free mass (low vs. high), and energy intake (meeting vs. exceeding guidelines). Second, low REE was associated with and predicted high GWG during the second trimester. More specifically, while 52% of the variance in second trimester GWG was explained by the contributions of energy intake, physical activity, and REE, low REE was the strongest determinant of GWG, followed by high energy intake (physical activity was not a significant determinant). Third, although REE increased on average from 14 to 28 weeks gestation, there were specific weekly point estimates that showed decreases (i.e., 17, 20, 21, 23, 26, and 28) and illustrated that REE fluctuated over the second pregnancy trimester. Also, there was a significant time-varying association between REE and weekly GWG such that low REE was associated with high weekly GWG but only during weeks when REE fluctuated (i.e., gestational weeks 25 to 28). Interestingly, during weeks 25 to 28, the majority of PW-OW/OB were categorized as exceeding energy intake recommendations and low active. These findings highlight that women may overestimate their energy intake and underestimate their physical activity needs during this critical period when REE is fluctuating, which in turn, may increase the risk for high second trimester GWG. Collectively, these dissertation studies are among the first to document the association between REE and GWG and illustrate the potential utility of REE within intervention designs to personalize energy intake and physical activity goals to effectively regulate GWG in PW-OW/OB.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

First and foremost, I would like to thank God for all the opportunities He has blessed me with. I would not be where I am today without His love and grace.

I am extremely grateful for my mentor and dissertation advisor, Dr. Danielle Symons Downs. Thank you for your unwavering support, patience, confidence, and guidance in making me the researcher I have always strived to be. In my time here, you have been an amazing role model and have always encouraged me and taught me to be confident in myself and to never forget why I worked so hard to get here today. You have greatly contributed to my professional and personal development and have been a huge influence on this dissertation and my time here at Penn State as a whole. For that I am forever thankful.

I would also like to thank my committee members, Dr. Joshua M. Smyth, Dr. Michael Blair Evans, and Dr. Zita Oravecz for their support. Your feedback and constant mentorship have helped make all of this work possible. Thank you to Abigail M. Pauley for all the work you have done in the Exercise Psychology Lab to help make this dissertation possible, for always being there for me, and for your friendship. I could not have asked for anyone better to walk through this process with.

Finally, a huge thank you to my family and friends for their unconditional support and love in all that I do. Omma, Nicole, Irving, Emmanuel, and Pastor Hanna, thank you for your constant love and prayers. Thank you for always pushing me to be the best that I can be and for always encouraging me to stay true to myself. You have always taught me to put God first, be strong, confident, and compassionate and to always work hard to earn my achievements. You are all the reason I continuously work hard and stay motivated and determined in my endeavors. I am blessed beyond measure and proud to have people like you in my life. Without you, I would not have been able to pursue my passions and would not be the person I am today. I love you all.

This material is based upon work supported by the National Heart, Lung, and Blood Institute (NHLBI) of the National Institutes of Health (NIH) through grant R01HL119245-01 (PI Downs) and the National Center for Advancing Translational Sciences (NCATS), NIH through grant UL1 TR000127 and TR002014. Support for this work was also provided by the United State Department of Agriculture National Institute of Food and Agriculture (#2011-67001-30117, A2121 Childhood Obesity Prevention Training Program of The Pennsylvania State University). The findings and conclusions from this dissertation do not necessarily reflect the views of any of the listed funding agencies.

Chapter 1

General Overview

Consistent with the obesity epidemic in the United States (U.S.), more than 60% of women enter pregnancy with overweight (body mass index [BMI] = 25-29.9 kg/m^2) or obesity (BMI $\geq$ 30 kg/m^2), elevating their risk for excessive gestational weight gain (GWG; Chen, Xu, & Yan, 2018; Deputy, Sharma, Kim, & Hinkle, 2015; Institute of Medicine [IOM], 2009). Excessive GWG is defined as weight in excess of the Institute of Medicine (IOM, 2009) guidelines for pre-pregnancy BMI (i.e., normal weight: >35 pounds total or >1 pound/week, overweight: >25 pounds total or >0.7 pounds/week, obese: >20 pounds total or >0.6 pounds/week). Pregnant women with overweight or obesity (PW-OW/OB) are at unique risk for exceeding guidelines because they underestimate their BMI, overestimate recommended GWG, and report having low self-efficacy, high food cravings, easy access to unhealthy foods, high sugar intake, low fruit/vegetable intake, and low physical activity (Daly et al., 2016; de Jersey, Nicholson, Callaway, & Daniels, 2013; Jeffs, Haszard, Sharp, Gullam, & Paterson, 2016; Nagourney et al., 2019; Symons Downs, Savage, & Rauff, 2014). High pre-pregnancy BMI and excessive GWG are strong, independent predictors of negative maternal outcomes (e.g., hypertension, preeclampsia, gestational diabetes, postpartum weight retention, long-term obesity). Similarly, high pregnancy BMI and excessive GWG are predictors of negative child health outcomes (e.g., high birth weight, macrosomia, neonatal mortality; Bianchi et al., 2018; Chen & Chauhan, 2019; Haugen et al., 2014; Mamun et al., 2010; Ren et al., 2018; Siega-Riz et al., 2010). Even more concerning is that mothers with overweight or obesity tend to have children with overweight or obesity, which is often called the “intergenerational cycle of obesity,” setting the stage for life-long health issues and early all-cause mortality (Dutton, Borengasser, Gaudet, Barbour, & Keely, 2018; IOM, 2009). Thus, there is a crucial need to identify modifiable factors of GWG, particularly in PW-OW/OB to reduce negative health risks.

Resting energy expenditure (REE), or the number of calories burned at rest (Taousani et al., 2017), is often used in non-pregnant individuals to create energy intake and physical activity goals to manage weight (McClave and Snider, 1992). This is due to the fact that REE accounts for 60-70% of total energy expenditure compared with the approximate 20% that is attributed to physical activity (Berggren et al., 2017; Taousani et al., 2017; Vander Wyst et al., 2020). Yet, little attention has been given to REE as a modifiable determinant of GWG. Thus, there is a need for research to understand the extent to which REE should be incorporated within GWG regulation interventions to effectively regulate GWG, especially in PW-OW/OB. Therefore, the overarching objective of this dissertation was to examine REE in relation to energy intake, physical activity, and GWG in PW-OW/OB in an effort to understand the extent to which REE can be used in future interventions to inform energy intake and physical activity goals as a strategy for effective GWG regulation and improve maternal and infant well-being (Figure 1.1).

GWG is largely influenced by the components of energy balance: energy intake and energy expenditure (physical activity, REE; McDowell et al., 2019). As such, Thomas and colleagues (2012) developed a dynamical model of energy balance based on the first law of thermodynamics and evidence from Butte and colleagues (2003; 2004) to predict GWG. The energy balance formula is:

$$ES(t) = EI(t) - TEE(t)$$

Net energy stored at time *t* is denoted as ES(t) while EI(t) and TEE(t) represent energy intake (EI) and total energy expenditure (TEE), respectively. TEE includes three separate subcomponents:

$$TEE(t) = PA(t) + TEF(t) + REE\ (t)$$

TEE is represented as the sum of physical activity (PA), thermic effect of food (TEF), and REE. In short, in non-pregnant individuals, energy intake higher than total energy expenditure leads to weight gain whereas energy intake lower than total energy expenditure leads to weight loss (energy intake equal to total energy expenditure = weight maintenance). However, it is important to note that body fat accumulates during pregnancy, and pregnant women will gain weight due to the growing baby and maternal physiological changes (e.g., placenta, increased blood volume, amniotic fluid) of pregnancy itself (Butte et al., 2003). Thus, effective GWG regulation is a result of net energy stored (i.e., energy intake – total energy expenditure), fetal growth (i.e., fetal body mass, birthweight-for-gestational-age), and the presumed weight gain due to maternal physiological changes (e.g., placenta, increased blood volume, amniotic fluid).

Studies aiming to regulate GWG have primarily focused on the combined effects of energy intake and physical activity behaviors. The literature has consistently shown that behavioral randomized controlled trials (RCTs) focusing on energy intake and physical activity can regulate GWG among women with normal weight (e.g., Hui et al., 2014; Phelan, Phipps, Abrams, Darroch, Schaffner, & Wing, 2011). Unfortunately, most of the RCTs focusing on moderating energy intake and improving physical activity to regulate GWG in PW-OW/OB have shown either no effect (Bruno et al., 2017; Dodd, Grivell, Crowther, & Robinson, 2010; Dodd et al., 2014; Guelinckx, Devlieger, Mullie, & Vansant, 2010; Hawkins et al., 2015; Szmeja et al., 2014) or a modest effect (e.g., Phelan et al., 2011; Redman et al., 2017) on GWG. One reason for these limited effects may be due to the fact that the majority of the existing GWG regulation interventions in PW-OW/OB have adopted a "one-size fits all" or packaged approach in which all PW-OW/OB received the same intensity of intervention over the course of an intervention period. Given the unique challenges PW-OW/OB face with GWG regulation (e.g., underestimate BMI, low self-efficacy, low physical activity, high energy intake), some researchers have speculated the need for a more tailored or adaptive approach to better understand PW-OW/OB as individuals and their needs for effective GWG regulation.

In an attempt to move away from the "one-size fits all" approach, Symons Downs and colleagues (under review; 2018; Dong et al., 2012; Dong et al., 2013; Dong et al., 2014; Pauley et al., 2018) developed Healthy Mom Zone, a feasibility study of an adaptive intervention to manage GWG in PW-OW/OB. Healthy Mom Zone was based on a theoretically-driven, mathematical, behavioral model of energy balance that was conceptualized based on the initial work of Thomas et al. (2012). It includes: (1) two dynamical models of the Theory of Planned Behavior (TPB; Ajzen, 1991) for energy intake and expenditure, (2) two dynamical models of Self-Regulation Theory for energy intake and expenditure (Carver & Scheier, 1998), and (3) an intervention delivery module that relates the magnitude and duration of intervention components to the inflows of the TPB models (Figure 1.2). The inclusion of dynamical and mathematical modeling allows for researchers to understand *how* an intervention may influence an outcome and also *when* to adapt an intervention dosage, which is advantageous for an adaptive intervention (Rivera, Pew, & Collins, 2007). The TPB posits that intention of performing a behavior increases when an individual has a positive *attitude* about the behavior, believes that significant others want him/her to perform the behavior (subjective norm), and has the perceived ability to be able to perform the behavior (perceived behavioral control; Ajzen, 1991). Self-regulation theory posits that behavior is a continual goal-directed process that occurs through feedback control processes (Carver & Scheier, 1998). Self-monitoring and goal-setting are key aspects of this feedback control process given that information from the consequence of a certain behavior (i.e., healthy eating, physical activity) is used to inform whether an individual chooses to continue, change, or end their behavior (Carver & Scheier, 1998). Within the conceptual framework of the Healthy Mom Zone, energy balance (i.e., energy intake and physical activity) is informed by the TPB motivational determinants (i.e., attitude, subjective norm, perceived behavioral control) whereas Self-Regulation Theory is used to understand how success expectancies and confidence of healthy eating and physical activity influences the perceived ability to perform a given behavior (Dong et al., 2012; Dong et al., 2013; Symons Downs et al., 2018). In Healthy Mom Zone, the TPB motivational determinants and self-regulation of healthy eating and physical activity behaviors were influenced by intervention components such as education, goal-setting, self-monitoring, and healthy eating/physical activity active learning activities (i.e., cooking demonstrations, grocery store guidance, physical activity sessions led by a fitness instructor) to improve healthy eating and physical activity behaviors, and in turn, regulate GWG within the IOM (2009) guidelines. In short, the premise of the Healthy Mom Zone intervention was to continually evaluate GWG and adapt the intervention dosage to the needs of each PW-OW/OB randomized to the intervention. Each intervention woman's GWG was monitored weekly and compared to her IOM weekly GWG goal (i.e., OW: <0.7 pounds/week, OB: <0.6 pounds/week). Every 3-4 weeks, if a woman exceeded her weekly GWG recommendations, she was "stepped-up" to receive a higher intensity dosage of the intervention (e.g., physical activity sessions, cooking demonstrations). Otherwise, if the woman gained below or within the weekly GWG recommendations, she maintained her current intervention dosage. Women randomized to the control group received standard prenatal care. Preliminary findings from PW-OW/OB (N = 31; intervention = 16, control = 15) showed that the intervention group had 4.1 pounds lower GWG compared to the controls. Although these findings were not statistically significant, the 20% difference in GWG between the groups was clinically meaningful. More specifically, the researchers found that weekly GWG in controls (*mean* = 1.05 lbs/week) was higher than the weekly GWG in intervention women (*mean* = 0.77 lbs/week; Symons Downs et al., 2019a; Symons Downs et al., 2019b; Symons Downs et al., under review). Also, the intervention women had a significantly smaller increase (*mean* = 410 kcals) in energy intake from pre- to post-intervention compared to controls (*mean* = 1135 kcals, p = 0.02). Finally, intervention women increased in physical activity (activity kcals) from pre-post intervention (*mean* = 34.91) whereas controls decreased (*mean* = -78.93), although this difference was not statistically significant ($p > 0.05$; Symons Downs et al., 2019a; Symons Downs et al., 2019b; Symons Downs et al., under review).

While Symons Downs and colleagues (2019a; 2019b; under review) found a statistically slower increase in energy intake and a non-significant increase in physical activity among intervention women compared to controls, the majority of existing RCTs continue to struggle with promoting physical activity and moderating energy intake in PW-OW/OB. PW-OW/OB have reported that if they do not moderate their energy intake or engage in physical activity at the start of pregnancy, then it will be difficult to break the habit of consuming excessive calories and inactivity throughout pregnancy regardless of behavioral intervention (Flannery et al., 2018). In addition, many studies including energy intake moderation and physical activity promotion have focused on recommending a specific calorie goal for energy intake (e.g., 2600 kcal/day; ACOG, 2016; Gilmore et al., 2016) or a goal of achieving the national recommendations of 150-minutes of moderate to vigorous physical activity per week (American College of Obstetrics and Gynecology [ACOG], 2015; United States Department of Health and Human Services [USDHHS], 2018). However, given the unique challenges PW-OW/OB face with underreporting energy intake and overestimating their energy requirements as well as engaging in sufficient physical activity (Moran et al., 2018; Mullaney et al., 2014; Nagourney et al., 2019; Nowicki et al., 2011; Symons Downs, Savage, & Rauff, 2014), meeting these energy intake and physical activity goals may seem too difficult to achieve, and thus, they struggle to regulate GWG with these behaviors. While moderating energy intake and promoting physical activity remain important targets of intervention, there is a need to identify useful ways to promote these behaviors and/or find other "achievable" targets to effectively regulate GWG in PW-OW/OB.

In the weight management literature among non-pregnant populations, traditionally REE is used to understand energy requirements and to develop nutritional regimens fit for each individual (McClave and Snider, 1992). Further, given that past research has shown that engaging in physical activity can increase REE, weight management programs often use REE to create activity goals (Gilliat-Wimberly et al., 2001; Taousani et al., 2017). For example, if REE is low, clinicians may recommend individuals to create a higher physical activity goal and/or engage in a certain type of physical activity to increase REE and thus, total energy expenditure. Put together, individuals can use this total energy expenditure to adjust their energy intake to induce weight loss, weight gain, or weight maintenance. However, no located interventions have been found that use this approach among pregnant women to regulate GWG. One reason for this may be due to the scant research examining the influence of prenatal REE on GWG. Recent observational evidence shows that low prenatal REE is associated with high GWG (Berggren et al., 2017). Specifically, Berggren and colleagues (2017) found that low REE at 34-36 weeks gestation was significantly associated with high total GWG. However, this was based on a one-time assessment of REE, limiting the full understanding of prenatal REE and its influence on GWG. Further, no published studies have been found that examine the collective influences of physical activity, energy intake, and

REE on explaining GWG in PW-OW/OB. Moreover, no studies have examined the extent to which REE provides any additional contribution or explanation of GWG beyond energy intake and physical activity given its large contribution to total energy expenditure, and whether the influence of REE on GWG changes over the course of pregnancy. Examining the extent to which energy intake, physical activity, and REE explain GWG among PW-OW/OB may provide useful insight regarding how to better promote behavioral strategies (e.g., moderating energy intake, promoting physical activity) to effectively regulate GWG. The following sections will outline the known associations between energy intake and GWG and physical activity and GWG followed by an explanation of the proposed association between REE and GWG.

Prenatal Energy Intake

Proper nutrition is essential for pregnant women to meet the extra energy demands from both their own body and of their growing baby (ACOG, 2016). Further, engaging in healthy eating behaviors can reduce the risk of excessive GWG, gestational diabetes, hypertensive disorders, preterm birth while regulating fetal growth and infant body composition, and improving maternal mental health (Chen et al., 2016; Crume et al., 2016; Baskin, Hill, Jacka, O'Neil, & Skouteris, 2015; Suliga et al., 2018). Prenatal energy intake guidelines differ based on individual characteristics (e.g., weight, age, rate at which a woman gains weight) and behaviors (e.g., physical activity, appetite). Several guidelines recommend that no additional calories are needed in the first trimester, and 340 calories/day can be added to calorie goals in the second trimester and about 450 calories/day to calorie goals in the third trimester (ACOG, 2016; IOM, 2009 Kaiser, Campbell, & Academy Positions Committee Workgroup, 2014; Kominiarek & Rajan, 2016). For example, a woman with normal weight achieving less than 30 minutes of exercise/day would be advised to consume about 2,000 calories/day during the first trimester, 2,340 calories/day in the second trimester, and 2,450 calories/day in the third trimester (ACOG, 2016). In addition, women are encouraged to maintain healthy intake of grains, fruits/vegetables, dairy, protein, carbohydrates, and fats/oils while limiting "empty" calorie foods such as sugary beverages, candy, chips, etc. (ACOG, 2016). For example, throughout each trimester, a woman with normal weight participating in less than 30 minutes of exercise/day would be advised to consume 6-8 ounces of grains, 2.5-3 cups of vegetables, 1.5-2 cups of fruits, 3 cups of dairy, 5-6.5 ounces of protein, and 5-8 teaspoons of fats/oils per day. However, these recommendations are largely based on pregnant women with normal weight. Research has shown that PW-OW/OB are most vulnerable to unhealthy nutrition and have poorer diet quality compared to women with normal weight (Dubois et al., 2018; Parker, Tovar, McCurdy, & Vadiveloo, 2019; Shin, Lee, & Song, 2016). Also, research has shown that PW-OW/OB have different energy expenditure (e.g., lower physical activity) and thus, have different energy intake needs (Daly et al., 2016; Donahue, Zimmerman, Starr, & Holt, 2010; Lindqvist et al., 2016). Thus, ACOG (2016) has recommended that PW-OW/OB may need "fewer" extra calories during pregnancy; however, "fewer" is not operationally defined. The lack of energy intake guidelines for PW-OW/OB is problematic and has led some researchers to attempt to develop recommendations specifically for PW-OW/OB (Most et al., 2019). Unfortunately, most of the researchers have overestimated the energy requirements for this special population often attributed to overestimating their true total energy expenditure. Thus, it is essential that PW-OW/OB have an appropriate estimate of their total energy expenditure (i.e., physical activity, REE). If women obtain an appropriate estimate of their total energy expenditure, they can then create personal energy intake goals in order to manage GWG. Nevertheless, there is still a lack of research appropriately identifying energy requirements in PW-OW/OB. Despite the differences in energy intake needs between women with normal weight and PW-OW/OB, it is important for all women to find the balance between eating enough of the necessary nutrients for a healthy pregnancy and a healthy weight, while at the same time, avoiding over-eating for excessive GWG. Unfortunately, most pregnant women struggle to moderate energy intake and eat a healthy, well-balanced diet (Moran et al., 2013; Talai Rad et al., 2011; Wennberg et al., 2016). Pregnant women have reported that although they want to change their eating habits, they commonly report barriers to eating healthy such as unmanageable cravings, easy access to unhealthy food, low self-efficacy, and low emotional and informational support (Nagourney et al., 2019; Nichols, Galesloot, Bondarianzadeh, & Buhler, 2019).

Moderating energy intake during pregnancy is protective against excessive GWG whereas high energy intake is associated with excessive GWG (Ancira-Morena et al., 2019; Dubois et al., 2018; Thomas et al., 2012). Gilmore and colleagues (2016) found that after controlling for weight status, women who gained above IOM guidelines had an average intake of 3,437 kcals/day whereas women who gained below or within the guidelines had an average of 2,687 kcals/day. The average energy intake/day was significantly different between the two groups of women and illustrated that women who gained above the IOM guidelines consumed 750 kcal/day higher than women who gained below or within the guidelines. In contrast, all women declined in physical activity and expended the same amount of active kcals/day suggesting that exceeding GWG guidelines may not be a result of reduced physical activity. Therefore, the investigators suggested that the result of high GWG was due to high energy intake rather than low physical activity. Unfortunately, a goal of restricting or lowering energy intake in PW-OW/OB does not consistently result in lower GWG. For example, Bruno and colleagues (2017) randomized PW-OW/OB to a lifestyle program ($N = 69$) or a control ($N = 62$) from ~9 to 36 weeks gestation to prevent high GWG and gestational diabetes. PW-OW/OB randomized to the lifestyle program received an energy intake goal of 1,500 kcals/day whereas women in the control group did not receive this goal. While the intervention women were able to improve their eating habits (i.e., high fruit/vegetable servings, low sugar servings), there were no significant differences in GWG between the intervention and control women. Some researchers have speculated that one reason why goals of moderating energy intake may not be successful for GWG regulation in PW-OW/OB may have to do with the fact that researchers are applying energy intake goals that are more appropriate for women with normal weight (i.e., 1,500 kcals/day). Another reason may be due to the difficulties of self-reported energy intake. For example, self-reported energy intake is associated with methodological issues such as recall bias, social desirability, misunderstanding of how to define and measure serving sizes, and underreporting (Moran et al., 2018;

Mullaney et al., 2014; Nowicki et al., 2011; Roark & Niederhauser, 2012). Research has shown that people may categorize fruits and vegetables differently and may not understand what constitutes a serving size (Roark & Niederhauser, 2012). In addition, the rates of under reporting energy intake during pregnancy are high in PW-OW/OB (Moran et al., 2018; Mullaney et al., 2015; Nowicki et al., 2011). Underreporting energy intake underestimates the true amount of energy intake, which can incorrectly predict GWG and thus misinform GWG regulation strategies. Symons Downs et al. (2019b) reported that in the Healthy Mom Zone Study with PW-OW/OB, 38% of the intervention group and 41% of the controls underreported energy intake. Thus, researchers (Symons Downs et al., 2018; 2019; Guo et al., 2016; Guo et al., 2018a; Guo et al., 2018b) have advocated using a back-calculation method to estimate daily energy intake as a function of maternal weight, physical activity, and REE:

$$EI_{est}(k) = \frac{-W(k+2T) + 8W(k+T) - 8W(k-T) + W(k-2T)}{12TK_1} - \frac{K_2}{K_1}\big(PA(k) + REE(k)\big)$$

The variables are as follows: k = 1, 2, …, *N* corresponding to day 1-day *N*. W represents maternal weight in kg while T represents sampling time which in this case was T = 1 day. PA represents physical activity in kcals. REE represents resting energy expenditure in kcals. The use of a back-calculation method to estimate daily energy intake in PW-OW/OB may help future researchers better understand energy intake behaviors in this special population in order to moderate energy intake and thus, inform strategies to better regulate GWG.

Prenatal Physical Activity

In the absence of obstetric contraindications or medical complications (e.g., preeclampsia, multiple gestation at risk of premature labor, ruptured membranes, severe anemia, incompetent cervix, etc.) women are encouraged to be physically active throughout pregnancy (ACOG, 2015; USDHHS, 2018). Healthy pregnant women, regardless of weight status, are recommended to engage in at least 150-minutes of moderate to vigorous intensity (i.e., walking, swimming, stationary cycling, jogging, strength training, etc.) physical activity per week (ACOG, 2015; USDHHS, 2018). Women who are active prior to pregnancy are encouraged to maintain their activity level throughout pregnancy while women who are inactive prior to pregnancy are recommended to start out slowly and gradually increase activity to reach the recommended guidelines (ACOG, 2015). There is ample evidence showing the benefits of prenatal physical activity including reducing risks of excessive GWG, gestational diabetes, preeclampsia, hypertension, pre- and postnatal anxiety/depression, and postpartum weight retention (ACOG, 2015; Aguilar-Cordero et al., 2019; Dipietro et al., 2019; Harrison, Brown, Hayman, Moran, & Redman, 2016; Symons Downs, Chasan-Taber, Evenson, Leiferman, & Yeo, 2012; USDHHS, 2018; Watson et al., 2018).

Despite the recommendations to stay active for GWG regulation, most studies have shown that pregnant women are less active than they were prior to pregnancy (Borodulin et al., 2009; Borodulin et al., 2008; Da Costa & Ireland, 2013; Engberg et al., 2012; Merkx et al., 2017; Most, Dervis, Harman, Adamo, & Redman, 2019; Symons Downs & Hausenblas, 2004). Women generally report their physical activity (i.e., both duration and volume) declines during pregnancy (Borodulin et al., 2008; Borodulin et al., 2009; Engberg et al., 2012; Renault et al., 2010). Specifically, most women show an inverted-u shape in which level of physical activity is higher at mid-gestation than earlier and later gestation, although levels are still lower than pre-conception (Borodulin et al., 2009; Borodulin et al., 2008; Da Costa & Ireland, 2013; Engberg et al., 2012; Merkx et al., 2017; Renault et al., 2010; Symons Downs & Hausenblas, 2004). Researchers have also found that women who were active before pregnancy show a greater decline in physical activity during pregnancy than women who were inactive prior to pregnancy (Merkx et al., 2017). In addition, high pre-pregnancy BMI is a predictor of prenatal physical activity such that PW-OW/OB report lower physical activity levels compared to women with normal weight (Daly et al., 2016; Donahue et al., 2010; Lindqvist et al., 2016). However, it is important to note that given the low levels of physical activity patterns among PW-OW/OB, it has been difficult for researchers to accurately assess whether PW-OW/OB are meeting recommended physical activity guidelines. The literature in this area is often limited by methodological challenges such as recall and social desirability bias from self-reported physical activity, differences in placement of accelerometers, and variations in protocol methods to analyze device-based data (Ainsworth et al., 2015; Mâsse et al., 2005). Nevertheless, all women have reported that low levels of prenatal physical activity may be attributed to perceived barriers such as a lack of time, pregnancy-related symptoms (e.g., nausea, vomiting, soreness, swelling), fatigue, fear for safety, lack of knowledge of safe exercises, back and pelvic pain, and lack of motivation (Connelly, Brown, van der Pligt, & Teychenne, 2015; Da Costa & Ireland, 2013; Flannery et al., 2018; Merkx et al., 2017).

Many meta-analytic reviews have examined the effect of physical activity on GWG and have consistently found that across age, parity, weight status, and ethnicity, engaging in the recommended levels of prenatal physical activity can help women to regulate GWG and reduce the risk of excessive GWG (da Silva, Ricardo, Evenson, Hallal, 2017; Du, Ouyang, Nie, Huang, & Redding, 2019; International Weight Management in Pregnancy [i-WIP] Collaborative Group, 2017; Ruchat et al., 2018; Sanabria-Martínez et al., 2015; Wang, Wen, Liu, & Liu, 2019). Specifically, women not meeting physical activity guidelines have higher GWG than women meeting physical activity guidelines (ACOG, 2015; Bisson et al., 2015; Ruchat et al., 2018). However, many GWG regulation interventions are unable to increase physical activity to the recommended guidelines and/or attenuate declines in prenatal physical activity. For example, Hawkins and colleagues (2015) randomized women to a lifestyle intervention group ($N = 33$) or to a standard of care group ($N = 33$) from ~14 to 36 weeks gestation to prevent excessive GWG and gestational diabetes. PW-OW/OB in the lifestyle intervention group were instructed to set goals to achieve the ACOG (2015) guidelines of 150 minutes of moderate physical activity per week whereas the women in the standard of care control group did not receive this instruction. While the mean level of physical activity was not reported, the investigators found that the intervention was not able to significantly attenuate the decrease in physical activity, and that there was no significant difference in GWG between the intervention and the control groups. It may be that a goal of reaching the physical activity recommendations (i.e., >150 minutes/week) throughout the entire pregnancy is simply "unachievable" for many women (especially PW-OW/OB) given the increasing weight and strain on their bodies as they progress toward delivery.

Prenatal Resting Energy Expenditure

REE is influenced by several factors including body composition, physical activity, nutrition, hormones, age, and race/ethnicity. Fat free mass is the largest determinant of REE with higher fat free mass associated with higher REE (Butte et al., 2004; Butte, 2005; Catalano, 1999; Gilliat-Wimberly et al., 2001; Stiegler & Cunliffe et al., 2006; Taousani et al., 2017). Also, researchers have found that engaging in healthy eating and physical activity behaviors can increase fat free mass and thus, increase REE (Careau, 2017; Gilliat-Wimberly et al., 2001; Hronek et al., 2013; Taousani et al., 2017; Yoo, 2018). Researchers have traditionally worked under the assumption that prenatal REE is non-fluctuating with a linear increase in response to the average increase in prenatal weight. More specifically, the existing literature has shown that REE increases on average from pre-pregnancy to late third trimester (Butte et al., 2003; Butte et al., 2004; Butte, 2005; Byrne et al. 2011; Catalano et al., 1999; Damjanovic et al., 2009; Forsum & Löf, 2007; Löf et al., 2005; Most et al., 2019; Taousani et al., 2017). The greatest increase in REE generally occurs during the second trimester – corresponding with the rapid increase in fetal growth that occurs during this time in addition to maternal changes in hormones, fat free mass, body weight, and increased cardiac output (Butte et al., 2004; Forsum & Löf, 2007; Löf et al., 2005; Most et al., 2019). This increase in REE is particularly apparent in PW-OW/OB, who gain the majority of their weight during the second trimester (Overcash, Hull, Moore, & LaCoursiere, 2015). However, more recent research has shown evidence that prenatal REE may not increase in a linear fashion and that there is wide variability in change in prenatal REE with some women even decreasing in REE (Berggren et al., 2017; Jackemeyer et al., 2017; Vander Wyst et al., 2020).

However, these studies based their conclusions of variation in prenatal REE on “pre-post” study assessments, which limits the ability to truly understand variation in prenatal REE. Due to the traditional assumption that REE is non-fluctuating during pregnancy and increases in a linear trajectory, researchers have often limited prenatal assessments of REE to once during each trimester or one pre (or early) pregnancy and another post (or late) pregnancy (Butte et al., 2004; Byrne et al. 2011; Damjanovic et al., 2009; Lof et al., 2005; Melzer et al., 2010) using indirect calorimetry under standardized conditions (gold standard). The lack of frequent assessments may limit the ability to understand how REE fluctuates (e.g., week to week) across pregnancy. To obtain more frequent assessments of REE, some studies utilize a predictive equation to estimate the linear increase in REE (Frankenfield, Roth-Yousey, & Compher, 2005; Shaneshin, Rezazadeh, Jessri, Neyestani, & Rashidkhani, 2011). For example, Symons Downs and colleagues (under review; 2018; 2019a; 2019b) used a validated equation to estimate REE within the context of the Healthy Mom Zone. The equation was proposed by Thomas et al. (2012) and fit using quadratic regression on data in pregnant women from Butte and colleagues (2004) as a function of maternal weight:

$$REE = 0.1976W^2 - 13.424W + 1457.6$$

This estimated equation allows for repeated and frequent assessments of REE in PW-OW/OB because it requires only maternal weight estimates, which can be feasibly obtained (e.g., Wi-Fi weight scales). However, it does not account for other individual factors that have been shown to influence REE such as energy intake, physical activity, fat mass vs. fat-free mass, and demographic factors (e.g., age, race; Gilliat-Wimberly et al., 2001; Lof et al., 2005; Taousani et al., 2017). Therefore, some researchers have suggested that REE equations may not be appropriate for predicting individual values and variation in REE (Frankenfield et al., 2005; Shaneshin et al., 2011). Recent advancements in technology have allowed researchers (e.g., Symons Downs et al., under review; 2018; 2019a; 2019b) to expand their assessment of REE. Symons Downs and colleagues (under review; 2018; 2019a; 2019b) utilized an indirect calorimetry mobile device (Breezing™), within the Healthy Mom Zone study to examine the extent to which there was variability in prenatal REE among PW-OW/OB. PW-OW/OB were instructed to collect weekly point estimates of REE via Breezing™ by breathing into the handheld indirect calorimetry device. Before breathing into the device, women were asked to input certain personal characteristics that may influence their measurement such as age, physical activity level, and race/ethnicity. The algorithm within the

Breezing™ device calculated REE according to the Weir equation, a well-known equation used with indirect calorimetry (Weir, 1949; Xian et al., 2015):

$$[3.9 * VO_2 + 1.1*VCO_2]* 1.44$$

VO_2 represents the volume of oxygen consumed and VCO_2 represents the volume of carbon dioxide produced.

