The relationship between gait mechanics and walking economy throughout pregnancy

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It all starts here ™

PREFACE

Ако будем имао среће да остварим барем неке од својих идеја, то ће бити доброчинство за цијело човјечанство. Ако се те моје наде испуне, најслађа мисао бит ће ми та, да је то дијело једног Србина.

Ја сам као што видите и чујете, остао Србин и преко мора, гдје се испитивањима бавим. То исто треба да будете и ви, и да својим знањем и радом подижете славу српства у свијету.

Никола Тесла

ABSTRACT

Pregnancy is characterized by significant physiological changes that manifest through variability of symptoms, largely stemming from the weight gain, and foetal development. Consequent adaptations in posture, balance, and walking, reduce women's ability to create most comfortable and efficient movement during daily activities throughout pregnancy. As pregnancy progresses, discomfort and movement inefficiency, may significantly contribute to the total energy expenditure. However, current studies do not take in consideration the significance of gait changes and their potential in energy sparing during pregnancy. Therefore, the aim of this study was to investigate the relationship between changes in various biomechanical gait parameters, and energy expenditure during pregnancy.

Thirty-five (35) women (27.5 ± 5.8 yrs) from the Tlokwe municipality volunteered for the study at different stages of pregnancy. Gas exchange via indirect calorimetry, and three-dimensional gait, and ground reaction force data were recorded while they walked at a self-selected speed. External (W_{ext}) work was estimated assuming no energy transfer between segments, while internal work (W_{int}) assumed energy transfer between segments. Hence, the total energy of the body (W_{tot}) during gait was calculated based on the segmental changes relative to the surrounding, and relative to the centre of mass of the body.

Walking speed during pregnancy was inversely associated with participants' weight ($r = -0.38$, $p = 0.03$), while weight gain during pregnancy demonstrated significant correlation with double support stance time ($r = 0.37$, $p = 0.03$). Walking speed was also significantly related to vertical excursion of the centre of gravity ($r = 0.73$, $p \leq 0.01$), which allows for an increase in walking energy recovery with an increase in speed ($r= 0.63$, $p \leq 0.01$).

A partial correlation controlled for weeks of pregnancy showed significant, strong, positive relationship between walking speed and net O_2 rate ($r = 0.70$, $p \leq 0.001$), and no significant relationship was noted between walking speed and gross O_2 rate ($r = 0.32$, $p = 0.08$) or cost ($r = 0.17$, $p = 0.28$). The weeks of gestation did not have significant influence in controlling for the relationship between walking speed and either gross or net O_2 walking energy expenditure. However, 72% of variability in gross O_2 was accounted for by REE which showed strong significant correlation with weight ($r = 0.82$, $p \leq 0.01$).

Stride length, adjusted for leg length, showed strong inverse correlation with the COP/COG inclination angle during walking ($r = -0.44$, $p \leq 0.01$), while step width, also adjusted for leg length, showed strong positive relationship with the lateral trunk lean during walking ($r = 0.61$, $p \leq 0.001$) which was not influenced with the weeks of pregnancy, which would contribute to lateral deviations of the COG.

The effect of these alterations on energy expenditure during walking may be assessed using measures of mechanical work. Both, external and internal mechanical work showed significant correlation with the indirect calorimetry. However, the strongest positive correlation was demonstrated between internal work with gross O_2 cost ($r = 0.81$, $p \leq 0.001$), and gross O_2 rate ($r = 0.67$, $p \leq 0.001$), while moderate-to-strong correlation was depicted between internal work and net O_2 cost ($r = 0.51$, $p \leq 0.01$).

During pregnancy the magnitude of weight gain dictates the kinematic changes in gait and posture. While subsequent walking pattern demonstrates the need for an increase in stability, the respective changes in gait kinematics result in an increase in walking energy expenditure. Although walking economy during pregnancy may be improved via faster walking speeds, women in this study walked significantly slower, not taking the advantage of the principle of energy recovery. This demonstrates that women during pregnancy prefer a comfortable state that may be maintained the longest, rather than mechanically more economical walking. Hence, the future studies may use mechanical work and indirect calorimetry to assess changes in gait, and their contribution to walking energy expenditure.