The Healthy Mom Zone study (Symons Downs et al., under review; 2018; 2019a; 2019b) provided a novel opportunity to compare objectively measured REE via Breezing™ and estimated REE from the pregnancy-based equation described above (Thomas et al., 2012) because both were obtained frequently over the course of pregnancy in PW-OW/OB. Breezing™ was initially validated by Xian and colleagues (2015) in non-pregnant adults and resulted in a significant correlation coefficient ($R^2 = 0.998$) to the Douglas Bag, which is a gold standard, laboratory-based indirect calorimetry method. In contrast to estimated equations such as the pregnancy specific one used by Thomas and colleagues (2012) and other non-pregnancy specific equations (Jackemeyer et al., 2017), Breezing™ may account for individual characteristics (e.g., age, race/ethnicity, physical activity) associated with REE variability. Jackemeyer and colleagues (2017) found that REE values measured by the Breezing™ device were not consistent with REE estimated from equations. However, the equation was not pregnancy-specific, and the study only included four pregnant women. No located studies have examined the agreement between Breezing™ and a pregnancy-based estimated REE equation in PW-OW/OB. Identifying the agreement between Breezing™ and the pregnancy-based estimated equation (Thomas et al., 2012) can inform whether these methods can be used interchangeably. One advantage of being able to substitute measures from either method can allow researchers to increase the frequency of REE assessments in PW-OW/OB. Increasing frequency of REE assessments will allow researchers to better understand prenatal REE in this special population in an effort to provide insight about variation in prenatal REE and its influence on GWG.

Understanding variation prenatal REE is important because there has been some evidence suggesting that low prenatal REE and/or fluctuations in REE may be a warning sign for excessive GWG

(Berggren et al., 2017; Damjanovic et al., 2009; Lof et al., 2005; Marginean et al., 2016; Meng et al., 2018; Taousani et al., 2017; Vander Wyst et al., 2020). However, no located studies have examined the time-varying associations between REE and GWG particularly at the weekly level. Given that researchers have found that both REE and GWG vary over time, it is necessary to further understand their association in more detail and the extent to which it changes over time. Further, PW-OW/OB are only recommended to gain <0.07 (OW) or <0.06 (OB) pounds per week during the second and third trimesters in order to stay within the recommended guidelines for total GWG. Unfortunately, most PW-OW (88%) and PW-OB (80%) exceed these weekly guidelines by almost double (Jarman et al., 2016; Santos et al., 2018). Researchers have stated that although the rapid rates of weekly GWG are well documented, the reasons that contribute to these rates are not fully understood. Nevertheless, the rates of exceeding weekly GWG guidelines in PW-OW/OB illustrate the difficulty these women have adhering to the little weight gain allowed each week, and thus, total GWG. Research is needed to understand whether the associations between weekly REE and weekly GWG change over time to understand whether REE should be incorporated as a target for GWG regulation interventions. For example, similar to the weight management literature in non-pregnant individuals (McClave and Snider, 1992), weekly estimates of prenatal REE can inform women of their weekly individualized energy intake and physical activity goals in order to stay within the weekly GWG guidelines to regulate total GWG. Specifically, REE can be used to create an activity kcal goal for the day to increase their total energy expenditure. Once a full picture of their total energy expenditure goal is obtained, women can create personal energy intake goals and adapt their energy intake to manage GWG. However, little is known about how this approach of using REE to inform individualized energy intake and physical activity goals can be incorporated within the context of an intervention to regulate GWG in PW-OW/OB.

Moreover, no studies have examined the time-varying associations between REE and GWG during critical periods of gestation that may influence GWG. For example, the second trimester is often marked by a rapid increase in GWG that is attributed to a nearly 50% increase in blood volume and amniotic fluid to accommodate the growing fetus (IOM, 2009). However, little is known about how these rapid physiological changes are related to REE because this second trimester is often overlooked within "pre-post" study designs. That is, because the pattern of GWG in a typical pregnancy is often described as sigmoidal where mean weight gain is higher in the second trimester than the first and third trimesters, pre-post assessments do not account for this variation (IOM, 2009). However, the IOM guidelines note that this sigmoidal pattern of GWG may not be apparent in PW-OB, as they tend to increase in weight in the second trimester and then sustain a linear increase through delivery. Nevertheless, the second trimester is characterized by a rapid increase in GWG in PW-OW/OB that predicts high overall GWG (Overcash et al., 2015). Examination of the time-varying association between prenatal REE and GWG in PW-OW/OB during critical time periods of rapid growth such as the second trimester is needed to identify whether and how interventions should be personalized or customized in an effort to understand the extent to which future GWG regulation interventions can use REE to inform energy intake and physical activity goals as a strategy to effectively regulate GWG in PW-OW/OB.

Summary and Introduction of Dissertation Chapters

There is sufficient evidence from the literature to support that prenatal energy intake and physical activity are associated with GWG. In contrast, the association between REE and GWG is less established but suggests that REE may be a potential useful strategy by informing energy intake and physical activity goals to regulate GWG among PW-OW/OB. Thus, research is needed to understand how to obtain more frequent assessments of REE, the contribution of REE on GWG beyond the influences of energy intake and physical activity, the pattern of change in prenatal REE, and whether the association between REE and GWG changes over time in PW-OW/OB. The overarching objective of this dissertation was to examine REE in relation to energy intake, physical activity, and GWG in PW-OW/OB in an effort to understand the extent to which REE can be used in future interventions to inform energy intake and physical activity goals as a strategy for effective GWG regulation and improve maternal and infant well-being. Outcomes from this dissertation may be used to inform future prenatal interventions to effectively regulate GWG in PW-OW/OB. This dissertation includes three studies that are presented in Chapters 2, 3, and 4. The proposed scope of work for the dissertation is as follows:

Chapter 2: Correspondence Between a Mobile Metabolism Device and a Validated Equation to Estimate Resting Energy Expenditure in Pregnant Women with Overweight/Obesity

- Research Question: What is the correspondence in weekly point estimates of REE measured objectively with a mobile metabolism device (Breezing™) compared with a validated equation to estimate REE?
- Aim 1: To examine the correspondence between Breezing™ and a pregnancy-derived estimated equation (Thomas et al., 2012) to assess REE from ~8-36 weeks gestation in PW-OW/OB.
    - Hypothesis: Based on past research (Jackemeyer et al., 2017; Xian et al., 2015), it was hypothesized that Breezing™ REE would be positively associated with estimated REE.
- Aim 2: To explore the extent to which there is proportional bias (i.e., extent to which one measure gives values that are higher or lower than another) between the two methods.
    - Hypothesis: Due to limited data, no a priori hypotheses were made about when (i.e., gestational week) there would be low agreement.
- Aim 3: To describe the extent to which Breezing™ and estimated REE differed from each other based on study (e.g., randomized to intervention vs. control groups) and participant (e.g., pre-pregnancy BMI, age, fat-free mass, physical activity, energy intake, GWG) characteristics.
    - Hypothesis: Given the estimated equation for REE does not take into account personal characteristics, it was hypothesized that these characteristics would be related to the correspondence between Breezing™ and estimated REE. However, due to the scant research, no a priori hypotheses were made about whether Breezing™ would produce higher or lower REE estimates compared to the equation for these characteristics.

Chapter 3: Low Resting Energy Expenditure and High Energy Intake but not Physical Activity Predicts High Second Trimester Gestational Weight Gain in Pregnant Women with Overweight/Obesity

- Research Question: How is physical activity, energy intake, and REE associated with and explain second trimester (i.e., 14 to 28 weeks gestation) GWG in PW-OW/OB.
- Aims: To examine the extent to which physical activity, energy intake, and REE were associated with and explained second trimester GWG among PW-OW/OB.
    - Hypothesis: Based on past research (Berggren et al., 2017; Bisson et al., 2015; Dubois et al., 2018; McDowell et al., 2019; Ruchat et al., 2018) it was hypothesized that high energy intake, low physical activity, and low REE would be associated with and predict high GWG. Also, based on the abundant research examining energy intake and physical activity as determinants of GWG and because there are no located studies examining the contribution for REE predicting GWG, it is hypothesized that high energy intake would emerge as the strongest determinant of GWG followed by low physical activity and low REE.

Chapter 4: The Association Between Low Resting Energy Expenditure and High Gestational Weight Gain in Pregnant Women with Overweight or Obesity is Only Evident when Resting Energy Expenditure Fluctuates

- Research Questions: (1) How does prenatal REE change from 14 to 28 weeks gestation in PW-OW/OB, (2) what is the association between REE-GWG from 14 to 28 weeks gestation and does it vary over time, and (3) what does the energy intake and physical activity pattern look like during these associations?
- Aim 1: To describe patterns in mean change in REE from 14 to 28 weeks gestation and the proportion of women who increased and decreased in REE.

- Hypothesis: Based on past research (Berggren et al., 2017; Jackemeyer et al., 2017; Vander Wyst et al., 2020), it was hypothesized that REE would increase overall from 14 to 28 weeks gestation. However, it was hypothesized that not all women would increase such that 60-75% of women would increase and 25-40% would decrease. Due to the limited research, an a priori hypothesis could not be made about the magnitude of change in REE for the weekly point estimates.

- Aim 2: To examine associations between weekly point estimates of REE and weekly point estimates of GWG and the extent to which these associations changed over time from 14-28 weeks gestation.
    - Hypothesis: Based on past research (Berggren et al., 2017; Chapter 3), it was hypothesized that low REE would be associated with high weekly GWG during each week from 14-28 weeks gestation.
- Aim 3: To descriptively examine energy intake and physical activity patterns during the weeks when REE and GWG were significantly associated.
    - Hypothesis: Based on evidence from Chapter 3, it was hypothesized that during weeks when low REE was associated with high GWG, the majority of women would be categorized as exceeding energy intake recommendations and as low active.

Lastly, Chapter 5 will provide a comprehensive summary of the three studies and also provide recommendations for future research to improve and expand the literature in this area. Put together, these studies will provide the literature with a comprehensive understanding of the extent to which REE influences GWG and may be a useful target for GWG regulation by informing energy intake and physical activity goals for PW-OW/OB.

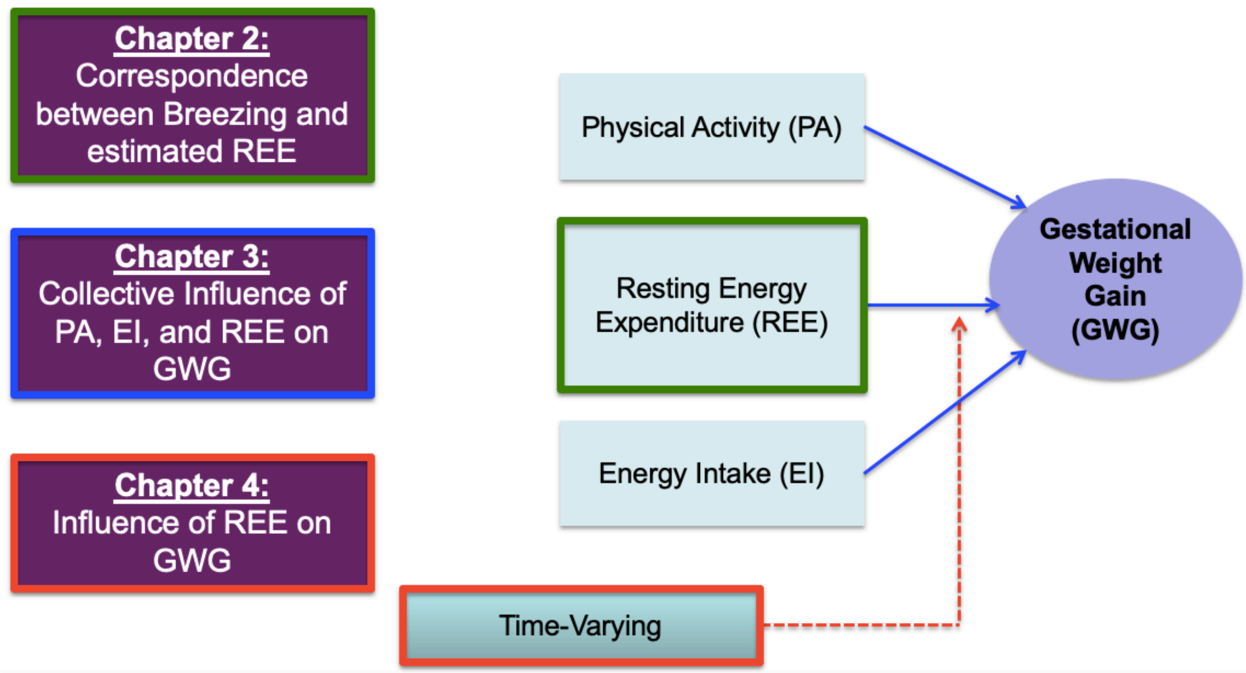


Figure 1.1. Conceptual Framework of Proposed Dissertation.

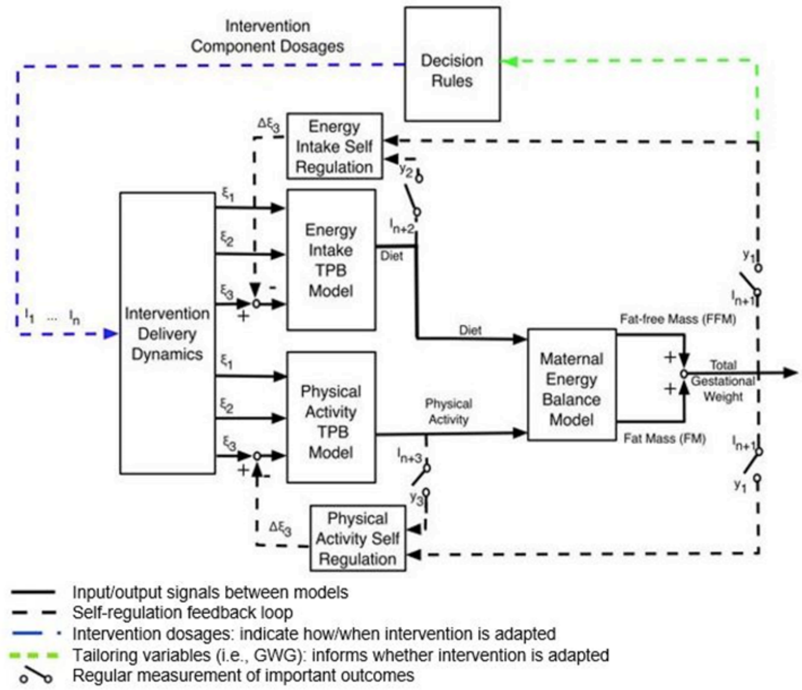


Figure 1.2. Dynamical Model of Energy Balance for the Healthy Mom Zone.
Note. TPB: Theory of Planned Behavior; $I_1 \ldots I_n$: Intervention components; i: exogenous variables that serve as inputs for behavioral models; y_i: system outputs; ξ_1: Behavioral belief × evaluation of outcome; ξ_2: Normative belief × motivation to comply; ξ_3: Control belief × power of control belief; I_1: Healthy Eating Education; I_2: Healthy Eating Weekly Plan; I_3: Healthy Eating Active Learning; I_4: Goal Setting; I_5: Physical Activity Education; I_6: Physical Activity Weekly Plan; I_7: Physical Activity Session; I_8: Daily Weight Scale; I_9: Dietary Record; I_{10}: PA monitor output. This model includes the following: 1) a 2-compartment energy balance model predicting changes in body mass as a result of energy intake and physical activity, 2) 2 Theory of Planned Behavior models describing how energy intake (diet) and physical activity are affected by behavioral variables, 3) a program delivery module relating magnitude and duration of components to inflows of the Theory of Planned Behavior models, and 4) 2 self-regulation units modeling how success expectancies in the intervention influence one's goal achievement motivation. Within the Healthy Mom Zone intervention, the output from this model informs decision rules to provide the framework for making adaptations to the intervention component dosages for each individual participant.

Chapter 2

Correspondence Between a Mobile Metabolism Device and a Validated Equation to Estimate Resting Energy Expenditure in Pregnant Women with Overweight/Obesity

Nearly 60% of childbearing women enter pregnancy with overweight (body mass index [BMI] = 25-29.9 kg/m^2) or obesity (BMI ≥ 30 kg/m^2), elevating their risk for excessive gestational weight gain (GWG; Chen, Xu, & Yan, 2018; Deputy, Sharma, Kim, & Hinkle, 2015; Institute of Medicine [IOM], 2009). Pregnant women with overweight and obesity (PW-OW/OB) who gain above the recommended IOM guidelines (i.e., OW > 11.3 kg, OB > 9.1 kg) are at risk for numerous adverse perinatal outcomes such as preeclampsia, postpartum weight retention, and long-term and obesity (Haugen et al., 2014; Mamun et al., 2010; Ren et al., 2018; Siega-Riz et al., 2010). Excessive GWG is also associated with adverse fetal outcomes such as macrosomia and neonatal mortality (Bianchi et al., 2018; Chen & Chauhan, 2019; Haugen et al., 2014). Resting energy expenditure (REE), or the number of calories burned at rest, is a large component of total energy expenditure energy expenditure (i.e., energy required to maintain essential body functions and calories burned from physical activity). Yet, the research examining prenatal REE is scant, and few studies have examined change in REE. Identifying change in prenatal REE is important to understand because some researchers have suggested that irregularities in prenatal REE (e.g., fluctuations, increases and/or decreases) may explain variable patterns in GWG (Berggren et al., 2017; Vander Wyst et al., 2020). That is, some women gain within or above GWG guidelines whereas others fail to gain weight or even lose weight. Further, fetuses do not grow in gestation at the same rate, points in time, or patterns of trajectory (Johnson et al., 2015; Santos et al., 2018). Because of this uncertainty, there is a need to better understand change in prenatal REE and the extent to which it is related to GWG.

Researchers have traditionally worked under the assumption that REE is non-fluctuating with a linear increase in response to the increase in prenatal weight. The majority of evidence has shown REE increases from pre-pregnancy to late third trimester (Berggren et al., 2017; Butte et al., 2003; Butte et al., 2004; Butte, 2005; Byrne et al. 2011; Catalano et al., 1999; Damjanovic et al., 2009; Forsum & Löf, 2007; Löf et al., 2005; Most, Dervis, Harman, Adamo, & Redman, 2019; Taousani et al., 2017). Because the general assumption is that REE increases in a linear trajectory, researchers have often limited prenatal assessments of REE. For example, the majority of studies include limited assessments of REE such as once during each trimester or one pre (or early) pregnancy and another post (or late) pregnancy (Butte et al., 2004; Byrne et al. 2011; Damjanovic et al., 2009; Lof et al., 2005; Melzer et al., 2010). Further, some studies utilize a predictive equation to estimate the linear increase in REE (Frankenfield, Roth-Yousey, & Compher, 2005; Shaneshin, Rezazadeh, Jessri, Neyestani, & Rashidkhani, 2011). However, the lack of frequent assessments and the use of an estimated equation may limit the ability to understand whether and how REE fluctuates (e.g., week to week) across pregnancy, and the extent to which this variation is related to GWG.

For example, Symons Downs and colleagues (2018; 2019a; 2019b) used a validated equation to estimate REE within the context of their adaptive, behavioral intervention to manage GWG in PW-OW/OB. The equation was proposed by Thomas et al. (2012) and fit using quadratic regression on data in pregnant women from Butte and colleagues (2004) as a function of maternal weight:

$$\text{REE} = 0.1976W^2 - 13.424W + 1457.6$$

This estimated equation allowed for repeated and frequent assessments of REE in PW-OW/OB because it required only maternal weight estimates, which can be feasibly obtained (e.g., Wi-Fi weight scales). However, given the equation only accounts for maternal weight, it may not accurately capture variability in prenatal REE. This is important because in contrast to past research suggesting REE increases in a linear pattern, recent research has shown evidence that this may not be the case for all women (Jackemeyer et al., 2017; Vander Wyst et al., 2020). For example, Jackemeyer and colleagues (2017) obtained weekly Breezing™ assessments in four pregnant women from preconception to 40 weeks gestation and found that each of the four women had distinctive REE changes across pregnancy; two women increased, and two women decreased in REE across pregnancy. Similarly, Vander Wyst and colleagues (2020) obtained Breezing™ assessments in 15 pregnant women every two weeks from ~14 to 28 weeks gestation and found that 60% of women increased in REE and 40% decreased. It may be that equations are unable to fully capture variability in prenatal REE due to the fact that most estimated equations do not account for other individual factors beyond maternal weight that have been shown to influence REE such as energy intake, physical activity, fat mass vs. fat-free mass, and demographic factors (e.g., age, race, etc.; Gilliat-Wimberly et al., 2001; Lof et al., 2005; Taousani et al., 2017). Thus, an estimated equation may not be fully representative of prenatal REE and may have reduced accuracy in predicting individual REE variation (Jackemeyer et al., 2017; Xian et al., 2015).

Moreover, recent advancements in technology have allowed researchers (e.g., Symons Downs and colleagues, 2018; under review) to expand their assessment of REE. Symons Downs and colleagues (2018; under review) utilized an indirect calorimetry mobile device (Breezing™), within the Healthy Mom Zone intervention to examine the extent to which there was variability in prenatal REE among PW-OW/OB. The Healthy Mom Zone study (Symons Downs et al., 2018; under review) provided this current study with a novel opportunity to compare objectively measured REE via Breezing™ and estimated REE from the pregnancy-based equation described above (Thomas et al., 2012) because both were obtained frequently over the course of pregnancy in PW-OW/OB. Breezing™ was initially validated by Xian and colleagues (2015) in non-pregnant adults and resulted in a significant correlation coefficient ($R^2 = 0.998$) to the Douglas Bag, which is a gold standard, laboratory-based indirect calorimetry method. In contrast to estimated equations such as the pregnancy specific one used by Thomas and colleagues (2012) and other non-pregnancy specific equations (Jackemeyer et al., 2017), Breezing™ may account for individual characteristics (e.g., weight status, fat-free mass, physical activity) associated with REE variability. Jackemeyer and colleagues (2017) found that REE values measured by the Breezing™ device were not consistent with REE estimated from equations. However, the equation was not pregnancy-specific, and the study only included four pregnant women. No located studies have examined the agreement between

Breezing™ and a pregnancy-based estimated REE equation. The Healthy Mom Zone study also provided a unique chance to examine particular study (e.g., randomized to intervention vs. control groups) and participant (e.g., pre-pregnancy BMI, age, fat-free mass, physical activity, energy intake, GWG) characteristics and whether these were related to the agreement between the two methods. These characteristics are of particular interest given that they are strong determinants of REE. For example, past researchers have shown that individuals with higher weight status, lower age, higher fat-free mass, higher physical activity levels, and higher energy intake have higher REE compared to individuals with lower weight status, older age, lower fat-free mass, lower physical activity levels, and lower energy intake (Gilliat-Wimberly et al., 2001; Lof et al., 2005; Taousani et al., 2017). Therefore, examining these characteristics may provide unique insight about changes in prenatal REE. Because the estimated equation does not consider these characteristics in the formula, the Breezing™ device may be more advantageous than the equation. However, the scant research using Breezing™ in PW-OW/OB precludes the ability to confirm this assumption.

Moreover, identifying correspondence between Breezing™ and the pregnancy-based estimated equation (Thomas et al., 2012) can inform whether these methods can be used interchangeably. One advantage of being able to substitute measures from either method can allow researchers to increase frequency of REE assessments in PW-OW/OB. Increasing frequency of REE assessments will allow researchers to better understand prenatal REE in this special population in an effort to provide insight about whether variation in REE is related to GWG regulation. For example, while some research has shown a significant association between REE and GWG, Vander Wyst and colleagues (2020) did not find a significant association between change in REE and GWG from 14 to 28 weeks gestation. The researchers suggested that this may have been because there were limited assessments of REE that did not span over the course of pregnancy and highlighted the need for future studies to include more regular and frequent sampling of REE across gestation. Further, examining characteristics associated with correspondence can provide insight and more information about variability in REE during pregnancy and thus, how this variability relates to GWG.

Thus, the first purpose of this secondary analysis study was to examine the correspondence between Breezing™ and a pregnancy-derived estimated equation (Thomas et al., 2012) to assess REE from ~8-36 weeks gestation in PW-OW/OB. Based on past research (Jackemeyer et al., 2017; Xian et al., 2015), it was hypothesized that Breezing™ REE would be positively associated with estimated REE. The second purpose was to explore the extent to which there is proportional bias (i.e., extent to which one measure gives values that are higher or lower than another) between the two methods. However, due to limited data, no a priori hypotheses were made about when (i.e., gestational week) there would be low agreement. The third purpose was to describe the extent to which Breezing™ and estimated REE differed from each other based on study (e.g., randomized to intervention vs. control groups) and participant (e.g., pre-pregnancy BMI, age, fat-free mass, physical activity, energy intake, GWG) characteristics. Given the estimated equation for REE does not take into account personal characteristics, it was hypothesized that these characteristics would be related to the correspondence between Breezing™ and estimated REE. However, due to the scant research, no a priori hypotheses were made about whether Breezing™ would produce higher or lower REE estimates compared to the equation for these characteristics.

Methods

Participants

Women ($N = 31$) were PW-OW/OB randomized to participate in the Healthy Mom Zone feasibility study, a theoretically-based behavioral intervention that adapted the intervention dosage and intensity over time in PW-OW/OB from ~8 to 36 weeks gestation to regulate GWG or to a usual care control group (a more detailed explanation of the study can be found in Symons Downs et al., 2018; Symons Downs et al., under review). Women were eligible to participate if they were ages 18-40 years and had: 1) overweight/obesity (BMI range 25-45 kg/m^2; >40 kg/m^2 with physician consultation), 2) singleton pregnancy >8 weeks gestation, 3) physician consent to participate, and 4) were English-speaking, residing in or near Central Pennsylvania. Exclusion criteria were: 1) multiple gestation, 2) diabetes at study entry, 3) did not have overweight/obesity, 4) severe allergies or dietary restrictions, 5) contraindications to prenatal physical activity (American College of Obstetrics and Gynecologists [ACOG], 2015) and, 6) not residing in area for duration of study. Of the $N = 31$ women, $n = 3$ had miscarriages prior to starting the intervention (not related to study participation) and $n = 1$ woman withdrew, resulting in a total sample of $N = 27$. Women were excluded from this current secondary analysis study if they were non-compliant with the Breezing™ device protocol ($n = 7$; i.e., did not complete any successful assessments). Thus, a final sample of $N = 20$ was used for the study analyses.

Procedures

The Healthy Mom Zone study was approved by the Pennsylvania State University Institutional Review Board (IRB Study# 00000122). Women completed a 30-minute baseline session at ~8 weeks gestation at the University's Clinical Research Center. Study procedures were explained to the participants and written informed consent was obtained for each woman. Each woman completed a BodPod assessment in minimal clothing to obtain body composition measurements (e.g., fat-free mass). Women received an Aria Fitbit Wi-Fi scale and were asked to self-weigh on a daily basis from 8 to 36 weeks gestation. Weights were transmitted via Bluetooth to research investigators each day. Women were also asked to wear a wrist-worn activity monitor (Jawbone UP3, San Francisco, CA) daily to assess physical activity. Women were instructed to wear an ActiGraph GT3x+ intermittently as a supplement to the wrist-worn activity monitor. Symons Downs et al. (2017) found that the Jawbone UP3 and the ActiGraph activity monitor had only a minor discrepancy of approximately a 79 kcals. Thus, ActiGraph data was used when wrist-worn activity monitor data was missing. Next, a study staff person downloaded the Breezing™ application onto each woman's Smartphone. All women were trained on how to use the Breezing™ device and sent home with detailed instructions. They were instructed to use the Breezing™ device one time per week (on the same day of the week) from ~8-36 weeks gestation. Women were recommended to obtain a Breezing™ measurement after 8 hours of sleep, immediately after waking up while lying down and in a fasting state (e.g., no food for the past 4-6 hours). Women opened the Breezing™ application on their phone and followed a checklist of instructions to obtain a measurement. They scanned the QR code on the sensor cartridge package, placed a nose clip onto their nose, and practiced breathing in the mouthpiece alone until breathing was consistent. Women were then prompted to insert one sensor cartridge into the tracking device and preform an actual measurement by picking up the device and blowing into the mouthpiece until the application said the test was completed (1-2 minutes). The device did not produce results if the woman had 'irregular breathing.' Women with irregular breathing were instructed to complete another measurement until a successful assessment was obtained. On average, 5% of the sample had to repeat at least one measurement due to irregular breathing. All data was transmitted via Bluetooth to the women's smartphone and sent to the research team. At ~36 weeks gestation, women completed their last assessment and returned the device.

Measures

Measured REE. The Breezing™ device is an indirect calorimetry analyzer of REE and is compatible with both iOS and Android software platforms. Sensor cartridges were used to determine the rate of oxygen consumption and carbon dioxide production. The scanned QR code carries calibration parameters for the sensor cartridge. The algorithm within the Breezing™ device then calculates REE according to the Weir equation, a well-known equation used with indirect calorimetry (Weir, 1949; Xian et al., 2015):

$$[3.9 * VO_2 + 1.1*VCO_2]* 1.44$$

VO_2 represents the volume of oxygen consumed and VCO_2 represents the volume of carbon dioxide produced.

Estimated REE. Research investigators calculated estimated REE as a function of maternal weight for each woman by using an empirical equation that was proposed (Thomas et al., 2012) and fit using a quadratic regression equation from data collected on pregnant women by Butte and colleagues (2003; 2004):

$$REE = 0.1976W^2 - 13.424W + 1457.6$$

W represents maternal weight in kilograms. Estimated REE was calculated for each day the women obtained a Breezing™ assessment.

Demographics and Personal Characteristics. At baseline, women self-reported personal demographics (i.e., age, race/ethnicity, income, marital status, education, employment) and current gestational age. Pre-pregnancy BMI was calculated from self-reported pre-pregnancy weight and height. Baseline fat-free mass in kg was obtained from the BodPod. Average energy intake/day was estimated for each week using a validated back-calculation method (Symons Downs et al., 2018; 2019; Guo et al., 2016; Guo et al., 2018a; Guo et al., 2018b):

$$EI_{est}(k) = \frac{-W(k+2T) + 8W(k+T) - 8W(k-T) + W(k-2T)}{12TK_1} - \frac{K_2}{K_1}(PA(k) + REE(k))$$

The variables are as follows: k = 1, 2, …, *N* corresponding to day 1-day *N*. W represents maternal weight in kg while T represents sampling time which in this case was T = 1 day. PA represents physical activity in kcals. REE represents resting energy expenditure in kcals calculated using the estimated equation. Back-calculated energy intake was averaged across the seven days for each week to obtain average weekly energy intake per day. Finally, activity kcal per day was obtained from the Jawbone UP3 (San Francisco, CA), a wrist-worn activity monitor, and averaged across the seven days of each week to obtain average activity kcal for each week.

Data Analyses

Data were analyzed using SAS 9.4 and SPSS v25. Means, standard deviations, and percentages were used to examine demographic variables and descriptives of Breezing™ and estimated REE. Breezing™ and estimated REE weekly point estimates that were 3 ± within person standard deviations above each woman’s mean Breezing™ and estimated REE across 8 to 36 weeks gestation were considered as outliers and are descriptively presented (Ruan, Chen, & Kerre, 2005). Time-varying effect modeling (TVEM) was used to examine the association between Breezing™ and estimated REE over time (Tan, Shiyko, Li, Li, & Dierker, 2012). TVEM was used to estimate regression coefficients (i.e., rates of association between Breezing™ and estimated REE) as a non-parametric function of gestational week. TVEM results are presented as figures. Time-varying associations are positive or negative when estimated coefficient is above or below zero, respectively. Associations are significant when the 95% confidence interval does not include zero. TVEM produced standardized beta coefficients for effect sizes. Effect size values of 0.20, 0.50, and 0.80 were considered small, medium, and large effects, respectively (Cohen, 1988). Bland-Altman plots were constructed to visually observe over- or under-estimation of the REE estimates between the two methods and to explore potential systematic bias in the estimates. Researchers have suggested the use of Bland-Altman plots rather than paired t-tests to examine agreement/correspondence given that this method asks the questions of which method will produce consistently accurate results and if one method can replace the other (Phatak & Nimbalkar, 2017). Limits of agreement were calculated as the mean difference between Breezing™ REE and estimated REE ± 95% confidence interval. Over- or under-estimation was considered significant if the 95% confidence intervals did not include zero.