Key words: pregnancy, gait biomechanics, energy expenditure, mechanical work, balance

OPSOMMING

Swangerskap word gekenmerk deur beduidende fisiologiese veranderinge wat deur ŉ verskeidenheid van simptome manifesteer, hoofsaaklik voortspruitend uit gewigstoename as gevolg van fetale ontwikkeling. Gevolglike aanpassings in postuur, balans en looppatroon verminder vroue se vermoë om tydens daaglikse aktiwiteite dwarsdeur swangerskap gemaklik en doeltreffend te beweeg. Na gelang swangerskap vorder, kan ongemak en ondoeltreffende beweging aansienlik tot die totale energieverbruik bydra. Huidige studies neem egter nie die beduidenis van loopatroonveranderinge en energiegebruik tydens swangerskap in ag nie. Daarom was die doel van hierdie studie om die verhouding tussen veranderinge in verskeie biomeganiese looppatroonparameters en die uitwerking daarvan op energiebesteding tydens swangerskap te ondersoek.

Vyf-en-dertig (35) vroue (27.5 ± 5.8 jaar) uit Tlokwe munisipaliteit, in verskillende stadiums van swangerskap het vrywillig aan die studie deel te neem. Gaswisseling via indirekte kalometrie, drie-dimensionele bewegingsanalise- en grond reaksie kragte was gemeet terwyl hulle teen ŉ selfgekose vaste stapspoed geloop het. Eksterne (W_{ext}) werk is beraam met die aanname dat daar geen energieoordrag tussen segmente plaasvind nie, terwyl daar by interne werk (W_{int}) aangeneem is dat energieoordrag tussen segmente plaasvind. Hieruit is die totale energie van die liggaam (W_{tot}) bereken, gebaseer op die segmentveranderinge relatief tot die omliggende area, en relatief tot die massamiddelpunt van die hele liggaam.

Stapspoed tydens swangerskap is omgekeerd geassosieer met die deelnemers se gewig ($r = -0.38$, $p = 0.03$), terwyl ‘n gewigstoename tydens swangerskap ‘n beduidende korrelasie met dubbele ondersteuningsfase tyd ($r = 0.37$, $p = 0.03$) tydens stap demonstreer. Stap spoed toon ook ‘n beduidende verwantskap met die vertikale ekskursie van swaartepunt ($r = 0.73$, $p \leq 0.01$), wat lei tot ‘n toemane in energie herstel tydens stap gepaard met ‘n toemane in snelheid ($r = 0.63$, $p \leq 0.01$).

Korrelasies aangepas vir weke van swangerskap wys beduidend sterk positiewe verwanskap tussen stapsnelheid en O_2 verbruik ($r = 0.70$, $p \leq 0.001$), met nie-beduidende verwanskap tussen stapsnelheid en brutto O_2 verbruik ($r = 0.32$, $p = 0.08$) of koste nie ($r = 0.17$, $p = 0.28$). Die verhouding tussen stapsnelheid en beide bruto en netto O_2 energieverbruik was nie beduidend beïnvloed deur die verskillende weke van swangerskap nie. Alhoewel, 72% van

die variasie in bruto O_2 kan toegeskryf word aan REE wat ‘n sterk beduidende korrelasie met gewig toon ($r = 0.82$, $p \leq 0.01$).

Tree lengte, aangepas vir been lengte, het sterk omgekeerde korrelasies getoon met COP/COG inklinasie hoek gedurende stap ($r = -0.44$, $p \leq 0.01$, tewyl tree wydte, ook aangepas vir been lengte, sterk positiewe verhoudings getoon het met laterale romp leen tydens stap ($r = 0.61$, $p \leq 0.001$), wat nie beïnvloed was tydens die weke van swangerskap nie, wat bydrae tot laterale drukmiddelpunte-swaartepunt versteurings.

Die effek van hierdie veranderinge in energieverbruik gedurende stap kan geëvalueer word met behulp van metings van meganiese werk. Beide eksterne en interne meganiese werk het ‘n beduidend positiewe verhouding getoon met gaswisseling. Die sterktste korrelasie was tussen interne werk en bruto O_2-koste ($r = 0.81$, $p \leq 0.001$) en bruto O_2 verbruik ($r = 0.67$, $p \leq 0.001$), terwyl matig-tot-sterk korrelasies gevind is tussen interne werk en netto O_2-koste ($r = 0.51$, $p \leq 0.01$).

Die omvang van gewigstoename tydens swangerskap bepaal die kinematiese veranderinge in gang en postuur. Gevolglike veranderinge toon dat vroue ‘n looppatroon verkies wat stabiliteit verhoog en dus verhoog energieverbruik gedurende stap. Alhoewel stap ekonomie tydens swangerskap kan verbeter deur vinniger stapsnelheid het vroue in die studie beduidend statiger gestap en dus nie die voordele verkry van die beginsel van energie herstel nie. Dit demonstreer dat vroue tydens swangerskap ‘n meer gemaklike stappatroon verkies wat vir langer volhou kan word, teenoor ‘n meer meganies ekonomise stappatroon. Dus, toekomstige studies kan meganiese werk en indirekte kalorimetrie gebruik om verandering in loopgang te evalueer, en hul bydrae tot energieverbruik in stap.

Sleutelwoorde: swangerskap, loop biomeganika, energie verbruik, meganiese werk, balans,

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LIST OF ABBREVIATIONS

ACSM	American college of sports medicine
AEE	Active energy expenditure
ANOVA	Analysis of variance
ASIS	Anterior-superior iliac spine
BMI	Body mass index
BMR	Basal metabolic rate
BOS	Base of support
BP	Blood pressure
COG	Centre of gravity
COG_{ML}	Medio-lateral of centre of gravity
COG_{wb}	Centre of gravity of the whole body
COM	Centre of mass
xCOM	Extrapolated centre of mass
COP	Centre of pressure
COP_{ML}	Medio-lateral deviation of centre of pressure
CV	Coefficient of variation
DIT	Diet-induced thermogenic energy expenditure
E	Energy
E_k	Kinetic energy
E_p	Potential energy
ECG	Electrocardiograph
GRF	Ground reaction force
GRF_{HS}	Vertical ground reaction force at heel strike
GRF_{MS}	Vertical ground reaction force at mid-stance
GRF_{TO}	Vertical ground reaction force at toe-off
vGRF	Vertical ground reaction force
HAPPY	Habitual Activity Patterns during PregnancY
HR	Heart rate
MET	Metabolic equivalent of task
NURB	Non-uniform rational basis
O_2	Oxygen
PAL	Physical activity levels
PPBMI	Pre-pregnancy body mass index
PPW	Pre-pregnancy weight

R	Energy recovery
RMR	Resting metabolic rate
RQ	Respiratory quotient
TEE	Total energy expenditure
VO_2	Volume of oxygen
W	Mechanical work
W_{ext}	External mechanical work
W_{int}	Internal mechanical work
W_{tot}	Total mechanical work
θ_{FT}	Angle in frontal plane
θ_{ST}	Angle in sagittal plane

CHAPTER 1 INTRODUCTION

1.1 Introduction

Pregnancy is characterised by the continuous anatomical changes resulting from the foetal growth. The many physiological fluctuations occurring at this time, potentially lead to substantial musculoskeletal changes, which may lead to alterations in total body posture and the gait. (Borg-Stein *et al.*, 2005:181; Foti *et al.*, 2000:627; Heckman & Sassard, 1994:1720; Ponnapula & Boberg, 2010:457). As the primary activity of daily living, any changes to gait may lead to altered walking economy, contributing to increased total energy expenditure. However, while the primary symptoms of gait alterations are musculoskeletal by nature, secondary, dermatological, vascular and neurological changes that also naturally occur during pregnancy, may also influence gait. Their influence on total energy expenditure, on the other hand, is not direct, and results from various individual adaptations women use to alleviate their symptoms, e.g. spending more time on the non-painful leg to alleviate pain from swelling while walking. Given that women experience pregnancy differently, the manifestation of the same symptoms and their coping strategies, also differ from person to person, leading to the development of various and individual gait patterns. Commonly, these coping strategies may vary based on physiological differences among individuals, but the differences in the lifestyle might also predispose women to some of the above-mentioned symptoms. This multivariate interaction between symptoms and the coping mechanism lead to an assumption that walking economy and lower energy expenditure are usually “sacrificed” to alleviate painful or uncomfortable stimuli during walking.