Means of Breezing™ and estimated REE were calculated as a function of study assignment (randomized to intervention vs. control group) and the following personal characteristics: pre-pregnancy BMI, maternal age, fat-free mass, average weekly energy intake per day, average weekly energy intake per day, and weekly GWG. Women were grouped based on their pre-pregnancy BMI as overweight (BMI = 25-29.9 kg/m^2) or obese (BMI ≥ 30 kg/m^2) using the IOM (2009) definitions. Women were also grouped based on their age: < 35 or ≥ 35 years, corresponding to the clinically defined "adverse maternal age" cut-off associated with adverse pregnancy outcomes (Lean, Derricott, Jones, & Heazell, 2017). Women were grouped by their fat-free mass: reference percentile distributions for fat-free mass show that a reference value for fat-free mass at the 50th percentile is 42.6kg for women between 25-44 years old (Kyle, Genton, Slosman, & Pichard, 2001). Thus, women with fat-free mass < 42.6kg were categorized as low and women with fat-free mass ≥ 42.6kg were categorized as high. Using average back-calculated energy intake/day, women were categorized as meeting versus exceeding energy intake guidelines for each week. Several guidelines recommend that while no additional calories are needed in the first trimester, women should intake an additional 340 kcals/day in the second trimester and 452 kcals/day in the third trimester (ACOG, 2016; IOM, 2009; Kaiser, Campbell, & Academy Positions Committee Workgroup, 2014; Kominiarek & Rajan, 2016). Therefore, for gestational weeks 8-13, average energy intake/day for each week was subtracted from the week prior (e.g., energy intake/day for gestational week 9 minus week 8) to obtain change in average energy intake/day. If the change was ≤ 0 kcals, women were categorized as meeting energy intake guidelines. If the change was > 0 kcals, women were categorized as exceeding the guidelines. For gestational weeks 14-36, average energy intake/day for each week was subtracted from average energy intake/day during the first trimester to obtain change in average energy intake/day in the second and third trimesters. If the change was ≤ 340 kcals at weeks 14-28 or ≤ 452 at weeks 29-36, women were categorized as meeting energy intake guidelines. If the change was > 340 kcals at weeks 14-28 or > 452 at weeks 29-36, women were categorized as exceeding the guidelines. Using the average activity kcal calculated each week from the Jawbone activity monitor, women were categorized low active vs. active. It was the original intention to categorize women based on the physical activity guidelines of 150 minutes of moderate to vigorous physical activity (ACOG, 2015), however the Jawbone activity monitor did not distinguish between the intensity of physical activity making it difficult to determine time spent in moderate to vigorous physical activity. Instead, researchers have shown that on average, PW-OB are considered low active and expend 569 active kcals/day during pregnancy (Most et al., 2018). Given there are no clinical recommendations for the number of active kcals to expend per day, a threshold of 569 active kcals/day was used. Women who had an active kcal/day < 569 were categorized as low active and women who had an active kcal/day ≥ 569 were categorized as active. Finally, using weekly average weight/day, women were categorized as meeting versus exceeding weekly GWG guidelines. Regardless of weight status, women are assumed to have a weekly weight gain of 0.09-0.33 pounds per week (IOM, 2009) during the first trimester. For the second and third trimester, women with overweight are recommended to gain 0.4-0.6 pounds per week whereas women with obesity are recommended to gain 0.5-0.7 pounds per week. Exceeding the upper bounds of these weekly recommendations (i.e., >0.33 pounds in the first trimester, >0.7 pounds for women with overweight and >0.6 pounds for women with obesity in the second/third trimester) increases the risk for total excessive GWG and adverse pregnancy outcomes (IOM, 2009; Knabl et al., 2014). Thus, weekly GWG was calculated for each woman at each week from 8-36 weeks gestation. For gestational weeks 8-13, women with a weekly weight gain ≤ 0.33 pounds were categorized as meeting GWG and women with a weekly weight gain > 0.33 pounds were categorized as exceeding GWG. For gestational weeks 14-36, women with a weekly weight gain ≤ 0.7 pounds (overweight) or ≤ 0.6 pounds (obese) were categorized as meeting GWG and women with a weekly weight gain > 0.7 pounds (overweight) or > 0.6 pounds (obese) were categorized as exceeding GWG.

Results

Participant Characteristics. Mean age of study participants was 30.6 (*SD* = 3.4) years, mean gestational week at study entry was 10.1 (*SD* = 1.7) and mean pre-pregnancy BMI was 32.0 kg/m^2 (*SD* = 3.4; overweight = 55%, obese = 45%). The sample was Non-Hispanic, White (100%), married (90%), employed full-time (85%), reported a family income ≥ $40,000 (75%), and reported a graduate/professional degree for their highest level of education (55%; Table 2.1).

REE Descriptives. Means and standard deviations of Breezing™ and estimated REE are presented in Table 2.2. Across all women, there was a total of 402 points of measurement for each Breezing™ and estimated REE. Of these, 12 (3%) of the Breezing™ estimates were excluded due to irregular breathing, thus resulting in 390 total estimates of Breezing™ and estimated REE. The number of women who completed Breezing™ assessments each week varied between *N* = 4 to *N* =18 resulting in 2 to 16 missing REE assessments (Figure 2.1). One outlier was identified at week 35 for estimated REE. However, given the purpose of the study was to examine the correspondence between the raw REE data, the outlier was not excluded from the analyses. Across 8-36 weeks gestation, average Breezing™ REE ranged from

1710.00 kcals to 2053.33 kcals and average estimated REE ranged from 1717.91 kcals to 2593.85 kcals. On average, Breezing™ REE was 87.60 kcals lower than estimated REE.

REE Correspondence. The TVEM figure illustrates that Breezing™ and estimated REE were positively associated with each other from 8 to 36 weeks gestation (Figure 2.2). The effect size of the positive associations from 8 to 36 weeks range from 0.26 (small) to 0.56 (medium). Bland-Altman plots can be found in Figure 2.3. The plots revealed that there was significant proportional bias between the Breezing™ and estimated REE at gestational week 11, 23, 32, 33, and 35, suggesting no agreement between the two methods at these time points. There was no proportional bias detected at the remaining gestational weeks, 8-10, 12-22, 24-31, 34, and 36, suggesting agreement between Breezing™ and estimated REE at these time points.

REE Means as a Function of Characteristics. The small sample size and diversity in study and personal characteristics precluded the ability to make statistically significant comparisons, however, descriptive comparisons were made (Tables 2.3-2.9) to summarize the data in an efficient way to identify if any meaningful patterns emerged (Vetter, 2017). The estimated equation was used as the reference group given that equations are currently more commonly utilized than Breezing™ (Jackemeyer et al., 2017; Thomas et al., 2012). Differences in Breezing™ and estimated REE means varied based on certain characteristics. On average, Breezing™ resulted in higher estimates of REE compared to the equation for intervention women, women with overweight, women with lower fat-free mass, and women exceeding energy intake guidelines. In other words, Breezing™ resulted in lower estimates of REE compared to the equation for control women, women with obesity, women with higher fat-free mass, and women meeting energy intake guidelines. Regardless of age, physical activity level, and GWG, Breezing™ resulted in lower estimates of REE compared to the estimated equation.

Discussion

The primary purpose of this secondary analysis study was to examine the association and correspondence between Breezing™ and a pregnancy-based estimated equation to assess REE in PW-OW/OB randomized to an intervention (Healthy Mom Zone) or usual care control group from ~8 to 36 weeks gestation. The secondary purpose was to describe the extent to which Breezing™ and the estimated equation differed from each other based on study (e.g., randomized to intervention vs. control group) and participant (e.g., pre-pregnancy BMI, age, fat-free mass, physical activity, energy intake, GWG) characteristics. In summary, while Breezing™ REE and the estimated REE equation were positively associated from 8 to 36 weeks gestation, proportional bias between the two methods was detected at gestational weeks 11, 23, 32, 33, and 35. Also, randomized group assignment (intervention vs. control), pre-pregnancy BMI, fat-free mass, and meeting or exceeding energy intake guidelines may be related to the correspondence between Breezing™ and the estimated equation. These findings suggest that Breezing™ and the estimated equation may be able to be used interchangeably at certain points during pregnancy to assess REE. However, certain study (i.e., randomized to intervention vs. control groups) and participant characteristics (i.e., weight status, fat-free mass, energy intake) should be taken into consideration given their association to the agreement between the two methods. These findings are described in more detail below.

In support of the first hypothesis, Breezing™ REE and the estimated REE equation were positively associated from 8 to 36 weeks gestation. However, the effect sizes for these associations were small to medium. It is important to note that due to the small sample size, the 95% confidence intervals across the time points are wide and should be taken into consideration when interpreting the TVEM finding. Nevertheless, the positive association is not surprising given that each method is a valid assessment of REE and because the two methods are designed to assess the same variable (Butte et al., 2003; Butte et al., 2004; Giavarina, 2015; Xian et al., 2015). Thus, Bland-Altman plots were constructed to better understand the agreement between the two methods. Bland-Altman plots revealed proportional bias at gestational weeks 11, 23, 32, 33, and 35 suggested a lack of agreement between the two methods at these time points. It is important to note that REE assessments at weeks 11, 23, 32, 33, and 35 were missing for 10, 5, 9, 5, and 10 women, respectively, which may have influenced the lack of agreement between methods. Nonetheless, mean Breezing™ REE values were 1761, 1866, 1968, 1916, and 1879 kcals at gestational weeks 11, 23, 32, 33, and 35, respectively. Means for the estimated equation were 2009, 2041, 2015, 2018, and 2068 kcals at gestational weeks 11, 23, 32, 33, and 35, respectively. Across the total sample on average, Breezing™ resulted in lower REE (*mean* = - 152.2kcals) compared to the estimated equation (range = -46.71 to -248.01). It is important to note that Bland-Altman plots do not suggest that one method is more appropriate over another, but rather quantifies the bias of the differences between the two methods and a range of agreement (Giavarina, 2015). A difference of zero between the two methods would either suggest there were no differences at all, or that the differences were linked to an analytical imprecision. Thus, the disagreement between Breezing™ and the estimated equation at gestational weeks 11, 23, 32, 33, and 35 suggest that the differences may be due to external factors. These external factors may be explained, in part, by study and personal characteristics, which are described in more detail below.

For example, when there was a lack of agreement between the two methods at gestational weeks 11, 23, 32, 33, and 35, the difference between Breezing™ and the estimated equation varied by study assignment, pre-pregnancy BMI, fat-free mass, and energy intake. On average, Breezing™ resulted in higher estimates of REE compared to the estimated equation for intervention women, women with overweight, women with lower fat-free mass, and women who exceeded energy intake guidelines. In other words, Breezing™ resulted in lower estimates of REE compared to the estimated equation for control women, women with obesity, women with higher fat-free mass, and women who met energy intake guidelines. Interestingly, correspondence during these points when there was a lack of agreement did not seem to vary based on maternal age and GWG. That is, regardless of the age cut-off or not meeting versus meeting the GWG guidelines, Breezing™ resulted in lower values compared to the estimated equation. Means by physical activity level at these specific time points could not be compared due to the limited sample size during these weeks. Nevertheless, in summary, these findings suggest that REE values from the two methods may differ slightly based on external characteristics, and they illustrate that REE assessments may be captured differently based on which method is used. One explanation for these findings is that the estimated equation only takes into account maternal weight whereas Breezing™ can be individualized and can take into account certain characteristics such as study assignment, BMI, fat-free mass, and energy intake, which have been shown to influence REE. However, future research is needed to test and confirm this assumption. More specifically, as mentioned above, the analyses conducted within this current study did not allow for conclusive statements regarding which method is more appropriate or accurate under certain conditions. Rather, these results suggest that differences between Breezing™ and the estimated equation exist during certain points of pregnancy and may be due to individual characteristics. However, it is important to note that at gestational week 35, there was one outlier with respect to REE calculated from the estimated equation. Upon further exploration, when this outlier was removed, the lack of agreement between Breezing™ and the estimated equation at week 35 disappeared and the methods were subsequently in agreement. Thus, it is important to examine the presence of outliers in the data with respect to correspondence of these measures for a more accurate picture of the agreement between the methods.

Although Breezing™ and the estimated equation are both established assessments of REE, the current study findings illustrate that correspondence between the two methods may vary during certain points of pregnancy, and may vary based on certain study (i.e., randomized to intervention vs. control group) and participant characteristics (i.e., weight status, fat-free mass, energy intake). Agreement may also be influenced by outliers in the dataset. Researchers may want to strongly consider these factors when assessing REE among pregnant women, especially if the goal is to obtain the most accurate assessment of REE. For example, researchers should explore the presence of outliers and consider the implications of including or excluding these data in relation to the study's overall objectives. In addition, researchers may want to examine REE data with and without interchanging both methods (Breezing™, estimated equation) to understand if variation between the methods has an impact on the target outcomes.

Accurate assessments of REE are important for self-monitoring behaviors such as adjusting caloric intake and physical activity behaviors and regulating GWG. Therefore, future researchers may want to consider using Breezing™ when possible (e.g., once a week) given its potential utility to understand individual differences in REE. Additionally, the Breezing™ device not only outputs a REE assessment, but it also provides the user with a caloric intake goal based on their REE measurement. Women can use Breezing™ as a self-monitoring tool to obtain their personalized caloric intake goal and adjust and regulate their daily caloric intake behaviors to regulate GWG. On the other hand, when Breezing™ is not feasible (e.g., daily) or when there is missing data from Breezing™, the estimated equation may serve as an appropriate substitute as a way to increase frequency of REE assessments depending on the gestational week and dependent on certain characteristics and the inclusion of potential outliers. Further, although the current findings showed a small to medium effect for the strength of agreement between Breezing™ and the estimated equation, this is the first study to provide initial evidence in support of interchanging these methods as a strategy to obtain more frequent measures of REE over the course of pregnancy. For example, daily Breezing™ assessments can be expensive and thus, researchers may want to limit the number of Breezing™ assessments to weekly or monthly frequencies but then supplement these measurements with estimates of REE using the equation when possible. Obtaining more frequent assessments of REE can help researchers to examine variability in REE and the extent to which REE may fluctuate over the course of pregnancy and impact outcomes such as GWG. However, researchers should use caution when substituting REE measures from Breezing™ and the estimated equation given this study showed a lack of agreement between the two methods during certain gestational weeks (e.g., 11, 23, 32, 33, and 35) potentially due to certain characteristics (e.g., study assignment, weight status, fat mass vs. fat-free mass, energy intake) and outliers. Future research with a larger sample size and with formal moderation analyses is necessary to replicate these study findings.

Strengths and Limitations

This study is the first to our knowledge to examine association and correspondence between Breezing™ and an estimated REE equation in PW-OW/OB. There are several strengths to this study. First, there were frequent measures of REE over the course of pregnancy. With the current literature limited to a maximum of two to three REE assessments during pregnancy, this study addresses this gap by allowing us to examine methods of assessment over time and in more detail. Second, this study focused on PW-OW/OB. There is a lack of standardized recommendations for energy balance (i.e., energy intake and expenditure) in PW-OW/OB. Thus, identifying feasible and accurate assessments of REE can inform future interventions aiming to manage energy balance and GWG in PW-OW/OB. Third, the analyses included multiple analyses of comparison (i.e., TVEM, Bland-Altman plots) to obtain a full picture of correspondence. A final strength was the ability to describe characteristics where a lack of correspondence was found. Providing the descriptive data allowed us to summarize the data in a meaningful way and allowed us to understand whether patterns of correspondence existed. Notwithstanding, it is important to address the study limitations. One limitation includes the generalizability of the study findings. The sample was representative of PW-OW/OB in Central Pennsylvania who were White, highly educated, and married. Another limitation was the inability to conduct formal moderation analyses due to limited sample size. Future studies should replicate these study findings in more diverse and large samples to understand generalizability of study findings and to allow for the ability to perform formal moderation analyses. Another limitation was the technological barriers women faced when using the Breezing™ device such as inability to connect to Bluetooth or the sensor cartridge not working. These barriers may explain the amount of missing Breezing™ data points. However, the current study findings may address this limitation suggesting that future researchers may want to consider imputing data from the estimated equation when Breezing™ data is unavailable during certain gestational weeks.

Conclusion

In summary, this study contributes to the literature by providing evidence that Breezing™ and an estimated prenatal equation may be used interchangeably at certain points during pregnancy to assess REE. However, certain study (i.e., randomized to intervention vs. control groups) and participant characteristics (i.e., weight status, fat-free mass, energy intake) as well as outliers should be taken into consideration within the REE data given their association to the agreement between the two methods. Given that Breezing™ may adjust to personal characteristics beyond maternal weight, Breezing™ may serve as an informative and user-friendly way to assess REE. However, when Breezing™ REE cannot be obtained, and depending on gestational week of pregnancy, the estimated REE equation might be a useful substitute to increase frequency of assessments of REE. Increasing frequency of REE assessments during pregnancy can help future researchers to better examine and understand variability in prenatal REE and its association with subsequent perinatal health outcomes such as GWG, especially among PW-OW/OB, who are at high risk of poor maternal-fetal outcomes due to excessive GWG.

Table 2.1. Participant Characteristics (N = 20).

	Mean	***SD***	***N* (%)**
Age	30.6	3.4	
Gestational Week at Study Entry	10.1	1.7	
Pre-pregnancy BMI	32.0	3.4	
OW			11 (55)
OB			9 (45)
Race			
White			20 (100)
Employment			
Full-Time			17 (85)
Other			3 (15)
Education			
High School			1 (5)
College			8 (40)
Graduate/Professional			11 (55)
Family Income			
$10-20,000			1 (5)
$20-40,000			4 (20)
$40-100,000			8 (40)
>$100,000			7 (35)
Marital Status			
Married			18 (90)
Single			1 (5)
Divorced			1 (5)
Parity			
Nulliparous			15 (75)
Primiparous			5 (25)

Note. *SD* = standard deviation; BMI = body mass index.

Table 2.2. Means and Standard Deviations of Breezing™ REE and the Estimated Equation.

		Breezing™ REE (kcal)		Estimated REE (kcal)	
Gestational Week	***N***	***M***	***SD***	***M***	***SD***
8	4	2042.50	366.91	2593.85	762.45
9	6	2053.33	351.95	2269.01	771.59
10	8	1736.87	354.97	1900.70	618.45
11	10	1761.00	272.66	2009.01	681.45
12	14	1751.43	355.07	1933.55	581.62
13	14	1890.00	400.86	1963.29	583.65
14	17	1800.88	426.63	1888.49	556.66
15	16	1831.88	346.95	1812.71	465.60
16	17	1928.53	404.34	1897.97	558.24
17	18	1860.56	370.30	1856.67	466.03
18	17	1924.71	321.06	1867.83	488.60
19	14	1893.57	238.86	1838.16	350.92
20	16	1897.19	341.12	1878.94	508.75
21	16	1985.63	444.61	1999.89	559.74
22	17	2041.76	353.06	1991.83	540.04
23	15	1866.33	327.17	2041.20	580.32
24	12	1826.67	335.43	1864.97	362.60
25	16	1856.88	408.57	1899.04	484.01
26	17	1848.24	457.59	1988.25	552.56
27	16	1896.50	420.18	1909.58	475.79
28	15	1813.33	400.73	1885.47	507.82
29	13	1838.46	419.38	1977.62	516.36
30	15	1810.67	363.56	1974.44	448.65
31	13	1902.31	318.39	1931.66	381.52
32	11	1968.18	317.89	2014.89	524.19
33	15	1916.00	331.74	2018.35	506.89
34	12	1827.08	407.24	1906.51	418.93
35	10	1879.00	357.44	2068.17	574.28
36	5	1710.00	305.35	1717.91	209.42

Note. M = mean; SD = standard deviation; REE = resting energy expenditure.

Table 2.3. Means and Standard Deviations of Breezing™ REE and the Estimated Equation by Study Assignment.

Study Assignment	Intervention					Control				
		Breezing™ REE (kcal)		Estimated REE (kcal)			Breezing™ REE (kcal)		Estimated REE (kcal)	
Gestational Week	***N***	***M***	***SD***	***M***	***SD***	***N***	***M***	***SD***	***M***	***SD***
8	2	1985.00	233.35	2273.09	1118.55	2	2100.00	579.83	2914.61	285.09
9	2	2140.00	268.70	2248.67	1094.80	4	2010.00	418.17	2279.18	769.62
10	5	1778.00	453.29	1859.06	679.94	3	1668.33	137.14	1970.10	634.40
11	5	1740.00	331.66	1876.42	678.22	5	1782.00	237.00	2141.59	735.48
12	6	1765.00	442.66	1890.17	588.16	8	1741.25	306.43	1966.08	615.08
13	6	1800.00	376.62	1956.62	560.00	8	1957.50	430.08	1968.30	639.20
14	7	1795.00	400.36	1892.70	554.38	10	1805.00	465.48	1885.55	588.19
15	6	1911.67	286.67	1900.42	612.68	10	1784.00	384.94	1760.09	380.21
16	6	1926.67	358.81	1903.51	616.90	11	1929.55	444.08	1894.96	555.25
17	6	1846.67	150.29	1715.75	253.78	12	1867.50	448.88	1927.13	538.63
18	6	1916.67	179.07	1717.79	266.39	11	1929.09	385.78	1949.67	570.62
19	5	1902.00	96.80	1778.14	254.49	9	1888.89	296.58	1871.50	405.25
20	5	1895.00	188.81	1714.67	291.47	11	1898.18	400.35	1953.61	578.47
21	6	2060.00	324.16	1975.79	565.86	10	1941.00	514.96	2014.35	586.23
22	7	2111.43	326.77	1927.88	525.25	10	1993.00	379.48	2036.59	573.72
23	6	1955.00	231.50	2005.89	559.01	9	1807.22	379.47	2064.73	626.48
24	4	2060.00	297.21	1863.29	261.83	8	1710.00	303.79	1865.82	420.98
25	5	1896.00	373.74	1733.36	180.38	11	1839.09	439.78	1974.35	564.29
26	7	1887.14	393.86	1929.31	551.75	10	1821.00	516.56	2029.51	579.00
27	5	1867.80	332.54	1768.73	282.74	11	1909.55	469.03	1973.61	541.44
28	6	1780.00	355.47	1762.29	264.04	9	1835.56	447.94	1967.59	623.49
29	3	1863.33	501.43	1809.30	362.42	10	1831.00	422.33	2028.11	560.40
30	5	1926.00	351.18	2097.37	556.82	10	1753.00	373.78	1912.97	403.39
31	5	1818.00	274.81	1797.10	310.13	8	1955.00	349.82	2015.76	416.59
32	2	1835.00	21.21	1613.17	18.98	9	1997.78	347.63	2104.16	542.33
33	6	1810.00	325.02	1786.24	294.18	9	1986.67	335.45	2173.09	572.89
34	5	1867.00	332.86	1827.82	335.21	7	1798.57	477.40	1962.72	487.86
35	4	1632.50	258.25	1741.56	186.81	6	2043.33	330.07	2285.91	656.10
36	1	1590.00	--	1650.24	--	5	1734.00	335.01	1731.45	231.18

Note. M = mean; SD = standard deviation; REE = resting energy expenditure.

Table 2.4. Means and Standard Deviations of Breezing™ REE and the Estimated Equation by Pre-Pregnancy Body Mass Index.

BMI		Overweight					Obese			
		Breezing™ REE (kcal)		Estimated REE (kcal)			Breezing™ REE (kcal)		Estimated REE (kcal)	
Gestational Week	***N***	***M***	***SD***	***M***	***SD***	***N***	***M***	***SD***	***M***	***SD***
8	1	1820.00	--	1482.16	--	3	2116.67	411.02	2964.42	219.27
9	3	2053.33	130.51	1584.86	192.75	3	2053.33	540.96	2953.15	216.96
10	6	1670.83	288.49	1580.19	168.79	2	1935.00	601.04	2862.25	263.42
11	6	1686.67	237.21	1555.26	136.20	4	1872.50	318.79	2689.63	576.87
12	7	1611.43	223.56	1537.42	139.82	7	1891.43	421.25	2329.68	589.27
13	7	1764.29	341.17	1555.47	176.45	7	2015.71	441.47	2371.12	564.68
14	10	1602.50	252.03	1545.66	151.87	7	2084.29	480.41	2378.25	562.13
15	10	1696.00	215.16	1551.47	155.34	6	2058.33	423.48	2248.13	492.86
16	10	1746.00	223.27	1554.64	159.23	7	2189.29	475.75	2388.46	562.01
17	10	1730.00	335.56	1559.03	160.66	8	2023.75	365.32	2228.72	457.72
18	10	1836.00	274.76	1563.89	163.47	7	2051.43	360.25	2302.04	471.81
19	7	1887.14	310.04	1578.98	188.59	7	1900.00	165.53	2097.33	272.99
20	9	1793.89	267.60	1546.00	138.58	7	2030.00	398.54	2307.01	491.31
21	8	1790.00	347.32	1596.29	175.23	8	2181.25	464.22	2403.49	518.01
22	9	1895.56	266.51	1617.08	152.40	8	2206.25	381.24	2413.42	506.34
23	7	1700.71	216.11	1593.06	162.99	8	2011.25	350.16	2433.32	523.66
24	7	1715.71	332.51	1638.88	188.11	5	1982.00	303.10	2181.51	306.25
25	10	1729.00	352.62	1640.42	160.18	6	2070.00	435.62	2330.07	547.63
26	9	1652.22	241.91	1616.02	142.80	8	2068.75	553.86	2407.01	544.07
27	9	1721.67	256.61	1609.38	145.46	7	2121.29	498.77	2295.56	478.27
28	10	1641.00	289.15	1620.94	140.02	5	2158.00	388.81	2414.54	577.59
29	8	1648.75	294.79	1638.65	169.06	5	2142.00	434.07	2519.97	390.38
30	8	1650.00	364.85	1650.73	155.83	7	1994.29	281.71	2344.40	376.76
31	6	1848.33	410.00	1620.71	157.78	7	1948.57	239.27	2198.19	301.34
32	6	1860.00	234.78	1692.20	193.96	5	2098.00	380.95	2402.11	544.33
33	8	1763.75	248.36	1675.48	175.12	7	2090.00	344.38	2410.20	477.36
34	8	1718.75	412.15	1667.48	182.88	4	2043.75	343.30	2384.57	329.24
35	6	1726.67	277.32	1755.44	165.46	4	2107.50	372.95	2537.27	674.35
36	5	1706.00	341.22	1673.00	199.23	1	1730.00	--	1942.47	--

Note. BMI = body mass index; M = mean; SD = standard deviation; REE = resting energy expenditure.

Table 2.5. Means and Standard Deviations of Breezing™ REE and the Estimated Equation by Maternal Age.

Age	<35					≥35				
		Breezing™ REE (kcal)		Estimated REE (kcal)			Breezing™ REE (kcal)		Estimated REE (kcal)	
Gestational Week	***N***	***M***	***SD***	***M***	***SD***	***N***	***M***	***SD***	***M***	***SD***
8	3	1886.67	237.14	2419.74	830.72	1	2510.00	--	3116.21	--
9	5	1984.00	344.65	2097.46	723.52	1	2400.00	--	3126.73	--
10	7	1825.00	272.99	1962.57	640.70	1	1120.00	--	1467.63	--
11	8	1785.00	201.71	1932.34	604.65	2	1665.00	601.04	2315.65	1176.93
12	12	1773.33	340.94	1870.93	496.23	2	1620.00	565.69	2309.25	1166.04
13	11	1926.36	304.67	1946.62	511.34	3	1756.67	739.21	2024.45	948.57
14	13	1836.54	386.36	1890.95	486.80	4	1685.00	591.81	1880.51	839.43
15	13	1898.46	342.39	1891.84	484.44	3	1543.33	213.85	1469.86	28.00
16	13	1986.15	386.10	1899.32	481.99	4	1741.25	463.11	1893.60	856.01
17	14	1877.86	305.54	1843.76	339.35	4	1800.00	605.15	1901.86	853.33
18	13	1889.23	291.73	1854.96	354.63	4	2040.00	431.43	1909.67	875.85
19	11	1931.82	247.74	1935.73	333.43	3	1753.33	162.58	1480.40	15.39
20	12	1822.92	231.68	1861.14	378.67	4	2120.00	544.73	1932.34	873.65
21	12	1970.83	344.05	2019.19	463.40	4	2030.00	742.20	1941.97	879.30
22	13	2033.08	315.66	2003.45	448.35	4	2070.00	514.65	1954.06	865.37
23	12	1852.92	244.79	2020.64	479.63	3	1920.00	643.66	2123.41	1038.98
24	11	1854.55	336.91	1894.60	364.75	1	1520.00	--	1539.13	--
25	12	1815.83	325.92	1876.11	343.17	4	1980.00	646.68	1967.84	855.05
26	13	1783.08	340.35	1989.20	471.17	4	2060.00	758.42	1985.16	860.44
27	12	1859.50	286.24	1889.50	355.99	4	2007.50	748.62	1969.83	812.86
28	11	1798.18	345.51	1847.12	381.99	4	1855.00	590.17	1990.94	834.76
29	9	1856.67	359.90	1984.28	420.08	4	1797.50	595.73	1962.63	771.70
30	13	1869.23	351.46	2035.19	452.39	2	1430.00	183.85	1579.56	48.48
31	11	1980.91	278.33	1992.71	384.72	2	1470.00	0.00	1595.91	9.82
32	8	1925.00	237.25	1973.49	392.73	3	2083.33	530.03	2125.27	899.41
33	12	1871.67	281.06	1978.54	382.44	3	2093.33	526.25	2177.59	972.92
34	10	1863.50	438.01	1961.28	441.02	2	1645.00	134.35	1632.67	9.73
35	7	1864.29	209.11	2012.82	419.82	3	1913.33	664.25	2197.32	958.96
36	5	1718.00	340.69	1728.61	232.29	1	1670.00	--	1664.41	--

Note. M = mean; SD = standard deviation; REE = resting energy expenditure.

Table 2.6. Means and Standard Deviations of Breezing™ REE and the Estimated Equation by Fat Free Mass Percentage.

Fat Free Mass	Low					High				
		Breezing™ REE (kcal)		Estimated REE (kcal)			Breezing™ REE (kcal)		Estimated REE (kcal)	
Gestational Week	***N***	***M***	***SD***	***M***	***SD***	***N***	***M***	***SD***	***M***	***SD***
8	1	1820.00	--	1482.16	--	3	2116.67	411.02	2964.42	219.27
9	2	1980.00	42.43	1473.58	1.34	4	2090.00	447.74	2666.72	599.63
10	3	1770.00	151.00	1473.42	29.20	5	1717.00	455.85	2157.07	670.69
11	3	1720.00	95.39	1469.81	37.13	7	1778.57	327.54	2240.09	698.89
12	5	1764.00	336.72	1547.06	207.80	9	1744.44	384.74	2148.26	618.79
13	3	1906.67	219.62	1443.47	79.67	11	1885.45	446.26	2105.06	581.73
14	4	1663.75	132.88	1456.41	64.10	13	1843.08	479.66	2021.44	575.11
15	5	1956.00	321.84	1546.62	212.09	11	1775.45	357.67	1933.66	505.66
16	5	2024.00	280.14	1549.48	213.52	12	1888.75	450.99	2043.18	598.75
17	5	1828.00	328.59	1548.89	212.60	13	1873.08	397.06	1975.05	487.81
18	5	1784.00	277.45	1551.63	197.97	12	1983.33	330.44	1999.59	518.27
19	3	1883.33	287.46	1605.03	263.09	11	1896.36	240.01	1901.74	354.25
20	4	1618.75	154.83	1470.89	67.70	12	1990.00	338.45	2014.96	520.54
21	3	1690.00	253.57	1580.26	254.86	13	2053.85	457.70	2096.72	571.51
22	4	1905.00	354.45	1614.02	195.77	13	2083.85	355.87	2108.08	563.08
23	4	1731.25	264.15	1596.00	220.58	11	1915.45	344.92	2203.09	590.57
24	4	1637.50	387.07	1585.33	219.29	8	1921.25	286.23	2004.80	344.92
25	4	1665.00	231.01	1622.37	207.83	12	1920.83	441.84	1991.26	520.15
26	4	1632.50	109.05	1616.20	210.71	13	1914.62	505.89	2102.73	579.36
27	5	1661.00	200.45	1602.91	187.70	11	2003.55	456.53	2048.98	507.02
28	4	1617.50	135.00	1526.57	75.79	11	1884.55	445.45	2015.98	537.63
29	3	1646.67	161.66	1528.53	94.65	10	1896.00	461.26	2112.35	515.87
30	4	1622.50	202.55	1635.42	198.08	11	1879.09	391.70	2097.72	455.35
31	4	1825.00	181.38	1631.80	199.61	9	1936.67	367.97	2064.94	372.09
32	3	1683.33	123.42	1669.10	237.86	8	2075.00	303.65	2144.56	553.10
33	3	1640.00	45.83	1542.97	85.84	12	1985.00	337.22	2137.20	498.63
34	4	1465.00	270.62	1543.87	61.56	8	2008.13	341.84	2087.83	401.81
35	2	1735.00	91.92	1781.38	200.58	8	1915.00	394.53	2139.87	623.62
36	4	1572.50	116.73	1659.19	199.55	2	1985.00	445.48	1835.35	241.74

Note. M = mean; SD = standard deviation; REE = resting energy expenditure.

Table 2.7. Means and Standard Deviations of Breezing™ REE and the Estimated Equation by Energy Intake.

EI	Meeting Guidelines					Exceeding Guidelines				
		Breezing™ REE (kcal)		Estimated REE (kcal)			Breezing™ REE (kcal)		Estimated REE (kcal)	
Gestational Week	***N***	***M***	***SD***	***M***	***SD***	***N***	***M***	***SD***	***M***	***SD***
8	1	1820.00	--	1482.16	--	3	2116.67	411.02	2964.42	219.27
9	1	2330.00	--	3022.81	--	5	1998.00	363.14	2118.25	757.45
10	3	1420.00	266.65	1882.90	687.08	4	1946.25	288.95	1937.62	756.72
11	5	1702.00	151.56	1859.53	495.05	5	1820.00	368.24	2158.49	862.51
12	6	1821.67	248.39	1844.23	666.04	8	1698.75	427.40	2000.54	547.18
13	8	1818.75	419.68	1845.35	433.18	6	1985.00	390.22	2120.55	755.68
14	10	1767.00	456.88	1996.79	533.77	7	1849.29	409.42	1733.78	592.87
15	7	1812.86	403.10	2085.90	565.43	9	1846.67	321.36	1600.23	224.92
16	11	1812.27	394.06	2004.59	652.31	6	2141.67	358.24	1702.52	274.52
17	9	1833.33	374.23	1971.40	573.06	9	1887.78	386.87	1741.94	321.71
18	4	1790.00	184.57	2088.40	488.11	13	1966.15	347.86	1799.97	487.38
19	6	1881.67	122.22	2143.22	266.10	8	1902.50	308.35	1609.36	196.29
20	5	2042.00	480.02	2344.29	596.15	11	1831.36	259.08	1667.42	297.63
21	7	1870.00	294.79	2149.28	563.76	9	2075.56	533.55	1883.69	560.68
22	5	1990.00	471.86	2175.02	767.84	12	2063.33	314.05	1915.50	433.83
23	7	1908.57	381.90	2289.01	574.45	8	1829.38	292.78	1824.36	524.91
24	6	1720.00	301.13	1964.24	444.45	6	1933.33	359.93	1765.71	260.90
25	6	1851.67	562.97	2146.25	683.07	10	1860.00	319.55	1750.71	256.98
26	9	1864.44	575.13	2218.98	652.92	8	1830.00	316.00	1728.68	255.39
27	6	2023.17	560.05	2257.75	589.50	10	1820.50	320.75	1700.69	234.38
28	10	1740.00	401.58	1964.07	582.57	5	1960.00	398.56	1728.28	304.33
29	10	1831.00	448.32	2084.94	535.37	3	1863.33	386.83	1619.87	245.80
30	10	1816.00	372.54	2105.67	489.54	5	1800.00	387.49	1711.98	190.10
31	8	1862.50	279.32	1903.25	441.09	5	1966.00	399.16	1977.13	303.30
32	6	2061.67	346.32	2220.68	630.18	5	1856.00	271.81	1767.93	225.33
33	6	1770.00	193.91	1857.65	274.73	8	2051.25	384.72	2101.11	645.73
34	6	1553.33	298.04	1778.47	343.41	6	2100.83	310.14	2034.54	478.37
35	5	1836.00	507.03	2054.17	717.49	5	1922.00	160.53	2082.17	476.19
36	2	1630.00	56.57	1657.33	10.03	4	1750.00	384.62	1748.20	263.42

Note. M = mean; SD = standard deviation; REE = resting energy expenditure; EI = energy intake.

Table 2.8. Means and Standard Deviations of Breezing™ REE and the Estimated Equation by Physical Activity Level.

	Low Active					Active				
PA		Breezing™ REE (kcal)		Estimated REE (kcal)			Breezing™ REE (kcal)		Estimated REE (kcal)	
Gestational Week	*N*	*M*	*SD*	*M*	*SD*	*N*	*M*	*SD*	*M*	*SD*
8	2	2165.00	487.90	2299.18	1155.45	1	1690.00	--	2713.02	--
9	6	2053.33	351.95	2269.01	771.59	-	--	--	--	--
10	3	1730.00	210.71	1863.72	703.51	2	1687.50	81.32	1645.94	199.19
11	5	1676.00	358.23	2061.40	750.31	4	1855.00	165.23	2067.99	742.08
12	9	1761.11	406.15	1917.00	681.37	3	1733.33	381.10	2140.61	468.18
13	6	1958.33	491.34	2045.87	810.48	6	1760.00	289.00	1887.30	442.93
14	8	1681.88	401.14	1847.85	668.20	5	1764.00	244.30	1741.73	232.02
15	8	1886.25	364.73	1891.77	624.77	5	1740.00	259.04	1660.73	235.67
16	9	1710.56	341.01	1811.03	638.61	3	2003.33	170.39	1787.35	261.92
17	8	1642.50	188.51	1645.06	408.03	5	2192.00	407.39	2094.38	637.82
18	12	1921.67	366.63	1806.55	562.77	2	2060.00	183.85	2001.22	101.28
19	6	1903.33	189.17	1715.73	331.85	7	1910.00	297.27	1896.17	371.68
20	10	1896.50	410.81	1821.30	585.70	5	1922.00	228.95	2011.22	408.35
21	12	1900.83	443.16	1869.39	521.30	3	2216.67	476.06	2179.19	419.90
22	10	2017.00	404.48	1820.68	534.05	4	2075.00	380.75	2049.26	467.11
23	9	1862.78	363.48	2101.43	600.83	5	1792.00	250.44	1732.34	279.64
24	5	1600.00	197.36	1782.48	517.03	4	2150.00	123.02	1951.31	117.28
25	11	1765.45	292.49	1833.88	375.77	4	2232.50	498.42	2174.80	730.72
26	11	1637.27	217.49	1811.55	393.32	4	2140.00	283.90	2171.57	631.88
27	12	1714.58	167.68	1779.93	367.64	2	2114.50	248.19	1917.99	57.58
28	10	1664.00	195.74	1769.36	397.66	3	1810.00	504.08	1718.82	131.71
29	7	1630.00	268.27	1757.11	445.63	2	1945.00	459.62	1762.00	193.76
30	8	1636.25	208.60	1712.75	192.31	3	2270.00	157.16	2526.31	564.09
31	8	1747.50	217.04	1746.17	281.48	1	2240.00	--	2752.11	--
32	7	1827.14	207.26	1830.68	424.05	1	2270.00	--	1925.34	--
33	5	1696.00	84.44	1631.01	165.27	3	1850.00	415.81	1735.84	179.60
34	5	1622.00	85.56	1722.22	358.16	2	1955.00	572.76	1796.96	222.60
35	4	1572.50	164.60	1648.88	14.35	1	2130.00	--	1965.26	--
36	6	1710.00	305.35	1717.91	209.42	--	--	--	--	--

Note. M = mean; SD = standard deviation; REE = resting energy expenditure; PA = physical activity.

Table 2.9. Means and Standard Deviations of Breezing™ REE and the Estimated Equation by Gestational Weight Gain.

GWG	Meeting Guidelines					Exceeding Guidelines				
		Breezing™ REE (kcal)		Estimated REE (kcal)			Breezing™ REE (kcal)		Estimated REE (kcal)	
Gestational Week	***N***	***M***	***SD***	***M***	***SD***	***N***	***M***	***SD***	***M***	***SD***
8	4	2042.50	366.91	2593.85	762.45	0	--	--	--	--
9	5	1998.00	363.14	2118.25	757.45	1	2330.00	.	3022.81	.
10	5	1927.00	253.91	1911.39	657.96	3	1420.00	266.65	1882.90	687.08
11	6	1845.00	253.44	2334.05	716.84	4	1635.00	284.08	1521.44	91.86
12	10	1734.00	378.10	1834.71	559.41	4	1795.00	337.49	2180.64	642.71
13	8	1916.25	499.37	2037.72	598.73	6	1855.00	257.12	1864.06	602.62
14	6	1715.83	115.34	1819.29	472.22	11	1847.27	527.13	1926.24	616.33
15	10	1899.00	384.32	1929.05	535.99	6	1720.00	266.91	1618.82	247.09
16	7	2012.86	389.18	1948.47	642.02	10	1869.50	424.58	1862.63	525.21
17	9	1975.56	351.89	2002.76	570.05	8	1646.25	236.76	1700.76	316.53
18	6	1753.33	234.32	1866.19	472.17	10	1971.00	308.67	1873.89	547.92
19	9	1922.22	287.91	1771.07	260.03	5	1842.00	120.29	1958.91	486.46
20	7	2025.00	406.52	2055.53	675.83	9	1797.78	262.34	1741.60	306.97
21	5	2042.00	213.94	2252.10	461.82	11	1960.00	525.26	1885.24	581.71
22	1	2110.00	--	1846.85	--	16	2037.50	364.19	2000.89	556.42
23	8	1908.75	389.12	2301.06	673.92	7	1817.86	260.70	1744.21	250.98
24	4	2022.50	184.82	1992.29	174.07	7	1782.86	351.46	1843.06	439.80
25	9	1868.89	448.57	2069.06	582.60	6	1921.67	352.39	1708.38	184.97
26	10	2000.00	536.80	2183.45	623.29	7	1631.43	181.42	1709.40	277.90
27	4	1834.75	140.35	1837.41	169.46	10	1922.00	475.13	1951.64	582.13
28	7	1904.29	376.20	2010.23	708.42	6	1666.67	377.34	1749.61	176.60
29	6	1866.67	484.71	2258.05	608.82	6	1866.67	402.92	1772.66	288.91
30	4	1855.00	238.96	2052.30	644.77	10	1839.00	401.54	1987.89	386.72
31	8	1895.00	239.40	1896.01	447.41	5	1914.00	451.14	1988.70	282.41
32	2	2060.00	296.99	1762.54	230.23	9	1947.78	335.74	2070.96	563.37
33	4	1800.00	322.18	1642.31	210.67	9	1973.33	375.57	2165.12	569.85
34	0	--	--	--	--	11	1895.91	346.27	1939.57	422.64
35	4	1742.50	187.51	1813.09	188.26	2	1835.00	148.49	1811.03	227.40
36	2	1660.00	99.00	1796.35	206.64	2	1985.00	445.48	1835.35	241.74

Note. M = mean; SD = standard deviation; REE = resting energy expenditure; GWG = gestational weight gain.

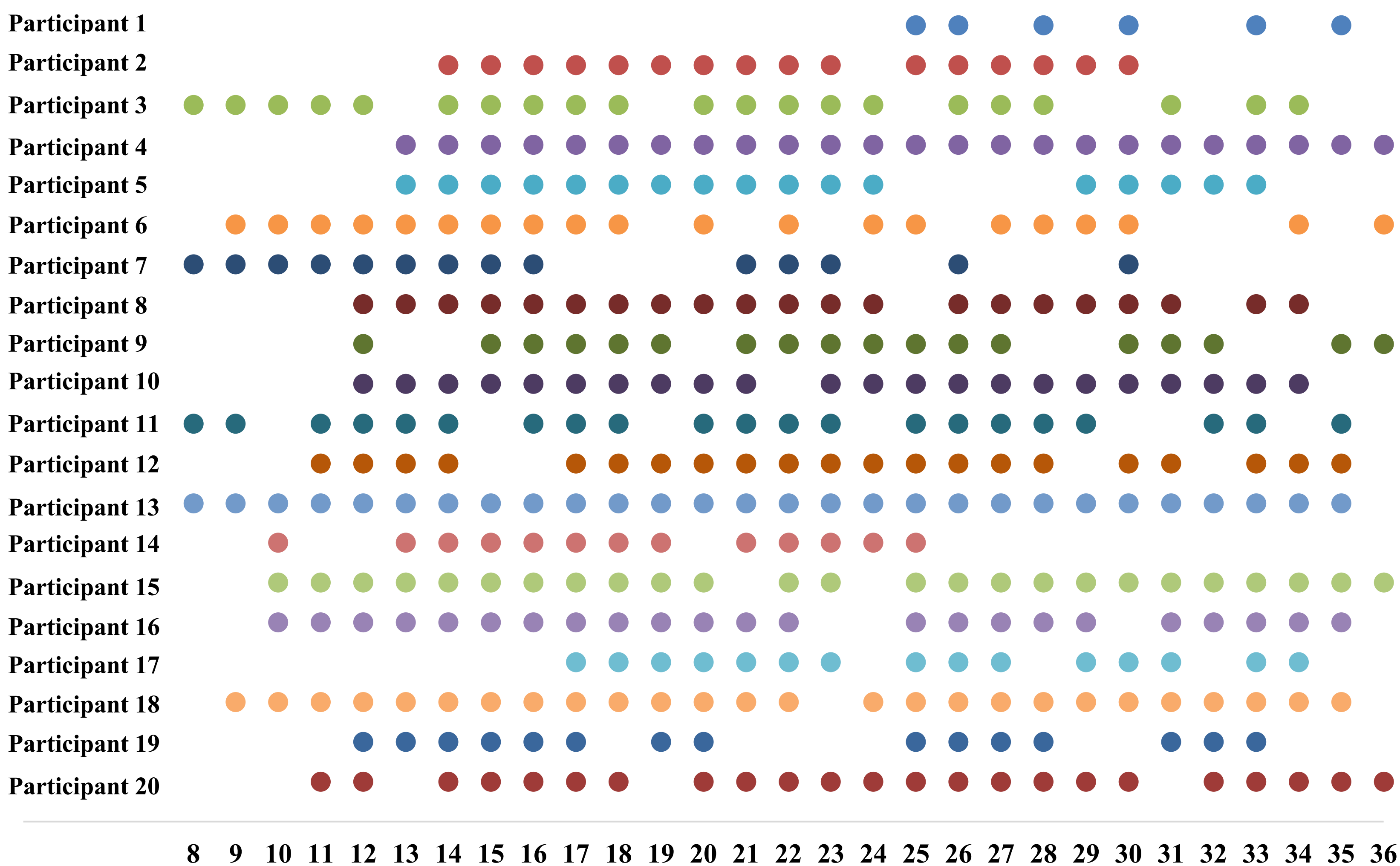


Figure 2.1. Available Resting Energy Expenditure Data for Each Participant.

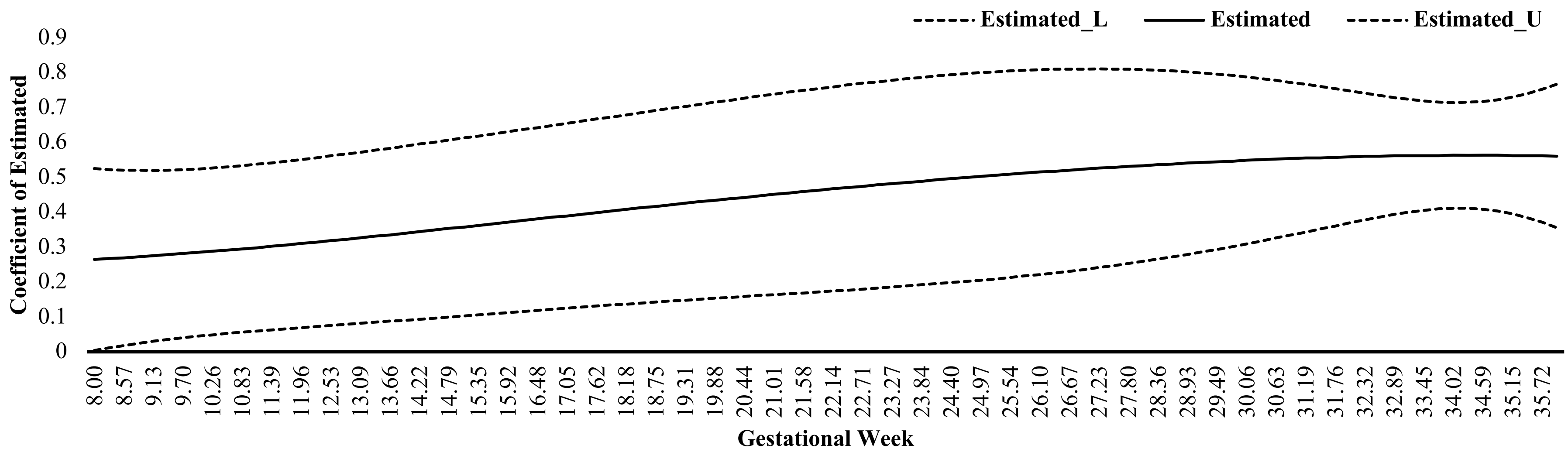
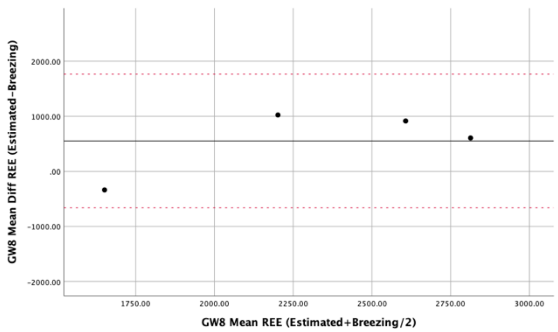
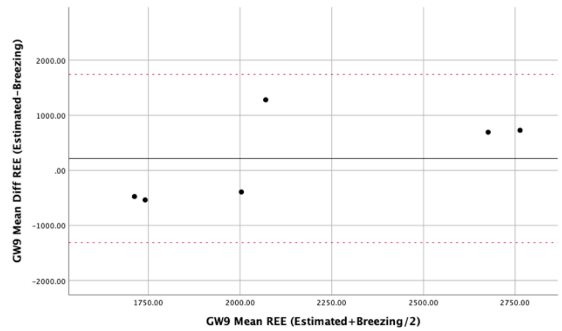
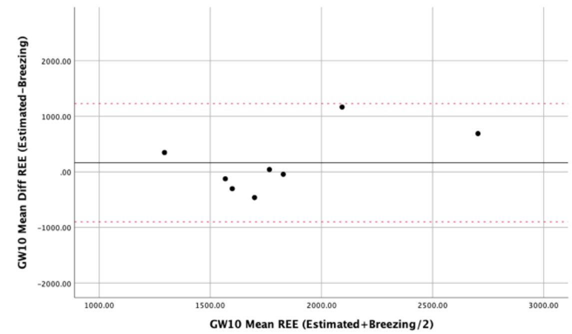
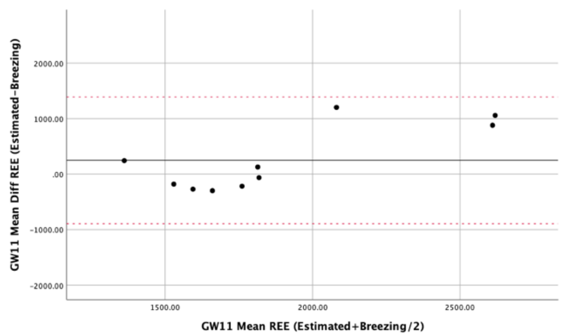


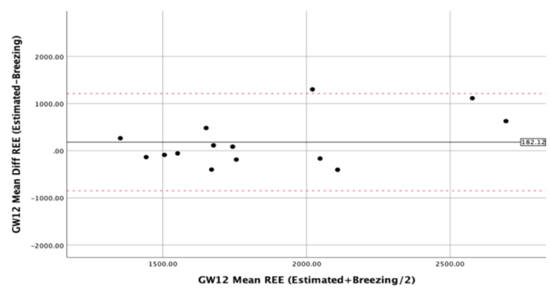
Figure 2.2. Time-Varying Effect Model Examining the Association Between Estimated (independent variable) and Breezing™ (dependent variable) Resting Energy Expenditure.
Note. Estimated = estimated REE; L = lower 95% confidence interval; U = upper 95% confidence interval.

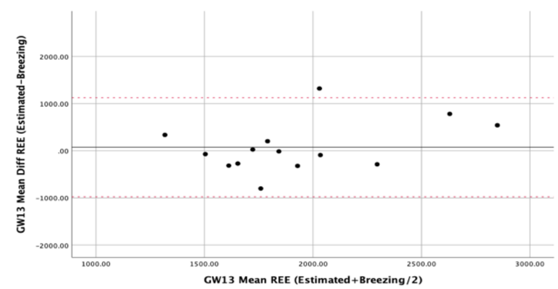

GW8 Mean Diff REE (Estimated−Breezing)
2000.00
1000.00
.00
−1000.00
−2000.00
1750.00
2000.00
2250.00
2500.00
2750.00
3000.00
GW8 Mean REE (Estimated+Breezing/2)

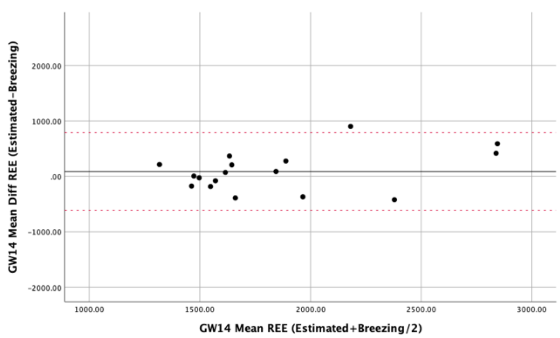

GW9 Mean Diff REE (Estimated−Breezing)
2000.00
1000.00
.00
−1000.00
−2000.00
1750.00
2000.00
2250.00
2500.00
2750.00
GW9 Mean REE (Estimated+Breezing/2)

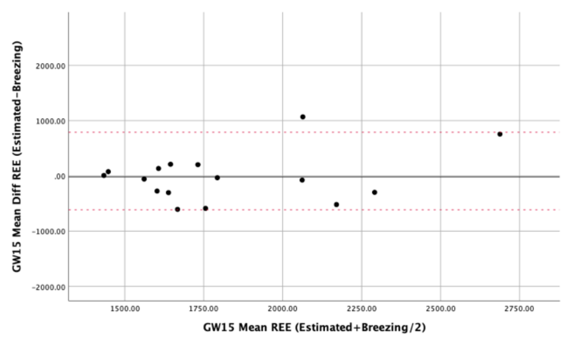

GW10 Mean Diff REE (Estimated−Breezing)
2000.00
1000.00
.00
−1000.00
−2000.00
1000.00
1500.00
2000.00
2500.00
3000.00
GW10 Mean REE (Estimated+Breezing/2)

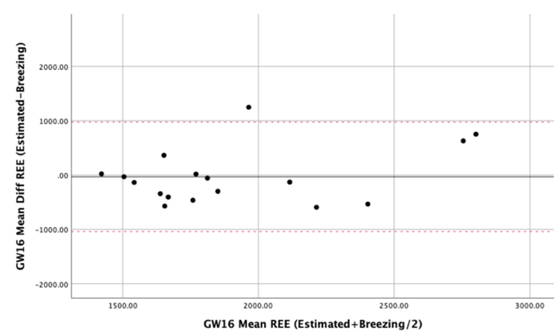

GW11 Mean Diff REE (Estimated−Breezing)
2000.00
1000.00
.00
−1000.00
−2000.00
1500.00
2000.00
2500.00
GW11 Mean REE (Estimated+Breezing/2)

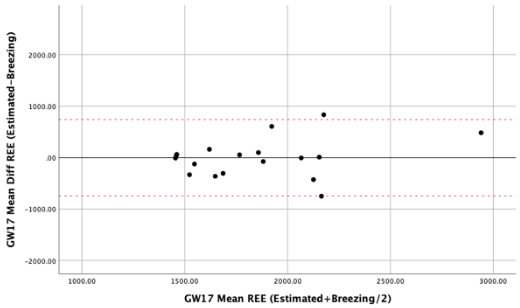

GW12 Mean Diff REE (Estimated−Breezing)
2000.00
1000.00
.00
−1000.00
−2000.00
182.12
1500.00
2000.00
2500.00
GW12 Mean REE (Estimated+Breezing/2)

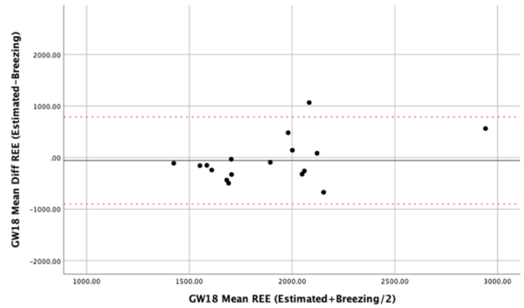

GW13 Mean Diff REE (Estimated−Breezing)
2000.00
1000.00
.00
−1000.00
−2000.00
1000.00
1500.00
2000.00
2500.00
3000.00
GW13 Mean REE (Estimated+Breezing/2)

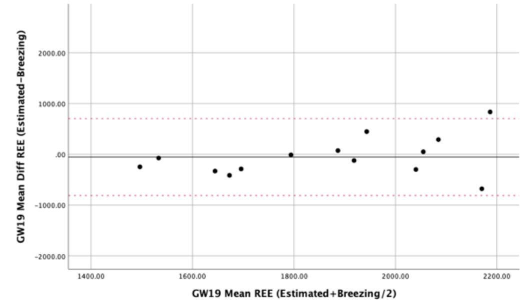

GW14 Mean Diff REE (Estimated−Breezing)
2000.00
1000.00
.00
−1000.00
−2000.00
1000.00
1500.00
2000.00
2500.00
3000.00
GW14 Mean REE (Estimated+Breezing/2)

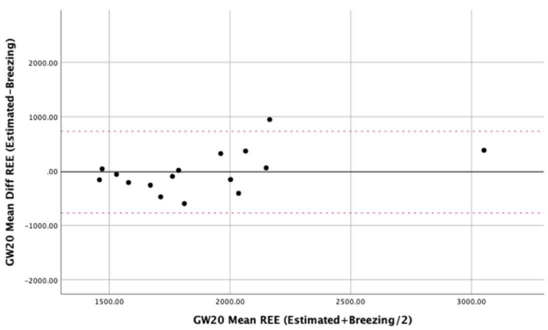

GW15 Mean Diff REE (Estimated−Breezing)
2000.00
1000.00
.00
−1000.00
−2000.00
1500.00
1750.00
2000.00
2250.00
2500.00
2750.00
GW15 Mean REE (Estimated+Breezing/2)

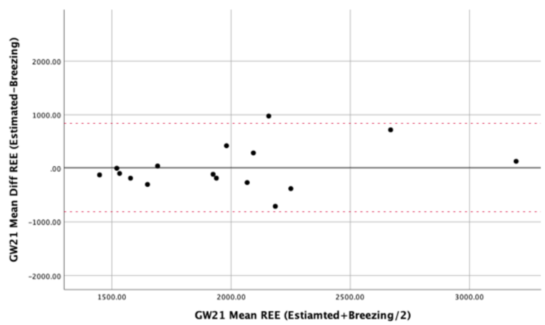

GW16 Mean Diff REE (Estimated−Breezing)
2000.00
1000.00
.00
−1000.00
−2000.00
1500.00
2000.00
2500.00
3000.00
GW16 Mean REE (Estimated+Breezing/2)

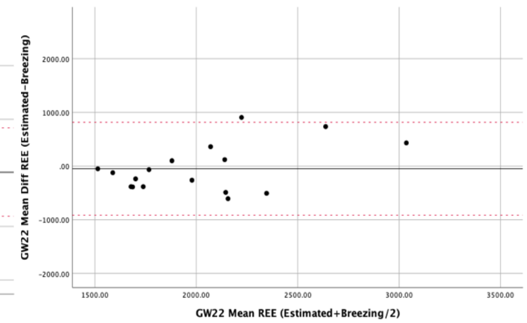

GW17 Mean Diff REE (Estimated-Breezing)
GW17 Mean REE (Estimated+Breezing/2)

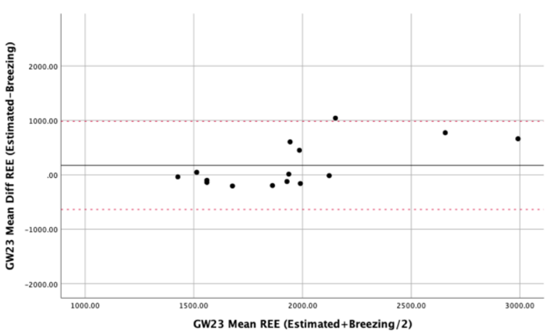

GW18 Mean Diff REE (Estimated-Breezing)
GW18 Mean REE (Estimated+Breezing/2)

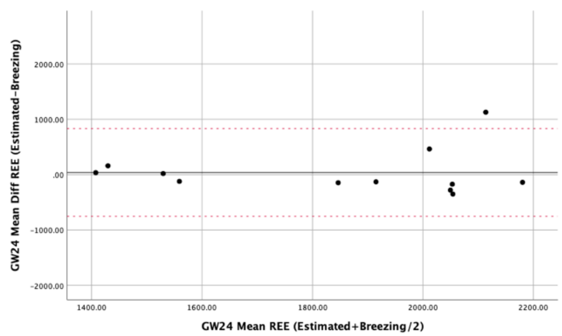

GW19 Mean Diff REE (Estimated-Breezing)
GW19 Mean REE (Estimated+Breezing/2)

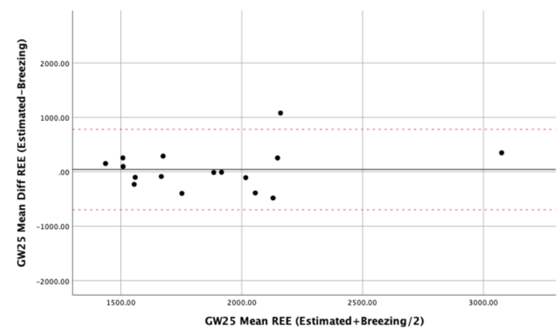

GW20 Mean Diff REE (Estimated-Breezing)
GW20 Mean REE (Estimated+Breezing/2)

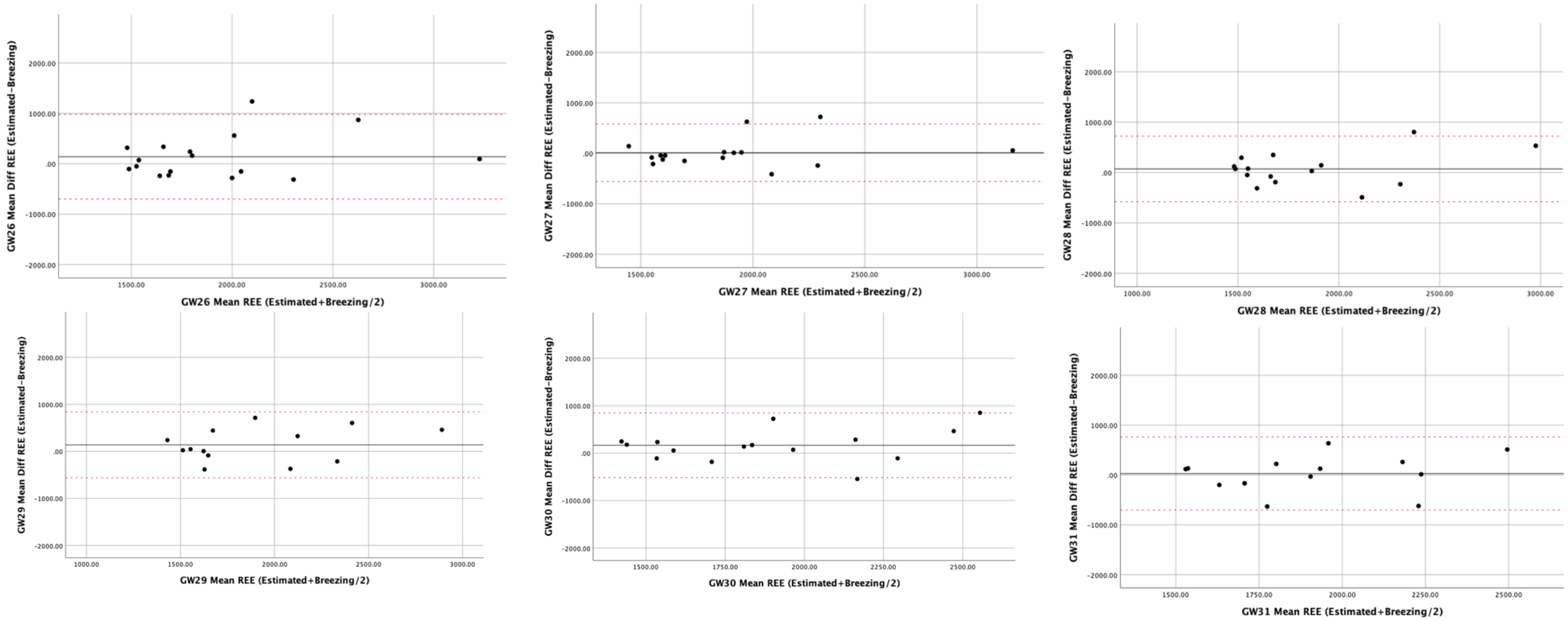

GW21 Mean Diff REE (Estimated-Breezing)
GW21 Mean REE (Estiamted+Breezing/2)


GW22 Mean Diff REE (Estimated-Breezing)
GW22 Mean REE (Estimated+Breezing/2)


GW23 Mean Diff REE (Estimated-Breezing)
GW23 Mean REE (Estimated+Breezing/2)


GW24 Mean Diff REE (Estimated-Breezing)
GW24 Mean REE (Estimated+Breezing/2)


GW25 Mean Diff REE (Estimated-Breezing)
GW25 Mean REE (Estimated+Breezing/2)


GW26 Mean Diff REE (Estimated−Breezing)
GW26 Mean REE (Estimated+Breezing/2)
GW27 Mean Diff REE (Estimated−Breezing)
GW27 Mean REE (Estimated+Breezing/2)
GW28 Mean Diff REE (Estimated−Breezing)
GW28 Mean REE (Estimated+Breezing/2)
GW29 Mean Diff REE (Estimated−Breezing)
GW29 Mean REE (Estimated+Breezing/2)
GW30 Mean Diff REE (Estimated−Breezing)
GW30 Mean REE (Estimated+Breezing/2)
GW31 Mean Diff REE (Estimated−Breezing)
GW31 Mean REE (Estimated+Breezing/2)

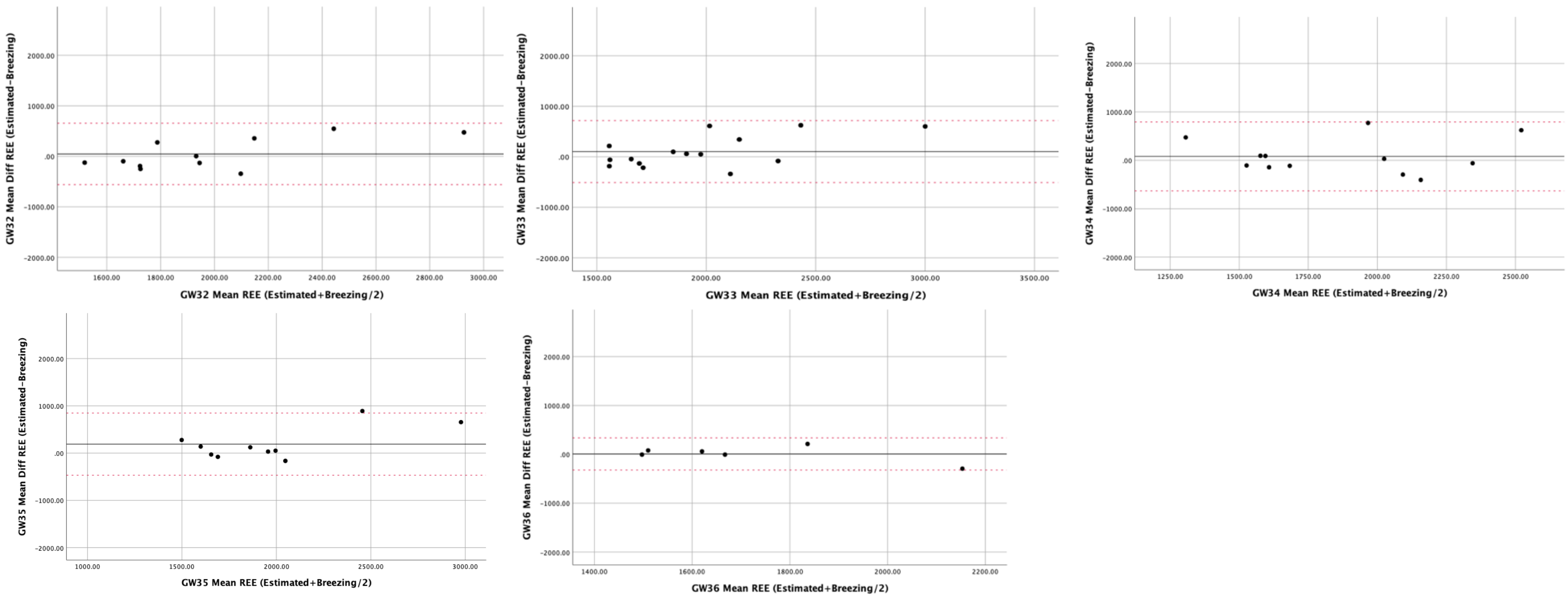


Figure 2.3. Bland-Altman Plots Between Estimated and Breezing™ Resting Energy Expenditure (kcal).
Note. GW = gestational week; REE = resting energy expenditure; Diff = difference; Solid black line = mean of the difference between the methods; red dashed lines = upper and lower 95% confidence intervals of the mean difference.