The most economical gait pattern is defined in this study as that which is associated with the lowest metabolic cost at a self-selected work rate. For pathological gait, as in pregnancy, it means the economy of the adaptations in performing that activity. The basic mechanism for gait changes during pregnancy stems from an increase of pelvic girdle width in order to accommodate the growing foetus (Foti *et al.*, 2000:625; Gutke *et al*., 2008:304; Heckman & Sassard, 1994:1725; Wu *et al.,* 2002:679; Wu *et al.,* 2004:482; Wu *et al.,* 2008:1164). A resulting change of the body’s centre of mass (COM) displacement leads to alterations in a vertical movement of COM, which is a crucial parameter in reducing the net external work (W_{ext}) and metabolic cost in walking (Ortega, *et al.,* 2005:2099). In addition, earlier mentioned symptoms of pregnancy might be confined only to a single body segment, affecting intra- and inter-segment coordination during general movements, also possibly increasing energy demand of moving.

Weight gain in the first and second trimester offers more drastic changes to women who are not used to additional weight. During this period, women might go through an "adjustment" phase, where there is limited time to adjust to a relatively fast weight gain. At this time, pregnant women might constantly adjust their posture and the way they move, and additionally perform activities of daily living, in order to achieve a certain level of comfort, or even alleviate any musculoskeletal pain that might result at this stage. However, already in the third trimester, women may get acclimated to the additional weight, and the continuous weight gain may not cause as drastic changes as in the first or second trimester. Hence, throughout late pregnancy, women may adopt two strategies. If there are no painful sensations while conducting activities of daily living, weakness in musculoskeletal system, or any other physiological "gait altering" symptoms, there would be no conscious reason to evoke any changes in walking pattern. On the other hand, women in late pregnancy will have time to reinforce gait patterns that help them alleviate any painful sensations, or improve feeling of stability.

The aim of this chapter is to present the problem statement from which the research question for the study is developed. The objectives of the study, hypotheses and structure of the thesis will furthermore be presented in this chapter.

1.2 Problem statement

Weight gain, or specifically weight distribution, is a direct cause of pregnancy induced postural adjustments, which are also a crucial factor influencing development of new gait characteristics. The changing shape and inertia of the lower trunk require postural adjustments such as an elevation of the head, hyperextension of the cervical spine and extension of the knee and ankle joints (Borg-Stein *et al.*, 2005:182; Butler *et al.*, 2006:1105). These postural adaptations along with the shift in centre of gravity may cause anterior-posterior postural sway, an indicator of decreased balance (Butler *et al.*, 2006:1107; Ilg *et al.*, 2007:197; Jang *et al.*, 2008:468). Because the human body is not rigid, a shift in the centre of gravity of the entire body (COG_{wb}) may lead to segmental movement during walking, impacting segment coordination, and possibly influencing movement economy.

Ultimately, the effect of many factors on the body may be analysed through changes in gait, energy expenditure during gait, and various gait parameters. However, studies analysing pregnancy-induced changes in gait metabolic expenditure (Poppitt, *et al.,* 1993:353; Prentice, *et al.,* 1989:5), gait kinetic and kinematic parameters (Wu, *et al.,* 2008:1160; Foti *et al.,* 2000:628) lack consensus in their findings due to high inter-subject variability which stems from two factors. Firstly, it is a reflection of the highly individual nature of women's responses to pregnancy, and adaptations to pregnancy-induced symptoms that further change throughout pregnancy (Poppitt, *et al.,* 1993:353). Inconsistent kinematic data such as speed of walking, stride length and width, and stance time, have been addressed in most studies examining either energy cost or specific biomechanical parameters. A study by Byrne *et al.* (2011:824), in which gait in pregnant participants from 15 to 30 weeks gestation was analysed, found that self-selected speed of walking significantly decreased during this period, while Foti *et al.* (2000:628), Ilg *et al.* (2007:791), and Lymbery & Gilleard (2005:247) analysed the same parameters during late gestation and post-partum, and found no significant differences in speed, nor gait-related parameters such as step length and stance time. This offers conflicting evidence concerning changes in basic gait kinematic parameters, based on the changes in the weight gain, weight distribution, or energy sparing through decrease of speed of walking.