Chapter 3

Low Resting Energy Expenditure and High Energy Intake but not Physical Activity Predict High Second Trimester Gestational Weight Gain in Pregnant Women with Overweight/Obesity

Pregnant women with overweight or obesity (PW-OW/OB) and/or excessive gestational weight gain (GWG) are at increased risk for maternal and infant morbidity and mortality such as gestational diabetes, hypertensive disorders, and long-term maternal and childhood obesity (Institute of Medicine [IOM], 2009). Excessive GWG is defined as weight gained above the IOM (2009) guidelines for pre-pregnancy body mass index (BMI; i.e., normal weight: >35 pounds, overweight >25 pounds, obesity >20 pounds). PW-OW/OB are at unique risk for exceeding weight gain guidelines because they often underestimate their BMI and overestimate how much weight they should safely gain in pregnancy (Jeffs, Haszard, Sharp, Gullam, & Paterson, 2016). They also report low self-efficacy, high sugar intake, low fruit/vegetable intake, and low physical activity; all of which make it challenging to regulate weight (Daly et al., 2016; de Jersey, Nicholson, Callaway, & Daniels, 2013; Nagourney et al., 2019; Symons Downs, Savage, & Rauff, 2014). Thus, there is an important need to identify strategies that effectively regulate GWG among PW-OW/OB to reduce short- and long-term adverse health risks.

GWG is largely influenced by the components of energy balance: energy intake and energy expenditure (physical activity, resting energy expenditure [REE]; McDowell et al., 2019). As such, Thomas and colleagues (2012) developed a dynamical model of energy balance based on the first law of thermodynamics and evidence from Butte and colleagues (2003; 2004) to predict GWG. The energy balance formula is:

$$ES(t) = EI(t) - TEE(t)$$

Net energy stored at time *t* is denoted as ES(t) while EI(t) and TEE(t) represent energy intake (EI) and total energy expenditure (TEE), respectively. TEE includes three separate subcomponents:

$$TEE(t) = PA(t) + TEF(t) + REE(t)$$

TEE is represented as the sum of physical activity (PA), thermic effect of food (TEF), and REE. It is important to note that body fat accumulates during pregnancy, and pregnant women will gain weight due to the growing baby and maternal physiological changes of pregnancy itself (e.g., developing placenta, increased blood volume and amniotic fluid; Butte et al., 2003). Thus, effective GWG regulation is a result of net energy stored (i.e., energy intake - expenditure), fetal growth (i.e., fetal body mass, birthweight-for-gestational-age), and the presumed weight gain due to maternal physiological changes (e.g., placenta, increased blood volume, amniotic fluid).

Studies aiming to regulate GWG have primarily focused on the combined effects of energy intake and physical activity behaviors. There is a growing body of research that shows women with higher energy intake and lower physical activity have higher GWG than women with lower energy intake and higher physical activity (Bisson et al., 2015; Dubois et al., 2018; Ruchat et al., 2018). Moreover, there is evidence to show that women increase in energy intake and decline in physical activity from the second to third trimester and that the increase in energy intake and decline in physical activity is associated with high GWG (Ancira-Morena et al., 2019; Borodulin et al., 2008; Borodulin et al., 2009; Dubois et al., 2018; Engberg et al., 2012; Johnson et al., 2015; Most, Dervis, Haman, Adamo, & Redman, 2019; Ruchat et al., 2018; Santos et al., 2018; Wang et al., 2019). It is important to note however, that recent researchers have suggested that while physical activity promotion remains important for GWG regulation, GWG may actually be more of a result of high energy intake rather than low prenatal physical activity (Gilmore et al., 2016). For example, Gilmore and colleagues (2016) categorized $N = 45$ healthy pregnant women of all weight statuses as "low + ideal gainers" ($n = 26$) if they gained below or within the IOM GWG guidelines or "high gainers" ($n = 19$) if they gained above the IOM GWG guidelines. They found that women categorized as "high gainers" consumed 750 kcals/day higher than women categorized as "low + ideal gainers." In contrast, all women declined in physical activity and expended the same amount of active kcals/day suggesting that exceeding GWG guidelines may not be a result of reduced physical activity. Nevertheless, the researchers recommended that GWG regulation interventions should continue to focus on moderating energy intake and maintaining physical activity during pregnancy. Unfortunately, most of the randomized controlled trials (RCT) focusing on moderating energy intake and improving physical activity to regulate GWG in PW-OW/OB have shown either no effect (Bruno et al., 2017; Dodd, Grivell, Crowther, & Robinson, 2010; Dodd et al., 2014; Guelinckx, Devlieger, Mullie, & Vansant, 2010; Hawkins et al., 2015; Szmeja et al., 2014) or a modest effect (e.g., Phelan, Phipps, Abrams, Darroch, Schaffner, & Wing, 2011; Redman et al., 2017) on GWG. This can partly be attributed to the lack of specific energy intake and physical activity guidelines for PW-OW/OB and the challenges associated with moderating energy intake and promoting physical activity in this special population. For example, PW-OW/OB have reported that if they do not engage in moderating their energy intake or engage in physical activity at the start of pregnancy, then it will be difficult to break the habit of consuming excessive calories and inactivity throughout pregnancy regardless of behavioral intervention (Flannery et al., 2018). In addition, many studies including energy intake moderation and physical activity promotion have focused on recommending a specific calorie goal for energy intake (e.g., 2600 kcal/day; ACOG, 2016; Gilmore et al., 2016) or a goal of achieving the national recommendations of 150-minutes of moderate to vigorous physical activity per week (ACOG, 2015; USDHHS, 2018) that are appropriate for women with normal weight. However, given the unique challenges PW-OW/OB face with underreporting energy intake and overestimating their energy requirements as well as challenges with engaging in sufficient physical activity (Moran et al., 2018; Mullaney et al., 2014; Nagourney et al., 2019; Nowicki et al., 2011; Symons Downs, Savage, & Rauff, 2014; Symons Downs et al., 2019), meeting these energy intake and physical activity goals may seem too difficult to achieve, and thus, they struggle to regulate GWG with these behaviors. While moderating energy intake and promoting physical activity remain important targets of intervention, there is a need to identify useful ways to promote these behaviors and/or find other "achievable" targets to effectively regulate GWG in PW-OW/OB.

One modifiable factor of GWG that may inform more achievable energy intake and physical activity recommendations and is often overlooked is REE, or the number of calories burned at rest (Taousani et al., 2017). REE accounts for 60-70% of total energy expenditure compared with the approximate 20% that is attributed to physical activity and is often used in non-pregnant individuals to create energy intake and physical activity goals to achieve weight loss (McClave and Snider, 1992). Yet, little attention has been given to REE as a determinant of GWG (Berggren et al., 2017; Taousani et al., 2017; Vander Wyst et al., 2020). REE is influenced by several factors including body composition, physical activity, nutrition, hormones, age, and race/ethnicity. Fat free mass is the largest determinant of REE with higher fat free mass associated with higher REE (Butte et al., 2004; Butte, 2005; Catalano, 1999; Gilliat-Wimberly et al., 2001; Stiegler & Cunliffe et al., 2006; Taousani et al., 2017). Also, researchers have found that engaging in healthy eating and physical activity behaviors can increase fat free mass and thus, increase REE (Careau, 2017; Gilliat-Wimberly et al., 2001; Hronek et al., 2013; Taousani et al., 2017; Yoo, 2018). Thus, it is assumed that energy intake, physical activity, and REE hold a cyclical relationship. However, limited research has examined the utility of REE to create individualized energy intake and physical activity goals in PW-OW/OB to regulate GWG.

Recent observational evidence shows that low prenatal REE at 34-36 weeks gestation was significantly associated with high total GWG (Berggren et al., 2017). However, this was based on a one-time assessment of REE, limiting the understanding of prenatal REE and its influence on GWG. Advancements in mobile technology are providing a unique opportunity for more readily available assessments of REE to better understand prenatal REE and its influence on GWG. Evidence from Chapter 2 of this dissertation showed that frequent measures of REE can be obtained from a mobile metabolism device or an estimated equation (Thomas et al., 2012) with agreement across both methods. However, the agreement was only apparent during certain gestational weeks (i.e., 8-10, 12-22, 24-31, 34, 36) and depended on certain characteristics (i.e., randomized to intervention vs. control, weight status, fat free mass, energy intake). Thus, researchers are recommended to run study analyses with or without using both assessments (i.e., mobile metabolism and estimated equation) to understand if the discrepancy between the methods impact outcomes. Nevertheless, there is a novel opportunity to better understand prenatal REE and its influence on GWG under the context of the Healthy Mom Zone intervention given that all components of energy balance (energy intake, physical activity, REE) and GWG were measured weekly (Symons Downs et al., 2018; Symons Downs et al., under review) in PW-OW/OB. Moreover, no published studies have been found that examined the collective influence of energy intake, physical activity, and REE for explaining GWG in PW-OW/OB. Specifically, no studies have been located that examine the extent to which REE predicts GWG beyond the contributions of energy intake and physical activity. Further, little to no research has examined these factors during crucial periods of gestation when GWG may be most difficult to regulate. For example, the pattern of GWG in a typical pregnancy is often described as sigmoidal where mean weight gain is higher in the second trimester than the first and third trimesters, marking the second trimester as a critical time period for GWG (IOM, 2009). The IOM guidelines note that this sigmoidal pattern of GWG may not be apparent in PW-OB, as most PW-OB tend to increase in weight in the second trimester and further increase in the third trimester. However, the second trimester remains a critical time period for PW-OW/OB as it is marked by a rapid increase in GWG due to nearly a 50% increase in blood volume and amniotic fluid to accommodate the growing fetus and this rapid increase has been shown to predict overall excessive GWG (IOM, 2009; Overcash et al., 2015). Examining the extent to which energy intake, physical activity, and REE explain GWG among PW-OW/OB, particularly during the second trimester, may provide useful insight regarding how to better promote these behavioral strategies to effectively regulate GWG.

The purposes of this secondary analysis study were to examine the extent to which energy intake, physical activity, and REE were associated with and explained second trimester GWG among PW-OW/OB. Based on past research (Berggren et al., 2017; Bisson et al., 2015; Dubois et al., 2018; McDowell et al., 2019; Ruchat et al., 2018) it was hypothesized that high energy intake, low physical activity, and low REE would be associated with and predict high GWG. Also, based on the abundant research examining energy intake and physical activity as determinants of GWG and because there are no located studies examining the contribution for REE predicting GWG, it is hypothesized that high energy intake would emerge as the strongest determinant of GWG followed by low physical activity and then low REE.

Methods

Participants

Women (N = 31) were PW-OW/OB participating in the Healthy Mom Zone feasibility study, a theoretically-based behavioral intervention that adapted the intervention dosage and intensity over time in PW-OW/OB to regulate GWG (Symons Downs et al., 2018; Symons Downs et al., under review). Women were randomized to an intervention or usual care control group from ~8-36 weeks gestation. Women were eligible to participate if they were ages 18-40 years and had: 1) overweight/obesity (BMI range 25-45 kg/m^2; >40 kg/m^2 with physician consultation), 2) singleton pregnancy >8 weeks gestation, 3) physician consent to participate, and 4) were English-speaking, residing in or near Central Pennsylvania. Exclusion criteria were: 1) multiple gestation, 2) diabetes at study entry, 3) not having overweight/obesity, 4) severe allergies or dietary restrictions, 5) contraindications to prenatal physical activity (American College of Obstetrics and Gynecologists [ACOG], 2015) and, 6) not residing in area for duration of study. A more detailed explanation of the Healthy Mom Zone Intervention can be found elsewhere (Symons Downs et al., 2018; Symons Downs et al., under review). Of the N = 31 women, n = 3 had miscarriages prior to starting the intervention and n = 1 woman withdrew, resulting in a total sample of N = 27. Of the N = 27 women, n = 1 women had limited physical activity data and was thus excluded from the current analyses. There were no differences in demographics or the remaining study variables (i.e., energy intake, physical activity, REE, GWG) when this woman was included versus excluded. Thus, the current secondary analyses are based on a total sample of N = 26.

Procedures

The Healthy Mom Zone study was approved by the Pennsylvania State University Institutional Review Board (IRB Study# 00000122). Women completed a 30-minute baseline session at ~8 weeks gestation at the University's Clinical Research Center. Study procedures were explained to the participants and written informed consent was obtained for each woman. Women received an Aria Fitbit Wi-Fi scale to weigh themselves daily from ~8-36 weeks gestation. Weights were transmitted via Bluetooth to research investigators each day. Women also wore a wrist-worn activity monitor daily throughout the study period to assess physical activity. Women were instructed to wear an ActiGraph GT3x+ intermittently as a supplement to the wrist-worn activity monitor given the ActiGraph is a widely utilized gold standard approach. Next, a study staff person explained how to download the Breezing™ application onto each woman's Smartphone. All women were trained on how to use the Breezing™ device and sent home with detailed instructions. They were instructed to use the Breezing™ device one time per week (on the same day of the week) from ~8-36 weeks gestation. Women were recommended to obtain a Breezing™ measurement after 8 hours of sleep, immediately after waking up while lying down and in a fasting state (e.g., no food for the past 4-6 hours). First, women opened the Breezing™ application on their phone and followed a checklist of instructions to obtain a measurement. Second, women scanned the QR code on the package of provided sensor cartridges. Third, women placed a nose clip onto their nose and practiced breathing in the mouthpiece alone until breathing was consistent. Finally, women were prompted to insert one sensor cartridge into the tracking device and preform an actual measurement. Women carefully picked up the tracker and blew into the mouthpiece until the application said the test was completed (1-2 minutes). The device did not produce results if the woman had 'irregular breathing.' Women were instructed to complete another measurement until a successful assessment was obtained. On average, 5% of the sample had to repeat at least one measurement due to irregular breathing. All data was transmitted via Bluetooth to the women's smartphone and sent to the research team. At ~36 weeks gestation, women completed their last assessment and returned the device.

Measures

Energy Intake. Energy intake, matched on the day REE was obtained, was estimated using a validated back-calculation method (Symons Downs et al., 2018; 2019; Guo et al., 2016; Guo et al., 2018a; Guo et al., 2018b):

$$EI_{est}(k) = \frac{-W(k+2T) + 8W(k+T) - 8W(k-T) + W(k-2T)}{12TK_1} - \frac{K_2}{K_1}(PA(k) + REE(k))$$

The variables are as follows: k = 1, 2, …, *N* corresponding to day 1-day *N*. W represents maternal weight in kg while T represents sampling time which in this case was T = 1 day. PA represents physical activity in kcals. REE represents resting energy expenditure in kcals calculated using Breezing™ or the estimated equation depending on which REE method was used for that data point. Average second trimester energy intake was calculated as the average of the weekly point estimates from 14 to 28 weeks gestation.

Physical Activity. Active kcal (calories burned during activity) was obtained from the Jawbone UP3 wrist-worn activity monitor for each day REE was measured. Based on Evenson and Wen (2011) and Mâsse and colleagues (2005) suggestions, if there was no data from the Jawbone or the ActiGraph on the day an REE assessment was obtained, active kcal was mean replaced with the weekly average if there was ≥ 4 days of data in the week. Average second trimester physical activity active kcal was calculated as the average of the weekly point estimates from 14 to 28 weeks gestation.

Resting Energy Expenditure. REE was assessed using the Breezing™ device. The Breezing™ device is an indirect calorimetry analyzer of REE and is compatible with both iOS and Android software platforms. Sensor cartridges were used to determine the rate of oxygen consumption and carbon dioxide production. The scanned QR code carries calibration parameters for the sensor cartridge. The algorithm within the Breezing™ device then calculated REE according to the Weir equation, a well-known equation used with indirect calorimetry (Weir, 1949; Xian et al., 2015):

$$[3.9 * VO_2 + 1.1*VCO_2]* 1.44$$

VO_2 represents the volume of oxygen consumed and VCO_2 represents the volume of carbon dioxide produced. Estimated REE was calculated for each day the women had a missing Breezing™ assessment. Research investigators calculated estimated REE as a function of maternal weight for each woman by using an empirical equation that was proposed (Thomas et al., 2012) and fit using a quadratic regression equation from data collected on pregnant women by Butte and colleagues (2003; 2004):

$$REE = 0.1976W^2 - 13.424W + 1457.6$$

W represents maternal weight in kilograms. Average second trimester REE was calculated as the average of the weekly point estimates from 14 to 28 weeks gestation.

Gestational Weight Gain. Second trimester GWG was calculated as the weekly point estimate of weight (matched on the day REE was obtained) from the Aria Wi-Fi weight scale at 28 weeks gestation minus the weekly point estimate of weight at 14 weeks gestation. The Aria Wi-Fi weight scale is a valid and reliable measure of weight (Hood et al., 2019).

Demographics and Personal Characteristics. At baseline, women self-reported personal demographics (i.e., age, race/ethnicity, income, marital status, education, employment) and current gestational age. Pre-pregnancy BMI was calculated from self-reported pre-pregnancy weight and height.

Data Analyses

Data were analyzed using SPSS v25. This current study limited analyses to the second trimester based on the following rationale: (1) data was maximized in the second trimester given that the majority of women were enrolled later in the first trimester (i.e., 10-13 weeks gestation), and (2) evidence supporting the second trimester is marked by rapid GWG in PW-OW/OB and fetal growth, which may influence REE (Overcash et al., 2015). Evidence from Chapter 2 of this dissertation showed agreement between estimated and Breezing™ REE at gestational weeks 7-10, 12-22, 24-31, 34, and 36. However, there was a lack of agreement between the two methods at gestational weeks 11, 23, 32, 33, and 35 (noting, however, that there was an outlier at week 35 and once removed, there was subsequent agreement at this time point). Thus, studies utilizing Breezing™ to assess REE should examine data with and without substituting the estimated equation when Breezing™ was missing to understand if the discrepancy between the methods impacts outcomes. Given the mixed findings from Chapter 2, the analyses in the current study were run with (1) REE from Breezing™ only and (2) REE from Breezing™ and the estimated equation (i.e., estimated equation substituting missing Breezing™ REE assessments) to understand whether the discrepancy between the two methods influenced the study analyses. Means and standard deviations were used to examine demographic variables and second trimester energy intake, physical activity, REE, and GWG. Estimates that were 3 ± within person standard deviations above each woman's mean second trimester energy intake, physical activity, REE, and GWG were considered as outliers (Ruan, Chen, & Kerre, 2005). Pearson bivariate correlations were used to examine the associations between second trimester energy intake, physical activity, REE, and GWG. Correlation coefficients represented standardized effect sizes. Effect size values of 0.20, 0.50, and 0.80 were considered small, medium, and large effects, respectively (Cohen, 1988). Finally, hierarchical regression analyses were used to examine the extent to which second trimester energy intake, physical activity, and REE predicted GWG. Based on past research (Abramowitz & Stegun, 1965; Cohen, 1988; Cohen, Cohen, West, & Aiken, 2003; Raudenbush & Bryk, 2002; Soper, 2020), a minimum sample size of 20 was required for a hierarchical regression model with three predictors to detect a medium effect size (i.e., based on Berggren et al., 2017; Bisson et al., 2015; Dubois et al., 2018) with power set at 80% and alpha set at $p = 0.05$. Given the evidence that physical activity and energy intake are strong predictors of GWG (Bisson et al., 2015; Dubois et al., 2018; McDowell et al., 2019), both were included in Block 1. Because less is known about the predictive influence of REE for explaining GWG, it was included in Block 2 to explore its additional contribution. Multicollinearity was examined by calculating the variance inflation factor (VIF) for each predictor (O'Brien, 2007). A VIF value of <10 is indicative of no multicollinearity. Study assignment (intervention vs. control) group differences in GWG were also analyzed.

Results

Participant Characteristics. Participant characteristics are presented in Table 3.1. Mean age of study participants was 30.6 (*SD* = 3.0) years, mean gestational week at study entry was 10.3 weeks (*SD* = 1.7) and mean pre-pregnancy BMI was 31.4 kg/m^2 (*SD* = 7.1; overweight = 62%, obese = 38%). The sample was Non-Hispanic, White (96%), married (92%), employed full-time (88%), reported a family income ≥ $40,000 (77%), and half of the sample had a graduate/professional degree (50%). Women in the intervention (*M* = 10.6 pounds) vs. control (*M* = 10.8 pounds) group did not significantly differ in GWG, thus the remaining study analyses were conducted without adjusting for study group assignment.

Means and Standard Deviations of the Study Variables. The current analyses revealed that all study findings did not differ when the estimated equation was used as a substitute when REE from Breezing™ was missing during all time points. Thus, to maximize data, estimated REE was substituted when Breezing™ was missing across all time points (Table 3.2). Across the sample, there were 151 instances where Breezing™ was missing. Of these, 145 were replaced with estimated REE resulting in a total of 384 total REE data points across 14 to 26 weeks gestation (6 missing points). Each week ranged from 8 to 13 substitutions of estimated REE with the most substitutions occurring between weeks 19 and 24. Analyses revealed there were no outliers for any of the study variables. Means and standard deviations of second trimester energy intake, physical activity, REE, and GWG are presented in Table 3.3. Mean energy intake was 2895.90 kcals/day (*SD* = 531.36, *range* = 2095.03 to 4239.31). Mean physical activity was 423.26 kcals/day (*SD* = 227.72, *range* = 133.36 to 988.31). Mean REE was 1875.66 kcals/day (*SD* = 382.19, *range* = 1497.32 to 2893.90). Mean GWG was 10.72 pounds (*SD* = 5.55, *range* = -0.10 to 23.90).

Bivariate Correlations. Bivariate correlations are presented in Table 3.4. Mean energy intake and physical activity were not significantly associated with GWG ($p > 0.05$). However, mean REE was significantly and negatively associated with GWG (e.g., low REE associated with high GWG; $r = -0.62$, $p < 0.05$), resulting in a medium effect size ($d = 0.62$).

Hierarchical Regression. Results from the hierarchical regression analysis are presented in Table 3.5. There was no significant multicollinearity. The model including second trimester energy intake and physical activity (Block 1) explained 12% of the variance in GWG, however the model was not significant. When REE was entered into the model in Block 2 along with energy intake and physical activity, the model significantly explained 52% of the variance in second trimester GWG ($p < 0.001$). Second trimester REE was the strongest significant predictor of GWG; low REE predicted high GWG ($\beta = -1.28$, $p < 0.001$). Second trimester energy intake emerged as a secondary significant predictor; high energy intake predicted high GWG ($\beta = 1.01$, $p < 0.05$). Second trimester physical activity was not a significant determinant of GWG.

Discussion

The overall purpose of this study was to examine the extent to which energy intake, physical activity, and REE were associated with and explained second trimester GWG in PW-OW/OB. In sum, energy intake and physical activity were not significantly associated with GWG, but low REE was significantly associated with high GWG. Also, the model of energy intake, physical activity, and REE explained 52% of the variance in second trimester GWG; low REE emerged as the strongest determinant followed by high energy intake. Physical activity was not a significant determinant of second trimester GWG. These findings are among the first to provide evidence that REE, in addition to energy intake, is a predictor of second trimester GWG and illustrate a need for future research to further explore the role of energy balance within GWG interventions targeting PW-OW/OB. These findings are described in more detail below.

In partial support of the hypothesis, mean REE (1875.66 kcals/day) was significantly and negatively associated with mean GWG (10.72 pounds) during the second trimester with a medium effect size. However, mean energy intake (2895.90 kcals/day) and physical activity (473.26 kcals/day) were not significantly associated with GWG. Specifically, low REE was associated with high GWG (and vice versa), which is consistent with past research (Berggren et al., 2017). The lack of significant association between energy intake and GWG and physical activity and GWG may be due to the large variation in energy intake and physical activity. While there was variability in mean REE (*range* = 1497.32 to 2893.90), the variability in mean energy intake (*range* = 2095.03 to 4239.31) and mean physical activity (*range* = 133.36 to 988.31) was considerably greater. More research is needed to better understand this variability and the extent to which this variability influences GWG.

As predicted, the model including energy intake, physical activity, and REE predicted GWG. However, in contrast to the hypothesis it was REE that emerged as the strongest determinant. More specifically, low REE was the strongest determinant of high GWG, followed by high energy intake; physical activity did not significantly predict GWG. These findings suggest that while energy intake and physical activity remain important determinants of GWG (e.g., Dubois et al., 2018), high GWG may also be attributed to low REE. One explanation for the lack of significant prediction with respect to physical activity may be due to the fact that despite the intervention's focus on promoting activity, the PW-OW/OB in this study were nevertheless considered to be low active during this time period. For example, past researchers have suggested that a threshold for low activity for PW-OB is generally around 570 active kcals/day during pregnancy (Most et al., 2018). The majority of women (73%) in this current study expended < 570 active kcals/day; the average was 473 kcals/day, thus, confirming their lack of activity. Also, REE accounts for the majority (60-70%) of total energy expenditure compared to physical activity, which only accounts for approximately 20% (Berggren et al., 2017; Taousani et al., 2017; Vander Wyst et al., 2020). That is, total daily energy expenditure is mostly made up of continuous energy expended at rest, rather than continuous energy expenditure due to structured physical activity. Therefore, it may be that REE captures more of the variance in GWG compared to physical activity, illustrating that the regression findings should be considered within the context of understanding energy balance. Thus, future interventions aiming to regulate GWG among PW-OW/OB using strategies to moderate energy intake and promote physical activity may also want to consider the usefulness of understanding REE in relation to GWG.

More specifically, in the weight management literature with non-pregnant individuals, REE is used to inform energy intake and physical activity goals to achieve weight loss by obtaining a comprehensive understanding of total energy expenditure (McClave and Snider, 1992). However, this approach is not commonly used in pregnant women given that the goal is not to achieve weight loss, but rather regulate weight gain. Because there are no standard guidelines on how to appropriately adjust calorie goals for PW-OW/OB, Symons Downs and colleagues (under review; 2018) relied on the suggestions of Vesco and colleagues (2012) to adapt energy intake goals for PW-OW/OB in the Healthy Mom Zone GWG intervention based on the following equation: Caloric Needs = [(Pre-pregnant weight in kg)(30 kcal/kg/day)(0.70)]+[(10 kcal)(gestational age in weeks)]. Within the equation, the 0.70 factor represented a 30% reduction in the recommended energy need established for pregnant women with normal weight (ACOG, 2016). This factor could then be altered to create a 20% or 25% reduction as well. For example, using a 30% reduction, a PW-OB with a pre-pregnancy weight of 133.5kg entering the study at gestational week 10 would receive a caloric goal of 2,903.5 kcal/day. While the Healthy Mom Zone study adapted the intensity of the intervention dosage based on the tailoring variable of GWG (e.g., extent to which each woman was within or above her GWG goal range), women's calorie goals were not adapted over the course of the intervention based on the influence of their REE. For example, intervention scientists can use REE to obtain a picture of a person's total energy expenditure in order to create an individualized energy intake goal for managing GWG. Also, given that physical activity can increase REE (Gilliat-Wimberly et al., 2001; Hronek et al., 2013; Taousani et al., 2017), women can create a physical activity goal to increase their total energy expenditure, and thus, better inform energy intake kcal goals to effectively regulate GWG. However, more research is needed to examine whether this is an appropriate approach during pregnancy. Further, given the potential cyclical relationship between energy intake, physical activity, and REE (Gilliat-Wimberly et al., 2001; Hronek et al., 2013; Taousani et al., 2017), there is a need to better understand the role of all three strategies within the context of interventions to regulate GWG in PW-OW/OB.

Strengths and Limitations

This study is the first to the author's knowledge to examine the extent to which energy intake, physical activity, and REE were associated with and predicted GWG during the second trimester in PW-OW/OB. There are several strengths of this study. First, this study included objective assessments of physical activity, REE, and GWG and used a back-calculation method to assess energy intake; all of these measures provided an accurate estimate of these outcomes. Second, this study is the first to examine the contributions of energy intake, physical activity, and REE on GWG during the second trimester. This increases the ability to identify effective GWG regulation strategies during a time period that is marked by rapid growth and indicative of excessive GWG in PW-OW/OB (Overcash et al., 2015). Nonetheless, there are some limitations worth noting. The sample was largely homogenous (i.e., PW-OW/OB residing in Central Pennsylvania, White, highly educated, married) which is representative of the residents in Central Pennsylvania but does not allow for comparisons with other heterogeneous samples (e.g., urban, non-White, non-married). Also, while the sample was sufficient to conduct the regression analyses, it was not large enough to examine moderation by OW and OB subgroups. Future studies with a larger and diverse sample are needed to formally conduct moderation analyses to examine the extent to which the collective influence of energy intake, physical activity, and REE on GWG differs by PW-OW vs. PW-OB. Also, it is important to note that the current analyses included mean second trimester REE which produced a rough estimate of average REE kcal/day for each woman. Recent research has suggested that REE is variable, particularly with large fluctuations observed week to week during the second trimester (Jackemeyer et al., 2017). Thus, more research is needed to examine how REE changes on a weekly basis during this time period and how these weekly estimates are associated with GWG. Further, given that PW-OW/OB are recommended a small threshold of GWG to gain each week (i.e., OW: <0.7 pounds, OB: <0.6 pounds), it may be insightful for future research to examine the association between weekly REE and weekly GWG during the second trimester and whether this association changes over time in order to better understand how to best regulate weekly GWG and in turn, total GWG.

Conclusion

In sum, energy intake, physical activity, and REE predicted 52% of the variance in GWG in PW-OW/OB during the second trimester. A unique finding from this current study that contributes to the literature is that in addition to high energy intake, low REE predicted high second trimester GWG in PW-OW/OB. These findings suggest that future interventions aiming to regulate GWG in PW-OW/OB using behavioral strategies to moderate energy intake and promote physical activity may find it useful to incorporate assessments of REE to help women set more accurate intake and physical activity kcal goals to achieve an appropriate GWG. Given these overall findings, there is a need for future research to examine if there is variation in the associations between REE and GWG at the weekly level to understand if REE may be useful for informing weekly energy intake and physical activity goals to meet weekly GWG goals over the course of pregnancy. That is, given the small threshold of GWG that PW-OW/OB are recommended to gain each week, small adjustments to individualized energy intake and physical activity goals based on REE on a weekly basis may help women meet weekly GWG goals in an effort to stay within the IOM guidelines for total GWG.

Table 3.1. Participant Characteristics (*N* = 26).

	Mean	***SD***	***N* (%)**
Age	30.6	3.0	
Gestational Week at Study Entry	10.3	1.7	
Pre-pregnancy BMI	31.4	7.1	
OW			16 (62)
OB			10 (38)
Race			
White			25 (96)
Asian			1 (4)
Employment			
Full-Time			23 (88)
Other			3 (12)
Education			
High School			1 (4)
College			12 (46)
Graduate/Professional			13 (50)
Family Income			
$10-20,000			1 (4)
$20-40,000			5 (19)
$40-100,000			11 (42)
>$100,000			9 (35)
Marital Status			
Married			24 (92)
Single			1 (4)
Divorced			1 (4)
Parity			
Nulliparous			20 (77)
Primiparous			6 (23)

Note. *SD* = standard deviation; BMI = body mass index.

Table 3.2. Descriptives of Missing Resting Energy Expenditure Assessments.

Gestational Week	Number Missing Breezing™ REE Assessments	Number of Substitutions of Estimated REE Assessments	Remaining Number of Missing Assessments
14	9	9	0
15	10	10	0
16	9	9	0
17	8	8	0
18	9	9	0
19	12	12	0
20	10	10	0
21	10	10	0
22	9	9	0
23	11	10	1
24	14	13	1
25	10	9	1
26	9	8	1
27	10	9	1
28	11	10	1

Note. REE = resting energy expenditure.

Table 3.3. Means and Standard Deviations of Second Trimester Energy Intake, Physical Activity, Resting Energy Expenditure, and Gestational Weight Gain.