Secondly, studies on pregnancy assume that changes during pregnancy occur at the same time of gestation in all women. Hence, most research is based on the trimester classification, which is also inconsistent between studies, or simply studies collect over a long period and consider it "during pregnancy" parameter. For example, Byrne *et al.* (2011:824) analysed gait in all participants between 15 and 30 weeks of gestation, while Wu *et al.* (2004:483) measured average kinematic variables for period between 20-34 weeks of pregnancy. Similalry, Butte *et al.* (2004:1081) determined wide range for each trimester such as 0-9 weeks for the first trimester, 9-22 weeks for second, and 22-36 weeks for third trimester. However, Butler *et al.* (2006:1110) chose the 3rd trimester that is between 36-39 weeks, which is further in pregnancy than any of the previous studies. The large diversity in changes occurring during this time results in high variance within parameters, and in parameters between studies. Due to vast individual responses to pregnancy, of which one is the rate of weight gain, all changes during pregnancy could not be expected at the same trimester. Furthermore, between trimesters analysis does not provide clear indication of the relationship between the large number of factors that influence gait mechanics and may impact walking energy consumption. These factors and consequent relationships are discussed in depth in Chapter 2, and demonstrate a more complex nature of changes in pregnancy, that incorporate physiological, metabolic, and mechanical changes throughout pregnancy. Considering the large inter-individual differences, even longitudinal analysis would not be adequate when large numbers of variables are investigated, and where previous results are conflicting (Institute for Work and Health, 2013).

Significance of posture and related alterations during normal walking on gait kinematics and consequent energy expenditure is vastly omitted in research, and generally investigated during steady conditions, or during falling. In addition, these results do not present a clear cause for the gait alterations, as some studies have analysed energy expenditure (Byrne *et al*., 2011:819) and other gait-specific parameters (Foti *et al.,* 2000:628), which limit conclusions as to which factors contribute to altered gait parameters: weight increase, pain-induced changes, or posture-related musculoskeletal adjustments.

Studies investigating energy expenditure during pregnancy largely attribute energy changes to foetal development and resulting changes in resting metabolic rate (RMR). Yet, some inconsistencies are present. For example, indications that net daily energy expenditure during pregnancy does not differ significantly from pre-pregnancy net cost for the same activity when adjusted for change in weight (Byrne *et al.*, 2011:825; Forsum *et al.*, 1992:338; Lof & Forsum, 2007:301; Meltzer *et al.*, 2009:1189; Van Raaj *et al.*, 1990:160) indicates either a decrease in pace of performing that activity (Van Raaij *et al.*, 1990:160), or an effective mechanical adaptation in the execution of that physical activity (Byrne *et al.*, 2011:827). In addition, an increase in resting metabolic rate (RMR) over gestation and a simultaneous decrease in net oxygen consumption (VO_2) may also be an indication of a more economical movement (Byrne *et al.*, 2011:826; Van Raaj *et al.*, 1990:159). Whether these differences in energy expenditure are related to mechanical efficiency or energy metabolism is unclear, as the contribution of each mechanical change to total energy expenditure (TEE) in pregnancy has not yet been identified.

Overall, during pregnancy, there are significant physiological changes in the body systems, manifesting through variability of symptoms and in the way they affect individual pregnant women. As a result, specific adaptations to these symptoms are relative to the individual's ability to create a pain-free and energy-efficient movement.

Using the theoretical framework, along with the results and suggestions of the relevant research reviewed for this study, we will gain a clear insight into mechanisms of efficient gait development during pregnancy and answer the following research questions: What is the relationship between various gait biomechanical parameters and energy expenditure during pregnancy?