	Mean	**Standard Deviation**
Energy Intake (kcal)	2895.90	531.36
Physical Activity (kcal)	473.26	227.72
REE (kcal)	1875.66	382.19
GWG (pounds)	10.72	5.55

Note. REE = resting energy expenditure; GWG = gestational weight gain.

Table 3.4. Bivariate Correlations Between Second Trimester Energy Intake, Physical Activity, Resting Energy Expenditure, and Gestational Weight Gain.

	Energy Intake	**Physical Activity**	**REE**	**GWG**
Energy Intake	1	0.81*	0.84*	-0.33
Physical Activity		1	0.54*	-0.20
REE			1	-0.62*
GWG				1

Note. *indicates p<0.05. REE = resting energy expenditure; GWG = gestational weight gain.

Table 3.5. Hierarchical Regression Analyses Predicting Second Trimester Gestational Weight Gain with Energy Intake, Physical Activity, and Resting Energy Expenditure.

	R^2	R^2 ***change p value***	***F***	***df***	***Model p value***	β^1	β^2
Block 1	0.12	0.22	1.63	2, 25	0.22		
Energy Intake						-0.49	1.01*
Physical Activity						0.19	-0.33
Block 2	0.52	<0.001	7.97	3, 25	0.001		
REE							-1.28**

Note. *indicates p<0.05; **indicates p<0.001. REE = resting energy expenditure.

Chapter 4

The Associations Between Low Resting Energy Expenditure and High Gestational Weight Gain in Pregnant Women with Overweight or Obesity is Only Evident when Resting Energy Expenditure Fluctuates

Excessive gestational weight gain (GWG) is defined as gaining weight in excess of the Institute of Medicine (IOM) guidelines (i.e., >35 pounds total or >1 pound/week for women with normal weight, >25 pounds total or >0.7 pounds/week for women with overweight, >20 pounds total or >0.6 pounds/week for women with obesity). High GWG increases the risk for adverse perinatal outcomes such as gestational diabetes, hypertensive disorders, macrosomia, and childhood obesity (Dutton, Borengasser, Gaudet, Barbour, & Keely, 2018; IOM, 2009; McDowell, Cain, & Brumley, 2019). Pregnant women with overweight/obesity (PW-OW/OB) often have excessive GWG in part due to their unique challenges with regulating weight (e.g., overestimating how much weight they should gain, underestimating their body mass index [BMI]; de Jersey, Nicholson, Callaway, & Daniels, 2013; Daly et al., 2016; Nagourney et al., 2019; Symons Downs, Savage, & Rauff, 2014). Thus, managing GWG in PW-OW/OB is especially important.

Past research has primarily focused on how energy intake and physical activity behaviors can be used to regulate GWG (Bruno et al., 2017; Dodd, Grivell, Crowther, & Robinson, 2010; Dodd et al., 2014; Guelinckx, Devlieger, Mullie, & Vansant, 2010; Hawkins et al., 2015; Phelan, Phipps, Abrams, Darroch, Schaffner, & Wing, 2011; Szmeja et al., 2014; Redman et al., 2017). Unfortunately, most PW-OW/OB have difficulty adhering to both prenatal energy intake goals (e.g., 2600 kcals/day; ACOG, 2016; Bruno et al., 2017) and physical activity recommendations (i.e., 150 minutes of moderate to vigorous physical activity per week; ACOG, 2015; USDHHS, 2018). Thus, there is a need to identify effective strategies to promote individualized intake and activity goals in this population. Chapter 3 of this dissertation was one of the first studies to examine the extent to which energy intake, physical activity, and resting energy expenditure (REE; the amount of calories burned at rest) were associated with and explained second trimester GWG in PW-OW/OB. Because REE accounts for 60-70% of total energy expenditure, it is often used to inform energy intake and physical activity goals to achieve weight loss in non-pregnant adults (Berggren et al., 2017; Catalano, 1999; McClave and Snider, 1992; Taousani et al., 2017; Vander Wyst et al., 2020). Given that weight loss is not typically recommended for pregnant women, this approach has not been widely adopted among pregnant women despite that REE may be associated with GWG. More specifically, the findings from Chapter 3 showed that 52% of the variance in second trimester GWG was explained by energy intake, physical activity and REE, with low REE emerging as the strongest determinant of GWG followed by energy intake (physical activity was not a significant determinant). However, because there are no specific prenatal energy intake and physical activity guidelines for PW-OW/OB, REE may provide some useful context to informing intake and activity goals to meet GWG guidelines.

More specifically, in an effort to create energy intake goals for PW-OW/OB to regulate GWG, Symons Downs and colleagues (under review; 2018) applied the recommendations of Vesco and colleagues (2012) and mathematically reduced the established recommendations for pregnant women with normal weight by 20-30% (ACOG, 2016) using the following mathematical equation: Caloric Needs = [(Pre-pregnant weight in kg)(30 kcal/kg/day)(0.70)]+[(10 kcal)(gestational age in weeks)]. Within the equation, the 0.70 factor represented the 30% reduction and could be altered to reflect a 20% (0.80) or 25% (0.75) reduction. The Healthy Mom Zone Study evaluated GWG each week and made decisions to adapt the intensity of the intervention dosage (i.e., "step-up" dosage intensity with interactive healthy eating and physical activity sessions) based on whether a woman was meeting or exceeding the GWG guidelines. However, given the limited research regarding the relationship between REE and GWG at the time the intervention was implemented, women's calorie goals were not adapted over the course of the intervention based on the influence of their REE. Examining the associations between REE and GWG at the weekly level may provide unique insight about how REE can be used to help PW-OW/OB regulate their energy intake and physical activity behaviors to meet weekly GWG ranges. This is particularly important because the GWG guidelines suggest a small amount of weekly weight gain for PW-OW (i.e., 0.05-0.07) and PW-OB (i.e., 0.04-0.06) to achieve their overall GWG goals. However, scant research has examined how to develop content within the context of an intervention to use REE to inform individualized weekly energy intake and physical activity goals to effectively regulate GWG in PW-OW/OB. One reason for this may be due to the limited research examining the influence of prenatal REE on GWG in PW-OW/OB.

There is some evidence that low prenatal REE and/or fluctuations in REE may be a “warning sign” of excessive GWG (Berggren et al., 2017; Vander Wyst et al., 2020). For example, Berggren and colleagues (2017) used laboratory-based indirect calorimetry to examine REE at 3 months preconception and 34-36 weeks gestation and its association with GWG among 51 healthy pregnant women. They found that low REE was significantly associated with high GWG, an increase in fat mass, and a decrease in fat free mass from pre-pregnancy to 34-36 weeks gestation. Further, these researchers found that change in REE from pre-pregnancy (i.e., 3 months preconception) to 34-36 weeks gestation was associated with fat free mass and fat mass accrual from pre-pregnancy to 34-36 weeks gestation. More specifically, 75% of women increased in REE from pre-pregnancy to 34-36 weeks gestation whereas the remaining 25% of women decreased in REE. An increase in REE was associated with an increase in fat free mass and a decrease in fat mass whereas a decrease in REE was associated with a decrease in fat free mass and an increase in fat mass. However, this study only included “pre-post” (i.e., 3 months preconception to 34-36 weeks gestation) change in REE and GWG and did not examine time-varying associations between REE and GWG to better understand how variation in REE over the course of pregnancy may influence GWG. Further, little is known about how REE is related to GWG during critical periods of fetal growth such as the second trimester because the middle of pregnancy is often overlooked within “pre-post” study designs. Specifically, the second trimester is often marked by rapid increase in GWG, especially for PW-OW/OB, and this rise in GWG is attributed to the nearly 50% increase in blood volume and amniotic fluid that is needed to accommodate the growing fetus (IOM, 2009; Overcash et al., 2015). Jackemeyer and colleagues (2017) examined the pattern of change in REE among four healthy pregnant women once a week from pre-pregnancy to 40 weeks gestation. They found that REE fluctuated (i.e., increased and decreased) rather than increasing in a linear pattern for all women, and this fluctuation was largely apparent during the second trimester. However, the researchers did not examine if REE was associated with GWG and if the associations changed over time during the second trimester.

Vander Wyst and colleagues (2020) partly addressed the limitations with pre-post designs and examined change in REE in 15 healthy pregnant women every two weeks throughout the second trimester from ~14 to 28 weeks gestation using a mobile indirect calorimetry (Breezing™) device to assess REE. The researchers observed a pattern of variation in REE at each study visit such that 53-63% of women increased in REE while 38-50% decreased in REE. They also found that although changes in REE from 21 to 28 weeks gestation (*mean* = 128 kcal increase) were nearly twice as much as the changes in REE from 14-21 weeks gestation (*mean* = 72 kcal increase), there were no significant associations between changes in REE and GWG. The researchers suggested that the lack of significant associations may have been due to the large variation in the amount of increase and decrease in REE across individuals. For example, among the women who increased in REE, there was substantial range in the increase such that some women only increased by 10 kcal/day whereas others increased by 350 kcal/day. Similarly, among the women who decreased in REE, there was a substantial range in the decrease with some women decreasing by 10 kcal/day whereas others decreased by 620 kcal/day. The researchers hypothesized that wide fluctuations (e.g., increase by 350 kcal/day or decrease by 620 kcal/day) in REE from 14 to 28 weeks gestation, rather than the mean level of REE, may increase their risk of excessive GWG.

The studies by Berggren et al. (2017), Jackemeyer et al. (2017), and Vander Wyst et al. (2020) provide evidence that REE may vary over the course of pregnancy, particularly during the second trimester. In addition, Berggren and colleagues (2017) suggested that low REE is associated with high GWG whereas Vander Wyst and colleagues (2020) posited that it may not be *low* REE, but rather *wide variation* in REE, that explains excessive GWG. However, these studies were based on limited assessments (i.e., pre-post or bi-weekly) of REE, which limits the ability to understand variability in REE. Further, these limited assessments precluded the ability to examine time-varying associations between REE and GWG particularly at the weekly level. As noted above, understanding the relationship between

REE and GWG at the weekly level is important because the range of recommended weight gain per week is limited to 0.04 to 0.07 for PW-OW/OB. In order to design interventions to use REE to inform energy intake and physical activity goals as a means to regulate GWG in PW-OW/OB, it is first necessary to examine associations between REE and GWG and to identify the extent to which these associations are time-varying.

Thus, the overall objective of this secondary analysis study was to describe weekly point estimates of REE in relation to weekly GWG over the second trimester in PW-OW/OB in an effort to understand the extent to which future interventions can use REE as a strategy to inform energy intake and physical activity goals to effectively regulate GWG. The first purpose was to describe patterns in mean change in REE from 14 to 28 weeks gestation and the proportion of women who increased and decreased in REE. Based on past research (Berggren et al., 2017; Jackemeyer et al., 2017; Vander Wyst et al., 2020), it was hypothesized that REE would increase overall from 14 to 28 weeks gestation. However, it was hypothesized that not all women would increase such that 60-75% of women would increase and 25-40% would decrease. Due to the limited research, an a priori hypothesis was not established about the magnitude of change in REE for the weekly point estimates. The second purpose was to examine associations between weekly point estimates of REE and weekly point estimates of GWG and the extent to which these associations changed over time from 14-28 weeks gestation. Based on past research (Berggren et al., 2017; Chapter 3), it was hypothesized that low REE would be associated with high weekly GWG during each week from 14-28 weeks gestation. The third purpose was to descriptively examine energy intake and physical activity patterns during the weeks when REE and GWG were significantly associated. Based on evidence from Chapter 3, it was hypothesized that during the weeks when low REE was associated with high GWG, the majority of women would be categorized as exceeding energy intake recommendations and low active.

Methods

Participants

Women ($N = 31$) were PW-OW/OB participating in the Healthy Mom Zone feasibility study, a theoretically-based behavioral intervention that adapted the intervention dosage and intensity over time in PW-OW/OB to regulate GWG (Symons Downs et al., 2018; Symons Downs et al., under review). Women were randomized to an intervention or usual care control group from ~8-36 weeks gestation. Women were eligible to participate in the randomized control trial if they were ages 18-40 years and had: 1) overweight/obesity (BMI range 25-45 kg/m^2; >40 kg/m^2 with physician consultation), 2) singleton pregnancy >8 weeks gestation, 3) physician consent to participate, and 4) were English-speaking, residing in or near Central Pennsylvania. Exclusion criteria were: 1) multiple gestation, 2) diabetes at study entry, 3) not having overweight/obesity, 4) severe allergies or dietary restrictions, 5) contraindications to prenatal physical activity (American College of Obstetrics and Gynecologists [ACOG], 2015) and, 6) not residing in area for duration of study. A more detailed explanation of the Healthy Mom Zone study can be found elsewhere (Symons Downs et al., 2018; Symons Downs et al., under review). Of the $N = 31$ women, $n = 3$ had miscarriages prior to starting the intervention and $n = 1$ woman withdrew, resulting in a total sample of $N = 27$, who were all eligible to be included in this secondary analysis.

Procedures

The Healthy Mom Zone study was approved by the Pennsylvania State University Institutional Review Board (IRB Study# 00000122). Women completed a 30-minute baseline session at ~8 weeks gestation at the University's Clinical Research Center. Study procedures were explained to the participants and written informed consent was obtained for each woman. Women received an Aria Fitbit Wi-Fi scale to weigh themselves daily from ~8-36 weeks gestation. Weights were transmitted via Bluetooth to research investigators each day. Women also wore a wrist-worn activity monitor daily throughout the study period to assess physical activity. Women were instructed to wear an ActiGraph GT3x+ intermittently as a supplement to the wrist-worn activity monitor given the ActiGraph is a widely utilized gold standard approach. Next, a study staff person explained how to download the Breezing™ application onto each woman's Smartphone. All women were trained on how to use the Breezing™

device and sent home with detailed instructions. They were instructed to use the Breezing™ device one time per week (on the same day of the week) from ~8-36 weeks gestation. Women were recommended to obtain a Breezing™ measurement after 8 hours of sleep, immediately after waking up while lying down and in a fasting state (e.g., no food for the past 4-6 hours). First, women opened the Breezing™ application on their phone and followed a checklist of instructions to obtain a measurement. Second, women scanned the QR code on the package of provided sensor cartridges. Third, women placed a nose clip onto their nose and practiced breathing in the mouthpiece alone until breathing was consistent. Finally, women were prompted to insert one sensor cartridge into the tracking device and preform an actual measurement. Women carefully picked up the tracker and blew into the mouthpiece until the application said the test was completed (1-2 minutes). The device did not produce results if the woman had ‘irregular breathing.’ Women were instructed to complete another measurement until a successful assessment was obtained. On average, 5% of the sample had to repeat at least one measurement due to irregular breathing. All data was transmitted via Bluetooth to the women’s smartphone and sent to the research team. At ~36 weeks gestation, women completed their last assessment and returned the device.

Measures

Energy Intake. Energy intake, matched on the day REE was obtained, was estimated using a validated back-calculation method (Symons Downs et al., 2018; 2019; Guo et al., 2016; Guo et al., 2018a; Guo et al., 2018b):

$$EI_{est}(k) = \frac{-W(k+2T) + 8W(k+T) - 8W(k-T) + W(k-2T)}{12TK_1} - \frac{K_2}{K_1}(PA(k) + REE(k))$$

The variables are as follows: k = 1, 2, …, *N* corresponding to day 1-day *N*. W represents maternal weight in kg while T represents sampling time which in this case was T = 1 day. PA represents physical activity in kcals. REE represents resting energy expenditure in kcals calculated using Breezing™ or the estimated equation depending on which REE method was used for that data point.

Physical Activity. Active kcal (calories burned during activity) was obtained from the Jawbone UP3 wrist-worn activity monitor for each day REE was measured. Symons Downs et al. (2017) found that the Jawbone UP3 and the ActiGraph activity monitor had only a minor discrepancy of approximately a 79 kcals. Thus, ActiGraph data was used when wrist-worn activity monitor data was missing. Based on Evenson and Wen (2011) and Mâsse and colleagues (2005) suggestions, if there was no data from the Jawbone or the ActiGraph on the day an REE assessment was obtained, active kcal was mean replaced by the weekly average if there was ≥ 4 days of data in the week.

Resting Energy Expenditure. REE was assessed using the Breezing™ device. The Breezing™ device is an indirect calorimetry analyzer of REE and is compatible with both iOS and Android software platforms. Sensor cartridges were used to determine the rate of oxygen consumption and carbon dioxide production. The scanned QR code carries calibration parameters for the sensor cartridge. The algorithm within the Breezing™ device then calculated REE according to the Weir equation, a well-known equation used with indirect calorimetry (Weir, 1949; Xian et al., 2015):

$$[3.9 * VO_2 + 1.1*VCO_2]* 1.44$$

VO_2 represents the volume of oxygen consumed and VCO_2 represents the volume of carbon dioxide produced. Estimated REE was calculated for each day the women had a missing Breezing™ assessment. Research investigators calculated estimated REE as a function of maternal weight for each woman by using an empirical equation that was proposed (Thomas et al., 2012) and fit using a quadratic regression equation from data collected on pregnant women by Butte and colleagues (2003; 2004):

$$REE = 0.1976W^2 – 13.424W + 1457.6$$

W represents maternal weight in kilograms.

Weekly GWG. Weekly GWG was calculated as weekly point estimate of weight from the Aria Wi-Fi weight scale at the week after the current week minus the weekly point estimate of weight at the current week (e.g., GWG for week 14 = weight at 15 weeks minus weight at 14 weeks).The Aria Wi-Fi weight scale has been shown to be a valid and reliable tool to estimate weight in the general population (Hood et al., 2019).

Demographics and Personal Characteristics. At baseline, women self-reported personal demographics (i.e., age, race/ethnicity, income, marital status, education, employment) and current gestational age. Pre-pregnancy BMI was calculated from self-reported pre-pregnancy weight and height.

Data Analyses

Data were analyzed using SPSS v25 and SAS v9. This current secondary analysis limited analyses to the second trimester based on the following rationale: (1) data was maximized in the second trimester given that the majority of women were enrolled later in the first trimester (i.e., 10-13 weeks gestation), (2) evidence supporting the second trimester is marked by rapid GWG in PW-OW/OB and fetal growth, which may influence REE (Overcash et al., 2015), and (3) evidence from Chapter 3 illustrated that REE was the strongest predictor of GWG during the second trimester. Evidence from Chapter 2 of this dissertation also showed agreement between REE assessed with the estimated equation and Breezing™ at gestational weeks 7-10, 12-22, 24-31, 34, and 36. However, there was a lack of agreement between the two methods at gestational weeks 11, 23, 32, 33, and 35 (noting, however, that there was an outlier at week 35 and once removed, there was subsequent agreement at this time point). Given these mixed findings, the analyses in the current study were run with (1) REE from Breezing™ only, and (2) REE from Breezing™ and the estimated equation (i.e., estimated equation substituting missing Breezing™ REE assessments) to understand whether the discrepancy between the two methods influenced the study analyses. Means, standard deviations, and percentages were used to examine demographic variables and descriptives of second trimester REE. Estimates that were 3 ± within person standard deviations above each woman's mean second trimester REE were considered as outliers (Ruan, Chen, & Kerre, 2005). Time-varying effect modeling (TVEM) was used to examine the associations between REE and weekly GWG across 14 to 28 weeks gestation. Specifically, REE was included as the time-varying independent variable to model its effect on the dependent variable of weekly GWG over time. The model produced beta coefficients of REE on weekly GWG. Coefficients above 0 signify positive associations and coefficients below 0 signify negative associations. TVEM produces 95%

confidence intervals of the coefficients across time. Confidence intervals overlapping with 0 indicate non-significant associations. The TVEM analysis included study group assignment (randomized to intervention vs. control) and pre-pregnancy BMI (overweight vs. obese) as time-invariant covariates to control for their effect on REE and weekly GWG. TVEM produced standardized beta coefficients for effect sizes. Effect size values of 0.20, 0.50, and 0.80 were considered small, medium, and large effects, respectively (Cohen, 1988). It is important to note that TVEM analyses do not require a specific sample size, rather the analyses require adequate coverage of data across time points (Tan et al., 2012). For the third purpose, women were categorized as meeting versus exceeding energy intake guidelines for each week using back-calculated energy intake/day. Several guidelines recommend that women should intake an additional 340 kcals/day in the second trimester (ACOG, 2016; IOM, 2009 Kaiser, Campbell, & Academy Positions Committee Workgroup, 2014; Kominiarek & Rajan, 2016). Therefore, energy intake/day for each week was subtracted from average energy intake/day during the first trimester to obtain change in average energy intake/day in the second trimesters. If the change was ≤ 340 kcals women were categorized as meeting energy intake guidelines. If the change was > 340 kcals women were categorized as exceeding the guidelines. Using activity kcal/day, women were categorized as low active vs. active. Researchers have shown that on average, PW-OB are considered low active and expend 569 active kcals/day during pregnancy (Most et al., 2018). Given there are no clinical recommendations for the number of active kcals to expend per day, a threshold of 569 active kcals/day was used. Women who had an active kcal/day < 569 were categorized as low active and women who had an active kcal/day ≥ 569 were categorized as active.

Results

Participant Characteristics. Participant characteristics are presented in Table 4.1. Mean age of study participants was 30.6 (*SD* = 3.0) years, mean gestational week at study entry was 10.2 (*SD* = 1.7) and mean pre-pregnancy BMI was 31.6 kg/m^2 (*SD* = 7.0; overweight = 59%, obese = 41%). The sample was Non-Hispanic, White (96%), married (92%), employed full-time (89%), reported a family income ≥ $40,000 (77%), and almost half of the sample had a graduate/professional degree (48%).

REE Missing Data and Outliers. From 14 to 28 weeks gestation across all participants, there were 166 instances (41%) when Breezing™ data were missing; there were only 3 women who had no Breezing™ missing data at any time point. Of the 166 instances, 159 (96%) were replaced with the estimated equation resulting in a total of 398 total REE data points across 14 to 28 weeks gestation (7 missing points). Each week ranged from 9 to 15 substitutions of the estimated equation. Analyses revealed there were no outliers in the data. The primary analyses did not significantly differ when the estimated REE equation was used in place of missing Breezing™ REE data, thus, the analyses are presented below using the estimated equation when Breezing™ was missing across all time points (Table 4.2).

REE Descriptives. Means and standard deviations for second trimester REE are presented in Table 4.3. Mean second trimester REE values across the total sample and for each participant are also depicted in Figures 4.1 and 4.2, respectively. While average REE/day increased by 113.99 kcals (*SD* = 225.36) from 14 to 28 weeks gestation on average across the total sample, 78% (*n* = 21) of women increased (*range* = 2.97 to 670.00 kcals) in REE, 19% (*n* = 5) of women decreased (*range* = -80.00 to -302.41 kcals), and 3% (*n* = 1) had no change. Further there was evidence of fluctuation within this time period. Specifically, REE increased from gestational weeks 14-16, 17-19, 21-22, 23-24, and 26-27 and decreased from gestational weeks 16-17, 19-21, 22-23, 24-26, and 27-28.

Time-Varying Effect. Time-varying associations are presented in Figure 4.3. There were no significant associations between REE and weekly GWG from gestational weeks 14 to 24. The effect sizes from gestational weeks 14 to 24 were small and ranged from 0.0003 to 0.0006. However, there were significant associations between REE and weekly GWG from gestational weeks 25 to 28 such that low REE was associated with high weekly GWG; the strength of these associations were nevertheless small, but they slightly increased during this time (range = 0.0006 to 0.002).

Energy Intake and Physical Activity Descriptives. Tables 4.4 and 4.5 present descriptives of energy intake and physical activity. Slightly over half of the women (54%) exceeded energy intake recommendations at gestational week 25, 50% exceeded recommendations at gestational week 26, 58% exceeded recommendations at gestational week 27, and 35% exceeded recommendations at gestational week 28. In contrast, 46% of women met energy intake recommendations at gestational week 25, 42% met energy intake recommendations at gestational week 26, 42% met energy intake recommendations at gestational week 27, and 65% met energy intake recommendations at gestational week 28. During gestational weeks 25 to 28, women who exceeded energy intake recommendations (M = 3220.61, *range* = 3051.78 to 3505.32) consumed an average of 616.46 (*range* = 371.78 to 1092.74) kcals higher each day than women who met energy intake recommendations (M = 2604.15, *range* = 2412.58 to 2750.22). Also, REE was 62.5 kcals/day higher and GWG was 0.03 pounds/week higher for women who exceeded energy intake recommendations (REE: M = 1955.50, *range* = 1845.00 to 2156.00; GWG: M = 0.49, *range* = -0.58 to 1.07) compared to women who met energy intake recommendations (REE: M = 1893.00, *range* = 1799.00 to 2002.00; GWG: M = 0.46, *range* = -0.56 to 2.36). The majority (77%) of women were categorized as low active at gestational week 25, 76% were categorized as low active at gestational week 26, 80% were categorized as low active at gestational week 27, and 76% were categorized as low active at gestational week 28. In contrast, 23% of women were categorized as active at gestational week 25, 24% were categorized as active at gestational week 26, 20% were categorized as active at gestational week 27, and 24% were categorized as active at gestational week 28. During gestational weeks 25 to 28, women who were categorized as low active (M = 324.30, *range* = 299.31 to 369.99) expended fewer kcals (M = 569.32, *range* = 371.78 to 1092.74) each day than women categorized as active (M = 893.62, *range* = 689.65 to 987.94). Also, REE was 525 kcals/day higher and GWG was 0.12 pounds/week lower for women categorized as active (REE: M = 2237.50, *range* = 2210.00 to 2293.00; GWG: M = 0.07, *range* = -0.52 to 0.70) compared to women categorized as low active (REE: M = 1712.50, *range* = 1634.00 to 1764.00; GWG: M = 0.19, *range* = -1.50 to 1.73).

Discussion

The overall objective of this secondary analysis study was to describe weekly point estimates of REE in relation to weekly GWG over the second trimester in PW-OW/OB in an effort to understand the extent to which future interventions can use REE as a strategy to inform energy intake and physical activity goals to effectively regulate GWG. In sum, REE fluctuated over the second trimester such that it increased on average from 14 to 28 weeks gestation, but decreased at gestational weeks 17, 20, 21, 23, 26, and 28. The majority of women increased in REE, however there was large between-person variability in the amount of increase and decrease in REE ranging from -302.41 to 670 kcals. The associations between REE and GWG were small but significantly time-varying such that low REE was associated with high weekly GWG between gestational weeks 25 to 28; significance was not observed from weeks 14 to 24. Compared to gestational weeks 14 to 24, there was an observably larger fluctuation in REE from weeks 25 to 28 such that there were large peaks of increases and decreases during this time. Moreover, during gestational weeks 25 to 28, slightly over half of the women were categorized as having excessive energy intake whereas the majority of women were categorized as low active. These findings suggest there is wide variability in REE change over time especially during gestational weeks 25 to 28 in PW-OW/OB, and low REE was associated with high weekly GWG, particularly during these weeks when REE fluctuates. The significant associations during the weeks of REE fluctuation may be attributed to engaging in poor energy intake and physical activity behaviors. These findings are described in more detail below.

In support of the first hypothesis, REE increased on average by 113.99 kcals from 14 to 28 weeks gestation. A similar pattern was found by Vander Wyst and colleagues (2020) who found that women increased in REE by 200 kcals from 14 to 28 weeks gestation. However, this current study also revealed that not all women increased in REE. Specifically, 78% of women increased, 19% of women decreased, and 3% had no change. Further, there was a wide range in the amount of increase and decrease. Upon further exploration, descriptives revealed that personal characteristics (i.e., BMI, race/ethnicity, fat-free mass) between women that increased versus decreased or had no change in REE were similar except for maternal age. Specifically, women were more likely to increase in REE from 14 to 28 weeks gestation if they were < 35 years old compared to if they were ≥ 35 years old. This is consistent with past research showing that increases in REE are more apparent in younger individuals than older individuals (Taousani et al., 2017). Moreover, the current study findings revealed that on average, there was fluctuation in REE from 14 to 28 weeks gestation such that there were certain gestational weeks when REE increased (i.e., weeks 14-16, 17-19, 21-22, 23-24, and 26-27) and other gestational weeks when REE decreased (i.e., weeks 16-17, 19-21, 22-23, 24-26). The greatest amount of fluctuation was observed from gestational weeks 22 to 28. It is important to note that there was a large decrease in REE observed from week 22 to 23, followed by a large increase in REE from week 23 to 24. Analyses revealed that there were no outliers and that this large decrease in REE was not due to missing data and/or due to substituting in the estimated equation for missing Breezing™ REE. There was also no apparent influence of missing data on the pattern of change in REE at any other time point. This suggests that the fluctuations, particularly during the large peaks (i.e., weeks 22 to 24) were not a result of measurement error but potentially influenced by other factors and behaviors attributed to pregnancy (e.g., energy intake, GWG, fetal growth). For example, some research has shown that fetal growth can rapidly increase later in gestation (e.g., 22 weeks; Savage et al., 2019). Also, upon further exploration, analyses revealed that at week 22, the majority of women were categorized as exceeding weekly energy intake recommendations whereas at weeks 22 and 24, the majority of women were categorized as meeting weekly energy intake recommendations. Given that high energy intake is associated with high REE (Hronek et al., 2013), it is likely that the large decrease in REE from gestational weeks 22 to 23 reflects a decrease in energy intake, although reasons for this decrease during this week are unknown. One possible explanation may be that women typically have their anatomical ultrasound somewhere between 21 and 25 weeks of pregnancy which can often generate feelings of anxiety and stress in anticipation of seeing their baby (often for the first time) and hoping there are no abnormalities (e.g., fetal growth or placental issues, markers for Downs Syndrome). Significant events such as this can often impact women's dietary intake patterns as they eat or restrict eating in response to psychosocial stressors (Blau et al., 2020; Savage et al., 2019). It is important to note that patterns of low physical activity remained similar across these weeks suggesting that the fluctuation in REE was less attributed to changes in physical activity and more likely due to changes in energy intake. Nevertheless, the fluctuations in REE are consistent with past researchers' conclusions that have shown some prenatal REE patterns that do not follow a linear trajectory (Jackemeyer et al., 2017), and highlight the importance of examining week-to-week variations in energy intake, physical activity, and REE over the course of pregnancy to better understand how these fluctuations at key points in gestation may impact maternal and infant outcomes.

In partial support of the second hypothesis and past research (Berggren et al. 2017; Chapter 3 of this dissertation), there were time-varying associations between REE and weekly GWG such that low REE was associated with high weekly GWG from 25 to 28 weeks gestation, but it was not associated with weekly GWG from 14 to 24 weeks gestation. Although the strength of the associations increased over time, it is important to note that all non-significant and significant associations were very small (range 0.00007 to 0.002). Similar to the patterns of change in REE noted above, the strength of the associations were not influenced by outliers and/or missing data. Instead, when the associations between REE and GWG were stronger and significant (i.e., weeks 25 to 28), there was an observable fluctuation in REE such that there were large increase and decreases during this time. In contrast, during gestational weeks 14 to 24, REE did not fluctuate as much, but rather increased. In contrast to Vander Wyst and colleagues (2020) who suggested that a drastic fluctuation in REE may be indicative of excessive GWG, these current findings suggest that it may not be the fluctuation itself that is a warning sign of high GWG, but rather *low REE during times of fluctuation*. Upon further exploration, follow-up TVEM analyses revealed that the strength of the associations between REE and GWG among women with higher within-person variability in REE (i.e., ≥ 50^{th} percentile) increased from 25 to 28 weeks gestation whereas the strength of the associations remained stable for women who had lower within-person REE variability (< 50^{th} percentile) during this time. Additional descriptive analyses revealed that women who had higher variability in REE from gestational weeks 25 to 28 had higher energy intake and physical activity behaviors compared to women who had lower variability in REE. Given the bi-directional nature of the relationships between energy intake, physical activity, and REE, these findings suggest that researchers and intervention specialists may want to consider using REE to inform energy intake and physical activity goals to reduce variability in REE, and in turn, better regulate GWG. More specifically, PW-OW/OB often exceed their weekly GWG targets (i.e., OW: <0.07 pounds, OB: <0.06 pounds). This may be attributed, in part, to the fact that the recommended energy intake and physical activity targets for PW-OW/OB are based on the same goals that were developed for women with normal weight, and these goals may not accurately reflect their energy intake and expenditure behaviors. For example, if an initial energy intake goal is set for a PW-OW/OB at 2600 kcal/day and her physical activity goal is set for 350 kcal/day, but her REE is 1900 kcal, researchers/clinicians may want to adjust her energy intake and/or physical activity goals. That is, her energy intake goal should be decreased to 2300 kcal/day to account for a total energy expenditure of approximately 2250 kcal (i.e., 1900 kcal from REE + 350 kcal from physical activity). On the other hand, if the goal is to increase a woman's total energy expenditure to 2350 kcal, researchers/clinicians would use the REE value of 1900 kcal to appropriately inform her physical activity goal. That is, her physical activity goal should be increased to 450 kcal to result in a total energy expenditure of 2350 kcal. As the current study illustrated, REE may vary from week to week and thus measuring and understanding REE on a weekly basis may be important for individualizing energy intake and physical activity goals from week to week. In other words, energy intake and physical activity goals do not need to be "set in stone" and can be adjusted weekly based on each woman's unique energy needs to personalize GWG regulation. Successfully using REE to inform energy intake and physical activity goals can remove the guesswork of how to best moderate energy intake and increase physical activity to effectively regulate GWG. However, because few, if any, studies have used REE to adjust prenatal energy intake and physical activity goals to regulate GWG, there is a need for research to better understand the impact of these adjustments over time on total GWG. The current study findings are novel as they are among the first to document that although the associations between REE and GWG in PW-OW/OB are small, they time-varying. Given the small associations, moderating energy intake and increasing physical activity remain important targets for effective GWG regulation in PW-OW/OB.

In partial support of the third hypothesis, slightly over half of the women were categorized as exceeding energy intake recommendations at most of the time points and the majority were categorized as low active from gestational week 25 to 28. This pattern was also observed from gestational weeks 14 to 24. Across gestational week 25 to 28, mean energy intake ranged from 2,413 to 2750 kcals/day in women who met energy intake recommendations and ranged from 3,052 to 3,505 kcals/day in women who exceeded energy intake recommendations. These findings are of clinical importance given that researchers have shown that women who have excessive GWG consume at least 750 kcals/day more than women who have an appropriate amount of GWG (Gilmore et al., 2016). Further, although women categorized as exceeding energy intake recommendations had higher REE, they also had higher weekly GWG compared to women categorized as meeting energy intake recommendations. Similarly, women who were categorized as low active expended approximately half the active kcals/day of women who were categorized as active. This finding is also of importance given that women who are less physically active have higher GWG than women who are more physically active (Bisson et al., 2015; Ruchat et al., 2018). These patterns of high energy intake and low physical activity may yield useful insight regarding how REE can be used to inform energy intake and physical activity recommendations to regulate GWG, which are non-existent for PW-OW/OB. For example, the traditional assumption is that there is a linear increase in prenatal REE (Berggren et al., 2017; Butte et al., 2003; Butte et al., 2004; Butte, 2005; Byrne et al. 2011; Catalano et al., 1999; Damjanovic et al., 2009; Forsum & Löf, 2007; Löf et al., 2005; Most et al., 2019; Taousani et al., 2017), which has partly informed the need for extra energy requirements during pregnancy (ACOG, 2016; IOM, 2009 Kaiser, Campbell, & Academy Positions Committee Workgroup, 2014; Kominiarek & Rajan, 2016). Within the context of GWG interventions, it may be that intervention scientists are not accounting for changes and/or fluctuations in REE and thus, when REE is low, may be overestimating energy intake needs and underestimating physical activity needs for PW-OW/OB which increases the risk of high GWG (Melzer, Schutz, Boulvain, & Kayser, 2009). For example, rather than reducing energy intake goals that were developed for women with normal weight by a set amount (e.g., 20-30%), intervention scientists may want to individualize goals for each PW-OW/OB based on her actual REE and total energy expenditure in an effort to regulate GWG. However, there is a need for research to test this assumption. In sum, the findings from this current study are consistent with prior research (Berggren et al., 2017) and Chapter 3 of this dissertation, and they suggest there is a need for future research to better understand points of fluctuation in REE in PW-OW/OB over the entire pregnancy.

Strengths and Limitations

This study is the first to examine change in prenatal REE in PW-OW/OB and the time-varying associations with weekly GWG in relation to energy intake and physical activity patterns during the second trimester. There are several strengths to this study. First, REE and GWG were assessed frequently over the course of the second trimester. The current literature is often limited to pre-post assessments or once each trimester, which precludes the ability to truly understand change in prenatal REE and its association with GWG and whether these associations changes over time. Another strength was the focus during the second trimester which is a time of rapid GWG, particularly for PW-OW/OB. Future research is needed to examine the time-varying associations between REE and GWG over the entire pregnancy to understand how transitions between the first and second trimesters and second and third trimesters may influence overall GWG. Finally, the use of TVEM to analyze the time-varying associations between REE and GWG was an additional strength given that this is an innovative statistical approach to examine associations over time and allows researchers to understand whether there are certain gestational periods when associations may be stronger or non-apparent. This increases the ability for future intervention scientists to identify opportune windows for personalization of GWG regulation interventions during specific gestational periods. However, there are also some limitations worth noting. The sample was a homogenous (i.e., White, highly educated, married) group of PW-OW/OB residing in Central Pennsylvania which limits the generalizability of study findings. Future research with a more diverse sample is needed to confirm and expand the current study findings. Another limitation was only including PW-OW/OB. Future research is needed to understand if the same pattern of fluctuation in REE and its influence on GWG holds in pregnant women with normal weight.

Conclusion

In sum, findings from this study found that REE among PW-OW/OB fluctuated during the second trimester, and low REE was associated with high GWG particularly during times of great fluctuation in REE (i.e., 25 to 28 weeks gestation). Interestingly, during weeks 25 to 28, the majority of PW-OW/OB were categorized as exceeding energy intake recommendations and as low active. These findings highlight that energy intake needs may be overestimated, and physical activity needs may be underestimated during this critical period when REE is fluctuating, which in turn, may increase the risk for high second trimester GWG. This chapter highlights the importance of future research to better understand prenatal REE in addition to moderating energy intake and promoting physical activity to identifying points of fluctuation in REE over the entire pregnancy. Researchers may want to consider the findings from this study when designing future interventions to regulate GWG in PW-OW/OB. For example, instead of recommending PW-OW/OB blanket goals of energy intake and physical activity based on women with normal weight, it may be useful to personalize goals particularly during the second trimester and during these critical time periods of fluctuation in REE. Moderating energy intake, promoting physical activity, and educating women about how REE relates to both, particularly during critical time periods in pregnancy, may be useful for developing personalized energy intake and physical activity goals to more efficiently regulate GWG, and in turn, improve short- and long-term maternal and infant well-being.

Table 4.1. Participant Characteristics (*N* = 27).

	Mean	*SD*	*N* (%)
Age	30.6	3.0	
Gestational Week at Study Entry	10.2	1.7	
Pre-pregnancy BMI	31.6	7.0	
OW			16 (59)
OB			11 (41)
Race			
White			26 (96)
Asian			1 (4)
Employment			
Full-Time			24 (89)
Other			3 (11)
Education			
High School			1 (4)
College			13 (48)
Graduate/Professional			13 (48)
Family Income			
$10-20,000			1 (4)
$20-40,000			5 (19)
$40-100,000			12 (44)
>$100,000			9 (33)
Marital Status			
Married			25 (92)
Single			1 (4)
Divorced			1 (4)
Parity			
Nulliparous			20 (74)
Primiparous			7 (26)

Note. *SD* = standard deviation; BMI = body mass index.

Table 4.2. Descriptives of Missing Resting Energy Expenditure Assessments.

Gestational Week	Number Missing Breezing™ REE Assessments	Number of Substitutions of Estimated REE Assessments	Remaining Number of Missing Assessments
14	10	10	0
15	11	11	0
16	10	10	0
17	9	9	0
18	10	10	0
19	13	13	0
20	11	11	0
21	11	11	0
22	10	10	0
23	12	10	2
24	15	14	1
25	11	10	1
26	10	9	1
27	11	10	1
28	12	11	1

Note. REE = resting energy expenditure.

Table 4.3. Descriptives of Resting Energy Expenditure.

Gestational Week	*N*	*Mean*	*SD*
14	27	1801.98	403.57
15	27	1868.75	424.50
16	27	1881.38	387.92
17	27	1873.32	435.10
18	27	1912.35	399.18
19	27	1913.27	459.81
20	27	1903.16	404.59
21	27	1885.97	418.32
22	27	1939.94	375.99
23	25	1817.99	317.30
24	26	1917.11	494.21
25	26	1916.63	454.25
26	26	1854.71	425.07
27	26	1940.55	450.65
28	26	1922.94	445.70

Note. *SD* = standard deviation.

Table 4.4. Descriptives of Energy Intake (kcals/day) by Energy Intake Recommendations

	Meeting		**Exceeding**	
Gestational Week	***Mean***	***SD***	***Mean***	***SD***
25	2680.00	441.11	3051.78	795.73
26	2573.83	683.32	3074.98	680.02
27	2750.22	742.61	3250.37	813.86
28	2412.58	479.96	3505.32	934.74

Note. SD = standard deviation.

Table 4.5. Descriptives of Physical Activity (kcals/day) by Physical Activity Categorization

	Low Active		**Active**	
Gestational Week	***Mean***	***SD***	***Mean***	***SD***
25	299.31	145.56	689.65	120.76
26	369.99	141.93	964.25	254.39
27	321.09	121.73	932.63	389.23
28	306.80	116.24	987.94	232.82

Note. SD = standard deviation.

Figure 4.1. Time Course of Mean Resting Energy Expenditure Across the Second Trimester.
Note. REE = resting energy expenditure; GW = gestational week.

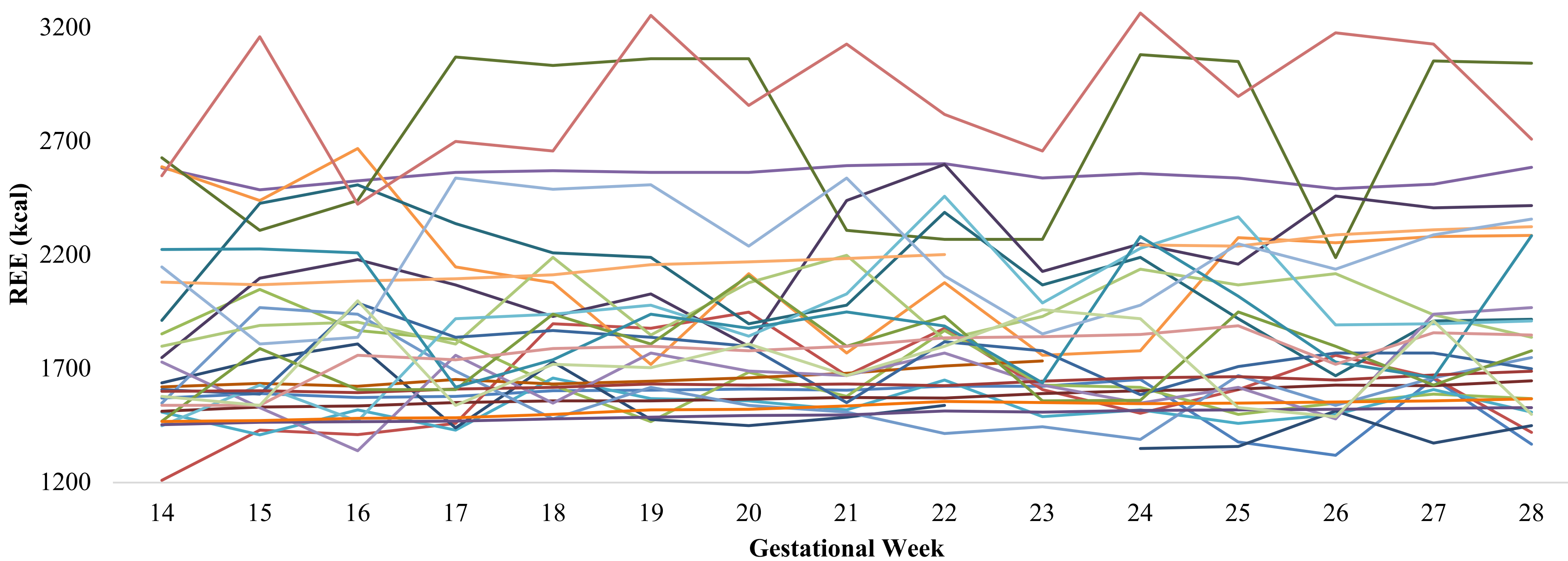


Figure 4.2. Time Course of Resting Energy Expenditure Across the Second Trimester for Each Participant.
Note. REE = resting energy expenditure.

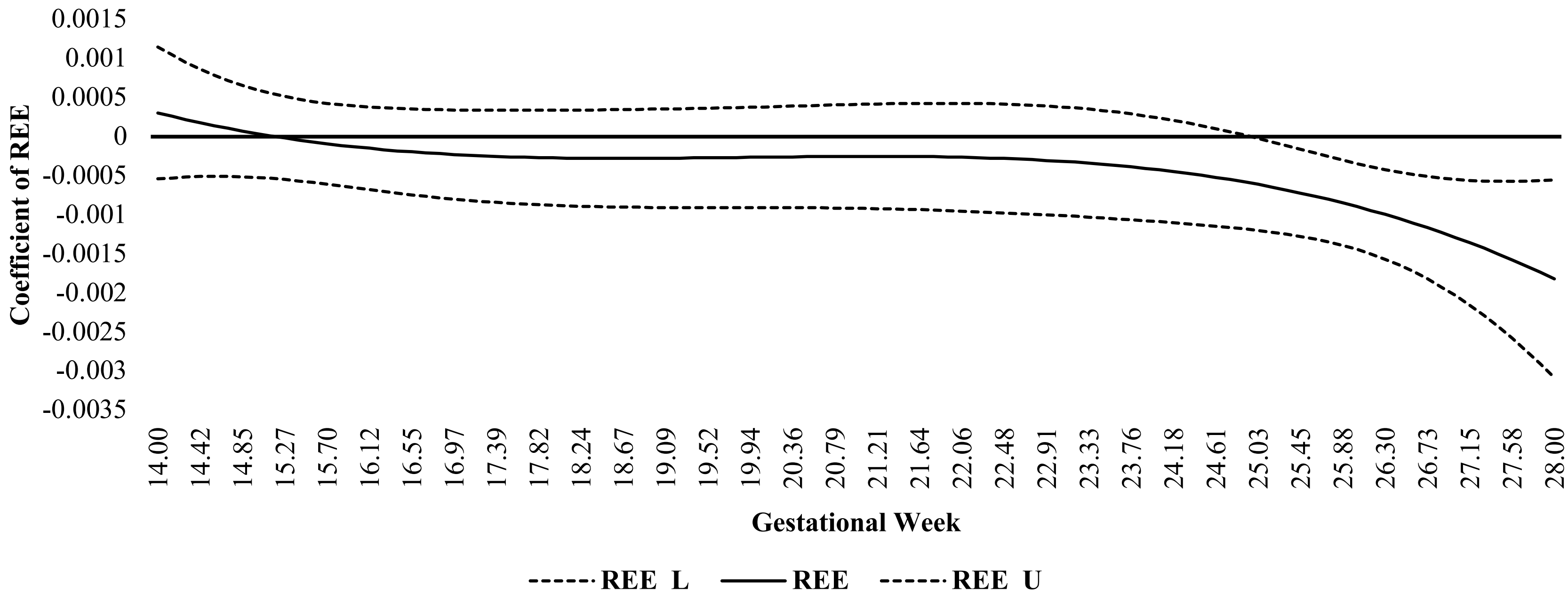


Figure 4.3. Time-Varying Effect Model of the Association Between Resting Energy Expenditure and Gestational Weight Gain Across the Second Trimester.
Note. REE = resting energy expenditure; L = lower bound 95% confidence interval; U = upper bound 95% confidence interval.

Chapter 5

General Discussion

The goal of this dissertation was to examine resting energy expenditure (REE) in relation to energy intake, physical activity, and gestational weight gain (GWG) in pregnant women with overweight/obesity (PW-OW/OB) in an effort to understand the extent to which REE can be used in future interventions to inform energy intake and physical activity goals as a strategy for effective GWG regulation and improve maternal and infant well-being. Three studies were conducted to achieve this goal. These studies capitalized on the existing infrastructure of the Healthy Mom Zone Study and conducted secondary data analyses using a sample of PW-OW/OB randomized to an intervention (Healthy Mom Zone) or usual care control group from ~8 to 36 weeks gestation. The dissertation studies aimed to understand: (1) correspondence between objective (mobile metabolism device) and estimated (equation) measures of REE to understand agreement between these methods and utilize REE assessments with both methods to better examine variability in REE and its influence on GWG, (2) the extent to which REE predicted second trimester GWG after considering the contributions of energy intake and physical activity, and (3) weekly point estimates of REE and its time-varying association with weekly GWG in relation to energy intake and physical activity patterns during the second trimester. In summary, these dissertation studies are among the first to document the association between REE and GWG and illustrate the potential utility of REE within intervention designs to personalize energy intake and physical activity goals to effectively regulate GWG in PW-OW/OB.

Chapter 2 aimed to examine the correspondence/agreement between a mobile metabolism device (Breezing™) and a validated estimated equation and to examine certain characteristics that may be related to the agreement between the methods. In summary, the findings showed that while the mobile metabolism device (Breezing™) and estimated equation measures of REE were positively associated from 8 to 36 weeks gestation, proportional bias between the two methods was detected at gestational weeks 11, 23, 32, 33, and 35. When there was a lack of agreement between the two methods, the difference between Breezing™ and estimated REE varied by the following study and participant characteristics: study assignment (randomized to intervention vs. control), pre-pregnancy BMI (overweight vs. obese), fat-free mass (low vs. high), and energy intake (meeting vs. exceeding guidelines). It is important to note that there was one outlier detected with respect to REE calculated from the estimated equation at gestational week 35. When this outlier was removed, the lack of agreement between Breezing™ and the estimated equation at week 35 disappeared and the methods were subsequently in agreement. Thus, it is important to examine the presence of outliers in the data with respect to correspondence of these measures for a more accurate picture of the agreement between the methods. Although the current findings showed a small to medium effect for the strength of agreement between Breezing™ and the estimated equation, this is the first study to provide initial evidence in support of interchanging these methods as a strategy to obtain more frequent measures of REE over the course of pregnancy. Obtaining more frequent REE assessments will allow researchers to better understand prenatal REE in an effort to provide insight about whether variation in REE is related to GWG. Findings from Chapter 2 illustrate that Breezing™ and an estimated equation may be used interchangeably among PW-OW/OB to estimate REE during certain gestational weeks. However, the current study findings illustrate that correspondence between the two methods may vary during certain points of pregnancy, and may vary based on certain study (i.e., randomized to intervention vs. control group) and participant characteristics (i.e., weight status, fat-free mass, energy intake). Agreement may also be influenced by outliers in the dataset. Researchers may want to strongly consider these factors when assessing REE among pregnant women, especially if the goal is to obtain the most accurate assessment of REE. For example, researchers should explore the presence of outliers and consider the implications of including or excluding these data in relation to the study's overall objectives. In addition, researchers may want to examine REE data with and without interchanging both methods (Breezing™, estimated equation) to understand if variation between the methods has an impact on the target outcomes.

Chapter 3 aimed to examine the extent to which REE provided any additional contribution to second trimester GWG beyond energy intake and physical activity. The study findings showed that low REE was significantly associated with high second trimester GWG among PW-OW/OB. In addition, 52% of the variance in second trimester GWG was explained by the model including energy intake, physical activity and REE; low REE emerged as the strongest determinant of GWG, followed by energy intake (physical activity was not a significant determinant). This study is one of the first to examine the predictive contributions of energy intake, physical activity, and REE for explaining GWG. These findings are among the first to provide evidence that REE, in addition to energy intake, is a predictor of second trimester GWG and illustrate a need for future research to further explore the role of energy balance within GWG interventions targeting PW-OW/OB. While energy intake and physical activity remain important determinants of GWG (e.g., Dubois et al., 2018), high GWG may also be attributed to low REE. Thus, similar to the weight management literature in non-pregnant individuals, REE may be utilized in interventions to personalize energy intake and physical activity goals to better regulate GWG. However, this approach is not commonly used in pregnant women given that the goal is not to achieve weight loss, but rather regulate weight gain. Instead, PW-OW/OB are often given blanket goals for energy intake and physical activity that were based on pregnant women with normal weight. In contrast, women can use their REE to create an activity kcal goal for the day to obtain a full picture of their total energy expenditure and thus inform energy intake goals. For example, GWG regulation interventions should include a program in which a counselor such as a registered dietician informs PW-OW/OB of their REE and counsels them on how to successfully use their REE to regulate GWG. If an initial energy intake goal is set for a PW-OW/OB at 2600 kcal/day and her physical activity goal is set for 350 kcal/day, but her REE is 1900 kcal, researchers/clinicians may want to adjust her energy intake and/or physical activity goals. That is, her energy intake goal should be decreased to 2300 kcal/day to account for a total energy expenditure of approximately 2250 kcal (i.e., 1900 kcal from REE + 350 kcal from physical activity). On the other hand, if the goal is to increase a woman’s total energy expenditure to 2350 kcal, researchers/clinicians would use the REE value of 1900 kcal to appropriately inform her physical activity goal. That is, her physical activity goal should be increased to 450 kcal to result in a total energy expenditure of 2350 kcal. Successfully using REE to inform energy intake and physical activity goals can remove the guesswork of how to best moderate energy intake and increase physical activity to effectively regulate GWG. Together, given the difficulty PW-OW/OB have achieving the recommended energy intake and physical activity appropriate for women with normal weight, these novel findings suggest that in addition to content with respect to moderating energy intake and promoting physical activity, including intervention content focusing on REE within GWG regulation interventions such as informing women of how REE can be used to create achievable and personalized energy intake and activity kcal goals can help PW-OW/OB effectively regulate GWG.

Building on findings from Chapter 3, Chapter 4 aimed to better understand the influence of REE on GWG by describing weekly point estimates of REE and its association with weekly GWG in relation to energy intake and physical activity patterns over the second trimester in PW-OW/OB. This study showed that although second trimester REE increased on average from 14 to 28 weeks gestation, there were specific weekly point estimates that showed decreases in REE (i.e., 17, 20, 21, 23, 26, and 28), illustrating fluctuation in REE during the second trimester, which may have been attributed to external factors such as pattern of energy intake rather than measurement error. Moreover, while most women increased in REE from 14 to 28 weeks gestation, there was large between-person variability in the amount of increase and decrease in REE. For example, REE kcals ranged from -302.41 to 670 kcals. There were also significant time-varying associations between weekly REE and GWG point estimates such that low REE was associated with high GWG between gestational weeks 25 to 28. Although the strength of the associations increased over time, it is important to note that all non-significant and significant associations were very small (range 0.00007 to 0.002). Similar to the patterns of change in REE noted above, the strength of the associations were not influenced by outliers and/or missing data. Instead, when the associations between REE and GWG were stronger and significant (i.e., weeks 25 to 28), there was an observable fluctuation in REE such that there were large increase and decreases during this time. In contrast, during gestational weeks 14 to 24, REE did not fluctuate as much, but rather increased.

Moreover, slightly over half of women were categorized as exceeding energy intake recommendations and the majority were categorized as low active during these time points suggesting that during these critical time periods of fluctuation investigators may overestimate PW-OW/OB energy intake needs and underestimate their physical activity needs which may explain why low REE is associated with high GWG. This study is novel because no located studies have focused on the weekly pattern of change in REE in PW-OW/OB during the second trimester and its time-varying association with weekly GWG. The traditional assumption is that there is a linear increase in prenatal REE, which has partly informed the need for extra energy requirements during pregnancy. Within the context of GWG interventions, it may be that intervention scientists are not accounting for changes and/or fluctuations in REE and thus, when REE is low, may be overestimating energy intake needs and underestimating physical activity needs for PW-OW/OB which increases the risk of high GWG. For example, rather than reducing energy intake goals that were developed for women with normal weight by a set amount (e.g., 20-30%), intervention scientists may want to individualize goals for each PW-OW/OB based on her actual REE and total energy expenditure in an effort to regulate GWG. As the current study illustrated, REE may vary from week to week and thus measuring and understanding REE on a weekly basis may be important for individualizing energy intake and physical activity goals from week to week. In other words, energy intake and physical activity goals do not need to be "set in stone" and can be adjusted weekly based on each woman's unique energy needs to personalize GWG regulation.

Collectively, the findings from these three dissertation studies can be used to inform the development of prenatal GWG interventions for promoting all aspects of energy balance for effective GWG regulation in PW-OW/OB. Thus, below are some recommendations that researchers and intervention scientists may consider to better understand the influence of REE on GWG and how to implement REE as a useful strategy for GWG interventions among PW-OW/OB:

- Given agreement between objective (Breezing™ mobile metabolism device) assessments and the estimated equation to measure REE, researchers can use both strategies to obtain more frequent assessments of REE. However, given the evidence that certain study (randomized to intervention vs. control) and personal (weight status, fat-free mass, energy intake) characteristics are related to the agreement between the two methods, researchers need to examine data with and without both methods to understand if variation between the methods impacts outcomes, particularly if the goal is for PW-OW/OB to obtain the most accurate value of REE.

- Accurate assessments of REE are important for self-monitoring behaviors such as adjusting energy intake and activity kcals in order to regulate GWG. Thus, researchers and intervention scientists should consider the use of Breezing™ as a self-monitoring tool for pregnant women to adjust and regulate their daily energy intake and activity kcals. However, when Breezing™ is not feasible (e.g., daily) or when there is missing data from Breezing™, the estimated equation may serve as an appropriate substitute.
- Future prenatal GWG interventions should measure REE in conjunction with energy intake and physical activity to better understand how these factors influence GWG. In addition, developing intervention content around REE may be particularly useful for PW-OW/OB because women can use REE to create a physical activity goal to increase total energy expenditure and use the total energy expenditure to create an energy intake goal to regulate GWG. Specifically, intervention content focusing on REE should be customized during the second trimester on at least a weekly basis to identify points of fluctuation in REE during this critical time period. Accurately informing women of their weekly REE during these times of fluctuation can help PW-OW/OB to create individualized and appropriate energy intake and physical activity goals for the week in order to regulate weekly and total GWG. Instead of recommending PW-OW/OB blanket goals of energy intake and physical activity based on women with normal weight, it may be useful to personalize goals particularly during the second trimester and during these critical time periods of fluctuation in REE.

Main Study Conclusions

Overall, these dissertation studies suggest that in addition to moderating energy intake and promoting physical activity, REE may be better utilized to help regulate GWG. Future prenatal interventions may wish to measure REE in conjunction with energy intake and physical activity using mobile devices and valid equations that estimate REE in an effort to develop personalized energy intake and physical activity goals to meet GWG goals. Researchers designing future GWG interventions may also wish to educate women about their REE in relation to their energy intake and physical activity behaviors and overall GWG. Future research is needed to test these suggestions and identify how to best incorporate REE in the context of an intervention to moderate energy intake and promote physical activity as a means for effective GWG regulation.

REFERENCES

Abramowitz, M. and Stegun, I.A., eds. (1965). Handbook of Mathematical Functions. New York, NY: Dover.

Aguilar-Cordero, M.J., Sánchez-García, J.C., Rodriguez-Blanque, R., Sánchez-López, A.M., & Mur-Villar, N. (2019). Moderate physical activity in an aquatic environment during pregnancy (SWEP study) and its influence in preventing postpartum depression.

Ainsworth, B., Cahalin, L., Buman, M., & Ross, R. (2015). The current state of physical activity assessment tools. *Progress in Cardiovascular Diseases, 57,* 387-395.

American College of Obstetrics and Gynecologists. (2015). Physical activity and exercise during pregnancy and the postpartum period. Committee Opinion No. 650. *Obstetrics & Gynecology, 126,* e135-e142.

American College of Obstetrics and Gynecologists. (2016). Nutrition during pregnancy. In *Your pregnancy and childbirth: Month to month* (6th ed., pp. 313-327). Washington, D.C.: ACOG.

Ancira-Moreno, M., Vadillo-Ortega, F., Rivera-Dommarco, J.Á., Sánchez, B.N., Pasteris, J., Batis, C., … O'Neil, M.S. (2019). Gestational weight gain trajectories over pregnancy and their association with maternal diet quality: Results from the PRINCESA cohort. *Nutrition, 65,* 158-166. doi: 10.1016/j.nut.2019.02.002. PMID: 31132630.

Azjen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes, 50,* 179-211.

Baskin, R., Hill, B., Jacka, F.N., O'Neil, A., & Skouteris, H. (2015). The association between diet quality and mental health during the perinatal period: A systematic review. *Appetite, 91,* 41-47.

Berggren, E.K., O'Tierney-Ginn, P., Lewis, S., Presley, L., Hauguel De-Mouzon, S., & Catalano, P.M. (2017). Variations in resting energy expenditure: Impact on gestational weight gain. *American Journal of Obstetrics & Gynecology, 217,* 445.e1-445.e6.

Bianchi, C., de Gennaro, G., Romano, M., Aragona, M., Battini, L., Del Prato, S., & Bertolotto, A. (2018). Pre-pregnancy obesity, gestational diabetes or gestational weight gain: Which is the strongest predictor of pregnancy outcomes? *Diabetes Research and Clinical Practice, 144,* 286-293. doi: 10.1016/j.diabres.2018.08.019. PMID: 30189224.

Bisson, M., Alméras, N., Dufresne, S.S., Robitallie, R., Rhéaume, C., Bujold, E., … Marc, I. (2015). A 12-week exercise program for pregnant women with obesity to improve physical activity levels: An open randomised preliminary study. *PLoS One, 10,* e0137742.

Blau, L.E., Lipsky, L.M., Dempster, K.W., Eisenberg Colman, M.H., Siega-Riz, A.M., Faith, M.S., & Nansel, T.R. (2020). Women's experience and understanding of food cravings in pregnancy: A qualitative study in women receiving prenatal care at the university of North Carolina-Chapel Hill. *Journal of the Academy of Nutrition and Dietetics, 120,* 815-824.

Borodulin K., Evenson, K.R., & Herring, A.H. (2009). Physical activity patterns during pregnancy through postpartum. *BMC Women's Health, 9,* 32.

Borodulin, K., Evenson, K.R., Wen, F., Herring, A.H., & Benson, A. (2008). Physical activity patterns during pregnancy. *Medicine & Science in Sports & Exercise, 40,* 1901-1908.

Bruno, R., Petrella, E., Bertarini, V., Pedrielli, G., Neri, I., & Facchinetti, F. (2017). Adherence to a lifestyle programme in overweight/obese pregnant women and effect on gestational diabetes mellitus: A randomized controlled trial. *Maternal & Child Nutrition, 13,* e12333.

Butte, N.F. (2005). Energy requirements during pregnancy and consequences of deviations from requirement on fetal outcome. *Nestlé Nutrition Workshop Series. Paediatric Programme, 55,* 49- 71. doi: 10.1159/000082593. PMID: 16632928.

Butte, N.F., Ellis, K.J., Wong, W.W., Hopkinson, J.M., & Smith, E.O. (2003). Composition of gestational weight gain impacts maternal fat retention and infant birth weight. *American Journal of Obstetrics & Gynecology, 189,* 1423-1432. PMID: 14634581.

Butte, N.F., Wong, W.W., Treuth, M.S., Ellis, K.J., & O'Brian Smith, E. (2004). Energy requirements during pregnancy based on total energy expenditure and energy deposition. *The American Journal of Clinical Nutrition, 79,* 1078-1087. PMID: 15159239.

Byrne, N.M., Groves, A.M., McIntyre, H.D., & Callaway, L.K. (2011). Changes in resting and walking energy expenditure and walking speed during pregnancy in obese women. *The American Journal of Clinical Nutrition, 94,* 819-830.

Careau, V. (2017). Energy intake, basal metabolic rate, and within-individual trade-offs in men and women training for a half marathon: A reanalysis. *Physiological and Biochemical Zoology, 90,* 392-398.

Carver, C. & Scheier, M.F. (1998). *On the self-regulation of behavior.* Cambridge, United Kingdom: Cambridge University Press.

Catalano, P.M. (1999). Pregnancy and lactation in relation to range of acceptable carbohydrate and fat intake. *European Journal of Clinical Nutrition, 53,* S124-S135.

Chen, C., Xu, X., & Yan, Y. (2018). Estimated global overweight and obesity burden in pregnant women based on panel data model. *PLoS One, 13,* e0202183. doi: 10.1371/journal.pone.0202183. PMID: 30092099.

Chen, H.Y. & Chauhan, S.P. (2019). Association between gestational weight gain adequacy and adverse maternal and neonatal outcomes. *American Journal of Perinatology, 36,* 615-623. doi: 10.1055/s-0038-1672196. PMID: 30282104.

Chen, X., Zhao, D., Mao, X., Xia, Y., Baker, P.N., & Zhang, H. (2016). Maternal dietary patterns and pregnancy outcome. *Nutrients, 8,* E351.

Cohen, J. (1988). Statistical Power Analysis for the Behavioral Sciences (2nd Edition). Hillsdale, NJ: Lawrence Earlbaum Associates.

Cohen, J., Cohen, P., West, S.G., and Aiken, L.S. (2003). Applied Multiple Regression/Correlation Analysis for the Behavioral Sciences (3rd edition). Mahwah, NJ: Lawrence Earlbaum Associates.

Connelly, M., Brown, H., van der Pligt, P., & Teychenne, M. (2015). Modifiable barriers to leisure-time physical activity during pregnancy: A qualitative study investigating first time mother's views and experiences. *BMC Pregnancy & Childbirth, 15,* 100.

Crume, T.L., Brinton, J.T., Shapiro, A., Kaar, J., Glueck, D.H., Siega-Riz, A.M., & Dabelea, D. (2016). Maternal dietary intake during pregnancy and offspring body composition: The healthy start study. *American Journal of Obstetrics and Gynecology, 215,* 609.e1-609.e8.

Da Costa, D. & Ireland, K. (2013). Perceived benefits and barriers to leisure-time physical activity during pregnancy in previously inactive and active women. *Women & Health, 53,* 185-202.

da Silva, S.G., Ricardo, L.I., Evenson, K.R. & Hallal, P.C. (2017). Leisture-time physical activity in pregnancy and maternal-child health: A systematic review and meta-analysis of randomized controlled trials and cohort studies. *Sports Medicine, 47,* 295-317. doi: 10.1007/s40279-016-0565-2. PMID: 27282925.

Daly, N., Mitchell, C., Farren, M., Kennelly, M.M., Hussey, J., & Turner, M.J. (2016). Maternal obesity and physical activity and exercise levels as pregnancy advances: An observational study. *Irish Journal of Medical Science, 185,* 357-370. doi: 10.1007/s11845-015-1340-3. PMID: 26220609.

Damjanovic, S.S., Stojic, R.V., Lalic, N.M., Jotic, A.Z., Macut, D.P., Ognjanovic, S.I. (2009). Relationship between basal metabolic rate and cortisol secretion throughout pregnancy. *Endocrine, 35,* 262-268. doi: 10.1007/s12020-008-9137-z. PMID: 19156546.

de Jersey, S.J., Nicholson, J.M., Callaway, L.K., & Daniels, L.A. (2013). An observational study of nutrition and physical activity behaviours, knowledge, and advice in pregnancy. *BMC Pregnancy and Childbirth, 13,* 115. doi: 10.1186/1471-2393-13-115. PMID: 23688111.

Deputy, N.P., Sharma, A.J., Kim, S.Y., & Hinkle, S.N. (2015). Prevalence and characteristics associated with gestational weight gain adequacy. *Obstetrics & Gynecology, 125,* 773-781. doi: 10.1097/AOG. 0000000000000739. PMID: 25751216.

Dipietro, L., Evenson, K.R., Bloodgood, B., Sprow, K., Troiano, R.P., Piercy, K.L., … 2018 Physical Activity Guidelines Advisory Committee. (2019). Benefits of physical activity during pregnancy and postpartum: An umbrella review. *Medicine & Science in Sports & Exercise, 51,* 1292-1302.

Dodd, J.M., Grivell, R.M., Crowther, C.A., & Robinson, J.S. (2010). Antenatal interventions for overweight or obese pregnant women: A systematic review of randomized trials. *BJOG, 117,* 1316-1326.

Dodd, J.M., Turnbull, D., Phee, A.J., Deussen, A.R., Grivell, R.M., Yelland, L.N., … Robinson, J.S. (2014). Antenatal lifestyle advice for women who are overweight of obese: LIMIT randomized trial. *BMJ, 348,* g1285.

Donahue, S.M., Zimmerman, F.J., Starr, J.R., & Holt, V.L. (2010). Correlates of pre-pregnancy physical inactivity: Results from the pregnancy risk assessment monitoring system. *Maternal and Child Health Journal, 14,* 235-244. doi: 10.1007/s10995-009-0441-x. PMID: 19156507.

Dong, Y., Deshpande, S., Rivera, D.E., Downs, D.S., & Savage, J.S. (2014). Hybrid model predictive control for sequential decision policies in adaptive behavioral interventions. *Proceedings of the 2014 American Control Conference,* 4198-4203. PMID: 25635157.

Dong, Y., Rivera, D.E., Downs, D.S., Savage, J.S., Thomas, D.M., & Collins, L.M. (2013). Hybrid model predictive control for optimizing gestational weight gain behavioral interventions. *Proceedings of the 2013 American Control Conference,* 1970-1975. PMID: 24336314.

Dong, Y., Rivera, D. E., Thomas, D. M., Navarro-Barrientos, J. E., Symons Downs, D., Savage, J. S., & Collins, L. M. (2012). A dynamical systems model for improving gestational weight gain behavioral interventions. *Proceedings of the 2012 American Control Conference, Montreal, CN*, 4059-4064. PMID: 24309837.

Du, M.C., Ouyang, Y.Q., Nie, X.F., Huang, Y., & Redding, S.R. (2019). Effects of physical exercise during pregnancy on maternal and infant outcomes in overweight and obese pregnant women: A meta-analysis. *Birth, 46,* 211-221. doi: 10.1111/birt.12396. PMID: 30240042.

Dubois, L., Diasparra, M., Bédard, B., Colapinto, C.K., Fontaine-Bisson, B., Tremblay, R.E., & Fraser, W.D. (2018). Adequacy of nutritional intake during pregnancy in relation to prepregnancy BMI: Results from the 3D cohort study. *British Journal of Nutrition, 120,* 335-344. doi: 10.1017/S0007114518001393. PMID: 29875026.

Dutton, H., Borengasser, S.J., Gaudet, L.M., Barbour, L.A., & Keely, E.J. (2018). Obesity in pregnancy: Optimizing outcomes for mom and baby. *Medical Clinics of North America, 102,* 87-106. doi: 10.1016/j.mcna.2017.08.008. PMID: 29156189.

Engberg, E., Alen, M., Kukkonen-Harjula, K., Peltonen, J.E., Tikkanen, H.O., & Pekkarinen, H. (2012). Life events and change in leisure time physical activity: A systematic review. *Sports Medicine, 42,* 433-447.

Evenson, K.R. & Wen, F. (2011). Prevalence and correlates of objectively measured physical activity and sedentary behavior among US pregnant women. *Preventive Medicine, 53,* 39-43.

Flannery, C., McHugh, S., Anaba, A.E., Clifford, E., O'Riordan, M., Kenny, L.C., … Byrne, M. (2018). Enablers and barriers to physical activity in overweight and obese pregnant women: An analysis informed by the theoretical domains framework and COM-B model. *BMC Pregnancy Childbirth, 18,* 178.

Forsum, E. & Löf, M. (2007). Energy metabolism during human pregnancy. *Annual Review of Nutriion, 27,* 277-292. doi: 10.1146/annurev.nutr.27.061406.093543. PMID: 17465854.

Frankenfield, D., Roth-Yousey, L., & Compher, C. (2005). Comparison of predictive equations for resting energy expenditure in healthy nonobese and obese adults: A systematic review. *Journal of the American Dietetic Association, 105,* 775-789.

Giavarina, D. (2015). Understanding bland altman analysis. *Biochemiaa Medica (Zagreb), 25,* 141-151.

Gilliat-Wimberly, M., Manore, M.M., Woolf, K., Sawn, P.D., & Carroll, S.S. (2001). Effects of habitual physical activity on the resting metabolic rates and body compositions of women aged 35 to 50 years. *Journal of the American Dietetic Association, 101,* 1181-1188. PMID: 11678489.

Gilmore, L.A., Butte, N.F., Ravussin, E., Han, H., Burton, J.H., & Redman, L.M. (2016). Energy intake and energy expenditure for determining excess weight gain in pregnant women. *Obstetrics & Gynecology, 127,* 884-892. doi: 10.1097/AOG.0000000000001372. PMID: 27054928.

Guelinckx, I., Devlieger, R., Mullie, P., & Vansant, G. (2010). Effect of lifestyle intervention on dietary habits, physical activity, and gestational weight gain in obese pregnant women: A randomized controlled trial. *The American Journal of Clinical Nutrition, 91,* 373-380.

Guo, P., Rivera, D. E., Symons Downs, D., Savage, J. S., Pauley, A. M., Hess, L. B., and Stetter, C. (2016). Semi-physical identification and state estimation of energy intake for interventions to manage gestational weight gain. *2016 American Control Conference*, Boston, MA, July 6-8, 2016. 1271-1276. doi: 10.1109/ACC.2016.7525092. PMID: 27570366.

Guo, P., Rivera, D. E., Pauley, A. M., Leonard, K. S., Savage, J. S., & Downs, D. S. (2018a). A "Model-on-Demand" methodology for energy intake estimation to improve gestational weight control interventions. *Proceedings of the IFAC World Congress. International Federation of Automatic Control. World Congress*, *51*(15), 144-149. PMID 30480263.

Guo, P., Rivera, D. E., Savage, J. S., Hohman, E. E., Pauley, A. M., Leonard, K. S., and Symons Downs, D. (2018b). System identification approaches for energy intake estimation: Enhancing interventions for managing gestational weight gain. *IEEE Transactions on Control Systems Technology,* published online, 1-16. doi: 10.1109/TCST.2018.2871871.

Harrison, C.L., Brown, W.J., Hayman, M., Moran, L.J., & Redman, L.M. (2016). The role of physical activity in preconception, pregnancy and postpartum health. *Seminars in Reproductive Medicine,34,* e28-e37.

Haugen, M., Brantsæter, A.L., Winkvist, A., Lissner, L., Alexander, J., Oftedal, B., … Meltzer, H.M. (2014). Associations of pre-pregnancy body mass index and gestational weight gain with pregnancy outcomes and postpartum weight retention: A prospective observational cohort study. *BMC Pregnancy & Childbirth, 14,* 201. doi: 10.1186/1471-2393-14-201. PMID: 24917037.

Hawkins, M., Hosker, M., Marcus, B.H., Rosal, M.C., Braun, B., Stanek 3rd, E.J., Markenson, G., & Chasan-Taber, L. (2015). A pregnancy lifestyle intervention to prevent gestational diabetes risk factors in overweight Hispanic women: A feasibility randomized controlled trial. *Diabetes Medicine, 32,* 108-115.

Hood, K.M., Marr, C., Kirk-Sorrow, J., Farmer IV, J., Lee, M., & Kern, M. (2019). Validity and reliability of a Wi-Fi smart scale to estimated body composition. *Health and Technology, 9,* 839-856.

Hronek, M., Doubkova, P., Hrnciarikova, D., & Zadak, Z. (2013). Dietary intake of energy and nutrients in relation to resting energy expenditure and anthropometric parameters of Czch pregnant women.

Hui, A., Back, L., Ludwig, S., Gardiner, P., Sevenhuysen, G., Dean, H.J., … Shen, G.X. (2014). Effects of lifestyle intervention on dietary intake, physical activity level, and gestational weight gain in pregnant women with different pre-pregnancy body mass index in a randomized control trial. *BMC Pregnancy and Childbirth, 14,* 331.

Institute of Medicine (US) and National Research Council (US) Committee to Reexamine IOM Pregnancy Weight Guidelines. (2009). *Weight gain during pregnancy: Reexamining the guidelines.* Yaktine AL, Rasmussen KM (eds). Washington (DC): National Academies Press.

International Weight Management in Pregnancy (i-WIP) Collaborative Group. (2017). Effect of diet and physical activity based interventions in pregnancy on gestational weight gain and pregnancy outcomes: Meta-analysis of individual participant data from randomised trials. *BMJ, 358,* j3119. doi: 10.1136/bmj.j3119. PMID: 28724518.

Jackemeyer, D., Forzani, E., & Whisner, C. (2017). Study of resting energy expenditure and weight changes during pregnancy. *Global Journal of Obesity, Diabetes, and Metabolic Syndrome, 4,* 016-023.

Jarman, M., Yuan, Y., Pakseresht, M., Shi, Q., Robson, P.J., & Bell, R.C. (2016). Patterns and trajectories of gestational weight gain: A prospective cohort study. *Canadian Medical Association Journal Open,4,* E338-E345.

Jeffs, E., Haszrd, J.J., Sharp, B., Gullam, J., & Paterson, H. (2016). Pregnant women lack accurate knowledge of their BMI and recommended gestational weight gain. *New Zealand Medical Journal, 129,* 37-45. PMID: 27507720.

Johnson, J.L., Farr, S.L., Dietz, P.M., Sharma, A.J., Barfield, W.D., & Robbins, C.L. (2015). Trends in gestational weight gain: The pregnancy risk assessment monitoring system, 2000-2009. *American Journal of Obstetrics & Gynecology, 212,* 806.e1-806.e8.

Kaiser, L.L., Campbell, C.G., & Academy Positions Committee Workgroup. (2014). Practice paper of the Academy of Nutrition and Dietetics: Nutrition and lifestyle for a healthy pregnancy outcome. *Journal of the Academy of Nutrition and Dietetics, 114,* 1447.

Knabl, J., Riedel, C., Gmach, Ensenauer, R., Brandlhuber, L., Rasmussen, K.M., … von Kries, R. (2014). Prediction of excessive gestational weight gain from week-specific cutoff values: A cohort study. *Journal of Perinatology, 34,* 351-356.

Kominiarek, M.A. & Rajan, P. (2016). Nutrition recommendations in pregnancy and lactation. *Medical Clinics of North America, 100,* 1199-1215.

Kyle, U.G., Genton, L., Slosman, D.O., & Pichard, C. (2001). Fat-free and fat mass percentiles in 5225 healthy subjects aged 15 to 98 years. *Nutrition, 17,* 534-541.

Lean, S.C., Derricott, H., Jones, R.L., & Heazell, A.E.P. (2017). Advanced maternal age and adverse pregnancy outcomes: A systematic review and meta-analysis. *PLoS ONE, 12,* 30186287.

Lindqvist, M., Lindkvist, M., Eurenius, E., Persson, M., Ivarsson, A., & Mogren, I. (2016). Leisure time physical activity among pregnant women and its associations with maternal characteristics and pregnancy outcomes. *Sexual & Reproductive Healthcare, 9,* 14-20. doi: 10.1016/j.srhc.2016.03.006. PMID: 27634659.

Lof, M., Olausson, H., Bostrom, K., Janerot-Sjöberg, B., Sohlstrom, A., & Forsum, E. (2005). Changes in basal metabolic rate during pregnancy in relation to changes in body weight and composition, cardiac output, insulin-like growth factor I, and thyroid hormones and in relation to fetal growth. *The American Journal of Clinical Nutrition, 81,* 678-685. PMID: 15755839.

Mamun, A.A., Kinarivala, M., O'Callaghan, M.J., Williams, G.M., Najman, J.M., & Callaway, L.K. (2010). Associations of excess weight gain during pregnancy with long-term maternal overweight and obesity: Evidence from 21 y postpartum follow-up. *The American Journal of Clinical Nutrition, 91,* 1336-1431. doi: 10.3945/ajcn.2009.28950. PMID: 20237138.

Marginean, C., Marginean, C.O., Banescu, C., Melit, L., Tripon, F., & Iancu, M. (2016). Impact of demographic, genetic, and bioimpedance factors on gestational weight gain and birth weight in a Romanian population: A cross-sectional study in mothers and their newborns: the Monebo study (STROBE-compliant article). *Medicine (Baltimore), 95,* e4098. doi: 10.1097/MD.0000000000004098. PMID: 27399105.

Mâsse, L.C., Fuemmeler, B.F., Anderson, C.B., Matthews, C.E., Trost, S.G., Catellier, D.J., & Treuth, M. (2005). Accelerometer data reduction: A comparison of four reduction algorithms on select outcome variables. *Medicine and Science in Sports and Exercise, 37,* S544-S554.

McClave, S.A. & Snider, H.L. (1992). Use of indirect calorimetry in clinical nutrition. *Nutrition in Clinical Practice, 7,* 207-221.

McDowell, M., Cain, M.A., & Brumley, J. (2019). Excessive gestational weight gain. *Journal of Midwifery & Women's Health, 64,* 46-54. doi: 10.1111/jmwh.12927. PMID: 30548447.

Melzer, K., Schutz, Y., Boulvain, M., & Kayser, B. (2009). Pregnancy-related changes in activity energy expenditure and resting metabolic rate in Switzerland. *European Journal of Clinical Nutrition, 63,* 1185-1191.

Melzer, K., Schutz, Y., Soehnchen, N., Othenin Girard, V., Martinez de Tejada, B., Pichard, C., … Kayser, B. (2010). Prepregnancy body mass index and resting metabolic rate during pregnancy. *Annals of Nutrition and Metabolism, 57,* 221-227. doi: 10.1159/000322369. PMID: 21124024.

Meng, Y., Groth, S.W., Stewart, P., & Smith, J.A. (2018). A exploration of the determinants of gestational weight gain in African American women: Genetic factors and energy expenditure. *Biological Research for Nursing, 20,* 118-125.

Merkx, A., Ausems, M., Budé, L., de Vries, R., & Nieuwenhuijze, M.J. (2017). Factors affecting perceived change in physical activity in pregnancy. *Midwifery, 51,* 16-23.

Moran, L.J., McNaughton, S.A., Sui, Z., Cramp, C., Deussen, A.R., Grivell, R.M., & Dodd, J.M. (2018). The characterization of overweight and obese women who are under reporting energy intake during pregnancy. *BMC Pregnancy and Childbirth, 18,* 204.

Most, J., Dervis, S., Harman, F., Adamo, K.B., & Redman, L.M. (2019). Energy intake requirements in pregnancy. *Nutrients, 11,* 1812. doi: 10.3390/nu11081812. PMID: 31390778.

Most, J., Vallo, P.M., Gilmore, L.A., St. Amant, M., Hsia, D.S., Altazan, A.D., … Redman, L.M. (2018). Energy expenditure in pregnant women with obesity does not support energy intake recommendations. *Obesity (Silver Spring), 26,* 992-999.

Mullaney, L., O'Higgins, A.C., Cawley, S., Doolan, A., McCartney, D., & Turner, M.J. (2015). An estimation of periconceptional under-reporting of dietary energy intake. *Journal of Public Health, 37* 728-736. doi: 10.1093/pubmed/fdu086. PMID: 25355686.

Nagourney, E.M., Goodman, D., Lam, Y., Hurley, K.M., Henderson, J., & Surkan, P.J. (2019). Obese women's perceptions of weight gain during pregnancy: A theory-based analysis. *Public Health Nutrition.* 1-9. doi: 10.1017/S1368980019000703. PMID: 31134872.

Nichols, S.F., Galesloot, S., Bondarianzadeh, D., & Buhler, S. (2019). Dietary changes Albertan women make during pregnancy: Thematic analysis of self-reported changes and reasons. *Canadian Journal of Dietetic Practice and Research, 80,* 39-43.

Nowicki, E., Siega-Riz, A.M., Herring, A., He, K., Stuebe, A., & Olshan, A. (2011). Predictors of measurement error in energy intake during pregnancy. *American Journal of Epidemiology, 173,* 560-568. PMID: 21273398.

O'Brien, R.M. (2007). A caution regarding rules of thumb for variance inflation factors. *Quality & Quantity, 41,* 673-690.

Overcash, R.T., Hull, A.D., Moore, T.R., & LaCoursiere, D.Y. (2015). Early second trimester weight gain in obese women predicts excessive gestational weight gain in pregnancy. *Maternal and Child Health Journal, 19,* 2412-2418.

Parker, H.W., Tovar, A., McCurdy, K., & Vadiveloo, M. (2019). Associations between pre-pregnancy BMI, gestational weight gain, and prenatal diet quality in a national sample. *PLoS One, 14,* e0224034. doi: 10.1371/journal.pone.0224034. PMID: 31626677.

Pauley, A.M., Hohman, E., Savage, J.S., Rivera, D.E., Guo, P., Leonard, K.S, & Symons Downs, D. (2018). Gestational weight gain intervention impacts determinants of healthy eating and exercise in overweight/obese pregnant women. *Journal of Obesity, 2018,* 12 pages.

Phatak, A.G. & Nimbalkar, S.M. (2017). Method comparison (agreement) studies: Myths and rationale. *Journal of Clinical and Diagnostic Research, 11,* J101-J103.

Phelan, S., Phipps, M.G., Abrams, B., Darroch, F., Schaffner, & Wing, R.R. (2011). Randomized trial of a behavioral intervention to prevent excessive gestational weight gain: The Fit for Delivery Study. *The American Journal of Clinical Nutrition, 93,* 772-779.

Raudenbush, S. and Bryk, A. (2002). Hierarchical Linear Models (Second Edition). Thousand Oaks, CA: Sage Publications.

Redman, L.M., Gilmore, L.A., Breaux, J., Thomas, D.M., Elkind-Hirsch, K., Stewart, T., … Martin, C.K. (2017). Effectiveness of SmartMoms, a novel eHealth intervention for management of gestational weight gain: Randomized controlled pilot trial. *JMIR Mhealth and Uhealth, 5,* e133.

Ren, M., Li, H., Cai, W., Niu, X., Ji, W., Zhang, Z., … Li, Y. (2018). Excessive gestational weight gain in accordance with the IOM criteria and the risk of hypertensive disorders of pregnancy: A meta-analysis. *BMC Pregnancy & Childbirth, 18,* 281. doi: 10.1186/s12884-018-1922-y.

Renault, K., Nørgaard, K., Andreasen, K.R., Secher, N.J., & Nilas, L. (2010). Physical activity during pregnancy in obese and normal-weight women assessed by pedometer. *Acta Obstetricia et Gynecological Scandinavica, 89,* 956-961.

Rivera, D.E., Pew, M.D., & Collins, L.M. (2007). Using engineering control principles to inform the design of adaptive interventions: A conceptual introduction. *Drug and Alcohol Dependence, 88,* S31-S40.

Roark, R.A. & Niederhauser, V.P. (2012). Fruit and vegetable intake: Issues with definition and measurement. *Public Health Nutrition, 16,* 2-7.

Ruan, D., Chen, G., & Kerre, E. (2005). Wets, G. (ed.). *Intelligent data mining: Techniques and applications.* Studies in computational intelligence Vol. 5. Springer.

Ruchat, S.M., Mottola, M.F., Skow, R.J., Nagpa, T.S., Meah, V.L., James, M., … Davenport, M.H. (2018). Effectiveness of exercise interventions in the prevention of excessive gestational weight gain and postpartum weight retention: A systematic review and meta-analysis. *British Journal of Sports Medicine, 52,* 1347-1356. doi: 10.1136/bjsports-2018-099399. PMID: 30337461.

Sanabria-Martínez, G., García-Hermoso, A., Poyatos-León, R., Álvarez-Bueno, C., Sánchez-López, M., & Martínez-Vizcaíno, V. (2015). Effectiveness of physical activity interventions on preventing gestational diabetes mellitus and excessive maternal weight gain: A meta-analysis. *BJOG: An International Journal of Obstetrics and Gynaecology, 122,* 1167-1174. doi: 10.1111/1471-0528.13429. PMID: 26036300.

Santos, S., Eekhout, I., Voerman, E., Gaillard, R., Barros, H., Charles, M.A., … Jaddoe, V.W.V. (2018). Gestational weight gain charts for different body mass index groups for women in Europe, North America, and Oceania. *BMC Medicine, 16,* 201.

Savage, J.S., Hohman, E.E., McNitt, K.M., Pauley, A.M., Leonard, K.S., Turner, T., … Symons Downs, D. (2019). Uncontrolled eating during pregnancy predicts fetal growth: The healthy mom zone trial. *Nutrients, 11,* 899.

Shaneshin, M., Rezazadeh, A., Jessri, M., Neyestani, T., & Rashidkhani, B. (2011). Validity of predictive equations for resting energy expenditure among Iranian women. *Asia Pacific Journal of Clinical Nutrition, 20,* 646-653.

Shin, D., Lee, K.W., & Song, W.O. (2016). Pre-pregnancy weight status is associated with diet quality and nutritional biomarkers during pregnancy. *Nutrients, 8,* 162. doi: 10.3390/nu8030162. PMID: 26987398.

Siega-Riz, A.M., Herring, A.H., Carrier, K., Evenson, K.R., Dole, N., & Deierlein, A. (2010). Sociodemographic, perinatal, behavioral, and psychosocial predictors of weight retention at 3 and 12 months postpartum. *Obesity (Silver Spring), 18,* 1996-2003. doi: 10.1038/oby.2009.458. PMID: 20035283.

Soper, D.S. (2020). A-priori Sample Size Calculator for Hierarchical Multiple Regression [Software]. Available from http://www.danielsoper.com/statcalc

Stiegler, P. & Cunliffe, A. (2006). The role of diet and exercise for the maintenance of fat-free mass and resting metabolic rate during weight loss. *Sports Medicine, 36,* 239-262.

Suliga, E., Rokita, W., Adamczyk-Gruszka, O., Pazera, G., Cieśla, E., & Gluszek, S. (2018). Factors associated with gestational weight gain: A cross-sectional survey. *BMC Pregnancy and Childbirth, 18,* 465.

Symons Downs, D. & Hausenblas, H.A. (2004). Women's exercise beliefs and behaviors during their pregnancy and postpartum. *Journal of Midwifery & Women's Health, 49,* 138-144.

Symons Downs, D., Chasan-Taber, L., Evenson, KR., Leiferman, J., & Yeo, S. (2012). Physical activity and pregnancy: Past and present evidence and future recommendations. *Research Quarterly for Exercise and Sport, 83,* 485-502.

Symons Downs, D., Feinberg, M., Hillemeier, M.H., Weisman, C.S., Chase, G.A., Chuang, C.H., … Francis, L.A. (2009). Design of the Central Pennsylvania Women's Health Study (CePAWHS) strong healthy women intervention: Improving preconceptional health. *Maternal and Child Health Journal, 13,* 18-28.

Symons Downs, D., Rivera, D. E., Savage, J. S., Stetter, C., Kunselman, A., Pauley, A. M., Leonard, K. S., Guo, P., & Hohman, E. E. (2019b). Optimizing an individually-tailored, adaptive intervention to manage weight in overweight and obese pregnant women. Annals of Behavioral Medicine, 53, S1, S149-150.

Symons Downs, D., Savage, J.S., & Rauff, E.L. (2014). Falling short of guidelines? Nutrition and weight gain knowledge in pregnancy. *Journal of Women's Health, 3*, 1000184. doi: 10.4172/2167-0420.1000184. PMID: 25599012.

Symons Downs, D., Savage, J. S., Rivera, D. E., Leonard, K. S., Pauley, A. M., Hohman, E. E., & Guo, P. (2017). Using mHealth and eHealth methods to promote weight control among women. *Annals of Behavioral Medicine*, *51 (S1)*, 1587-1588.

Symons Downs, D., Savage, J. S., Rivera, D. E., Pauley, A. M., Leonard, K., Hohman, E., Guo, P., Stetter, C., & Kunselman, A. (under review). Adaptive, behavioral intervention impacts weight gain, physical activity, energy intake, and motivational determinants: Results of a feasibility trial in pregnant women with overweight/obesity. *Journal of Behavioral Medicine*.

Symons Downs, D., Savage, J. S., Rivera, D. E., Pauley, A. M., Leonard, K. S., McNitt, K. M., Hohman, E. E., Guo, P., Kunselman, A., Stetter, C. (2019a). Gestational weight gain intervention for women with overweight impacts energy intake & expenditure. Submitted to Obesity Week Annual Meeting, November 3-7 2019, Las Vegas, Nevada.

Symons Downs, D., Savage, J.S., Rivera, D.E., Smyth, J.M., Rolls, B.J., Hohman, E.E., … Guo, P. (2018). Individually tailored, adaptive intervention to manage gestational weight gain: Protocol for a randomized controlled trial in women with overweight and obesity. doi: 10.2196/resprot.9220. PMID: 29884603.

Symons Downs, D., Rivera, D. E., Savage, J. S., Stetter, C., Kunselman, A., Pauley, A. M., Leonard, K. S., Guo, P., & Hohman, E. E. (2019b). Optimizing an individually-tailored, adaptive intervention to manage weight in overweight and obese pregnant women. Annals of Behavioral Medicine, 53, S1, S149-150.

Szmeja, M.A., Cramp, C., Grivell, R.M., Deussen, A.R., Yelland, L.N., Dodd, J.M. (2014). Use of a DVD to provide dietary and lifestyle information to pregnant women who are overweight or obese: A nested randomized trial. *BMC Pregnancy & Childbirth, 14,* 409.

Talai Rad, N., Ritterath, C., Siegmund, T., Wascher, C., Siebert, G., Henrich, W., & Buhling, K.J. (2011). Longitudinal analysis of changes in energy intake and macronutrient composition during pregnancy and 6 weeks post-partum. *Archives of Gynecology and Obstetrics, 283,* 185-190.

Tan, X., Shiyko, M.P., Li, R., Li, Y., & Dierker, L. (2012). A time-varying effect model for intensive longitudinal data. *Psychological Methods, 17,* 61-77.

Taousani, E., Savvaki, D., Tsirou, E., Poulakos, P., Mintziori, G., Zafrakas, M., … Goulis, D.G. (2017). Regulation of basal metabolic rate in uncomplicated pregnancy and in gestational diabetes mellitus. *Hormones (Athens), 16,* 235-250. doi: 10.14310/horm.2002.1743. PMID: 29278510.

Thomas, D.M., Navarro-Barrientos, J.E., Rivera, D.E., Heymsfield, S.B., Bredlau, C., Redman, L.M., … Butte, N.F. (2012). Dynamic energy-balance model predicting gestational weight gain. *The American Journal of Clinical Nutrition, 95,* 115-122. doi: 10.3945/ajcn.111.024307. PMID: 22170365.

U.S. Department of Health and Human Services. (2018*). Physical Activity Guidelines for Americans.* 2nd ed. Wasington, DC: US Dept of Health and Human Services.

Vander Wyst, K.B., Buman, M.P., Shaibi, G.Q., Petrov, M.E., Reifsnider, E., & Whisner, C.M. (2020). Resting energy expenditure relationship with macronutrients and gestational weight gain: A pilot study. *Nutrients, 12,* 450.

Vesco, K.K., Karanja, N., King, J.C., Gillman, M.W., Perrin, N., McEvoy, C., … Stevens, V.J. (2012). Healthy moms, a randomized trial to promote and evaluate weight maintenance among obese pregnant women: Study design and rationale. *Contemporary Clinical Trials, 33,* 777-785.

Vetter, T.R. (2017). Descriptive statistics: Reporting the answers to the 5 basic questions of who, what, why, when, where, and a sixth, so what? *Anesthesia & Analgesia, 125,* 1797-1802.

Wang, J., Wen, D., Liu, X., & Liu, Y. (2019). Impact of exercise on maternal gestational weight gain: An updated meta-analysis of randomized controlled trials. *Medicine (Baltimore), 98*, e16199. doi: 10.1097/MD.0000000000016199. PMID: 31277127.

Watson, S.J., Lewis, A.J., Boyce, P, & Galbally, M. (2018). Exercise frequency and maternal mental health: Parallel process modeling across the perinatal period in an Australian pregnancy cohort. *Journal of Psychosomatic Research, 111,* 91-99.

Weir, J.B. (1949). New methods for calculating metabolic rate with special reference to protein metabolism. *The Journal of Physiology, 109,* 1-9.

Wennberg, A.L., Isaksson, U., Sandström, H., Lundqvist, A., Hörnell, A., & Hamberg, K. (2016). Swedish women's food habits during pregnancy up to six months post-partum: A longitudinal study. *Sexual & Reproductive Healthcare, 8,* 31-36.

Xian, X., Quach, A., Bridgeman, D., Tsow, F., Forzani, E., & Tao, N. (2015). Personalized indirect calorimeter for energy expenditure (EE) measurement. *Global Journal of Obesity, Diabetes, and Metabolic Syndrome, 2,* 004-008.

Yoo, S. (2018). Dynamic energy balance and obesity prevention. *Journal of Obesity & Metabolic Syndrome, 27,* 203-212.

Curriculum Vitae – Krista S. Leonard

Education

Ph.D. Kinesiology – Psychology of Physical Activity 2017-2020
Minor: Human Development and Family Studies
Department of Kinesiology | The Pennsylvania State University, University Park, PA
M.S. Kinesiology – Psychology of Physical Activity 2015-2017
Department of Kinesiology | The Pennsylvania State University, University Park, PA
B.A. – Exercise Science, Willamette University, Salem, OR 2011-2015
B.A. – Psychology, Willamette University, Salem, OR 2011-2015

Honors/awards

Harold F. Martin Graduate Assistant Outstanding Teaching Award March 2020
College of Health and Human Development Professional Development Endowment February 2020
The Obesity Society eHealth/mHealth Section Poster Award November 2018
Penn State Rapid Research Competition Award April 2018
The Obesity Society eHealth/mHealth Section Poster Award October 2017
AT&T Graduate Award August 2017

Select publications

1. **Leonard, K.S.,** Evans, M.B., Oravecz, Z., Smyth, J.M., & Symons Downs, D. (in press). Effect of technology-supported interventions on prenatal gestational weight gain, physical activity, and healthy eating behaviors: A systematic review & meta-analysis. *Journal of Technology in Behavioral Science.*
2. **Leonard, K.S.,** Pauley, A.M., Guo, P., Rivera, D.E., Hohman, E., Savage, J.S., & Buman, M.P., Symons Downs, D. (in press) Identifying ActiGraph non-wear time in pregnant women with overweight or obesity. *Journal of Science and Medicine in Sport. doi: https://doi.org/10.1016/j.jsams.2020.08.003*
3. **Leonard, K.S.,** Evans, M.B., Kjerulff, K.H., & Symons Downs, D. (2020). Postpartum perceived stress explains the association between perceived social support and depressive symptoms. *Women's Health Issues, 30,* 231-239. doi: https://doi.org/10.1016/j.whi.2020.05.001
4. **Leonard, K.S.,** Kjerulff, K.H., & Symons Downs, D. (2019). Recommending Prenatal Exercise as a Source of Social Support to Reduce Postpartum Depression in First Time Moms. *Annals of Behavioral Medicine, 53 (S1),* S842.
5. **Leonard, K. S.,** Pauley, A. M., Guo, P., Hohman, E. E., Rivera, D. E., Savage, J. S., Buman, M. P., & Symons Downs, D. (2019). Accelerometer wear time threshold in pregnant women with overweight and obesity. *Annals of Behavioral Medicine, 53 (S1)*, S811.
6. **Leonard, K.S.,** Kjerulff, K.H., & Symons Downs, D. (2019). Risk of postpartum depression influences psychological well-being among first time moms. *Annals of Behavioral Medicine, 53 (S1)*, S777.
7. **Leonard, K. S.**, & Symons Downs, D. (2017). Exercising for two: Associations of maternal exercise, fetal growth, and infant birth weight in women with gestational diabetes. *Annals of Behavioral Medicine,51 (S1),* 286.

Grants

Childhood Obesity Prevention Seed Training Grant 2016-2017
National Institute of Food and Agriculture (#2011-67001-30117, A2121 Childhood Obesity Prevention) [$15, 820]

Teaching contributions

Lead Teaching Assistant: KINES 202 Functional Anatomy 2019-2020
Teaching Assistant: KINES 321 Psychology of Movement Behavior 2018-2019
Lead Teaching Assistant: KINES 202 Functional Anatomy 2017-2018
Teaching Assistant: KINES 321 Psychology of Movement Behavior 2015-2017

Committee contributions

Penn State Kinesiology Diversity, Equity, and Inclusion Committee 2018-2020