1.3 Significance of the study

This study will be one of the first to comprehensively examine biomechanical analysis of gait in a specific pregnant population in South Africa. At present there are no known studies to examine comprehensive analyses of gait in South African women. This study will also demonstrate the relationships that exist outside of the trimester classification, and are significant contributors to changes in gait kinematics and energy expenditure. Therefore, it may significantly contribute to the knowledge of the ever-evolving interaction between biomechanics and exercise physiology in clinical as well as sport settings. Various health professionals may use the information from this study to advise expecting mothers on possible effects of pregnancy, manifestations of certain symptoms, recognition of their specific needs, and as a result, education on benefits of exercise, and effective solutions with regard to performing activities of daily living while pregnant.

1.4 Objectives

The main objectives of this study are to:

- Determine the relationship between gait kinematics and kinetics with walking energy expenditure during pregnancy in South African women.
- Determine the relationship between gait kinematics and dynamic balance and posture during pregnancy in South African women.
- Determine the relationship between mechanical work prediction equations and indirect calorimetry in assessing changes in gait economy during pregnancy in South African women.
- Determine the relationship between gait energy expenditure and walking economy during pregnancy in South African women.

1.5 Hypotheses

This study is based on the following hypotheses:

- A significant positive relationship will exist between gait kinematics and kinetics with walking energy expenditure during pregnancy in South African women.
- A significant positive relationship will exist between gait kinematics and dynamic balance and posture during pregnancy in South African women.

- A significant positive relationship will exist between mechanical work predication equations and indirect calorimetry of gait economy during pregnancy in South African women.
- A significant negative relationship will exist between gait energy expenditure and walking economy during pregnancy in South African women.

1.6 Thesis structure

This thesis consists of six chapters. Chapter one will form the introduction to the full thesis where the problem statement, objectives and hypotheses set for the study will be presented.

In Chapter two an extensive review of the current literature will be presented with the title: "Biomechanics of gait during pregnancy". A computer-based literature search was done for articles published in English. The literature search included the following electronic databases: ScienceDirect, Google Scholar and Medline via Pubmed. Keywords such as "pregnancy", "gait", "energy expenditure", "pregnancy posture", "ground reaction forces", "mechanical work", "balance", "exercise", "physical activity level", "walking economy", "gait mechanics", were used separately and in combination. Additionally, the reference lists of all identified articles were manually checked for additional pertinent publications and these were also reviewed. This chapter will report the results of a narrative search through all available English publications on the topic of gait during pregnancy.

Chapter three will present the extensive methodology used, measures, and instruments, and statistical data analyses. The data collection involved biomechanical, physiological, and physical activity parameters.

Chapter four will present the results based on the statistical analysis, including the descriptive statistic and the inferential statistics in the order of the objectives.

Chapter five will discuss the results of the study, and determine the relation between physiological and biomechanical parameters occurring during pregnancy, also taking into consideration previous research.

Chapter six will summarise findings and draw a conclusion of the study. Limitations of the study will be identified and recommendations made for future research in pregnancy.

There are six appendices included in the following order: findings based on the Objective 3 have been published in BMC Pregnancy and Childbirth and an article is listed as an Appendix A; Appendix B - Reviewer's suggestions and rebuttal; Appendix C - Ethics approval; Appendix D - HAPPY study questionnaire; Appendix E - Informed consent; Appendix F - Acknowledgement of a language review.

1.7 Conceptual framework

This is an ancillary study of a conceptually larger project, the **H**abitual **A**ctivity **P**atterns during **P**regnanc**Y** (HAPPY) study, with an overarching aim of investigating impact of habitual physical activity on the health and wellness of pregnant women and foetal outcomes in South Africa. Data collected in the HAPPY study include measurements from several disciplines investigating multiple aspects of pregnancy (Figure 1.1). Data containing physiological and biomechanical parameters related to gait were conducted solely for purposes of this study. However, day-to-day measures of habitual physical activity were obtained through the overarching study, and included resting and active energy expenditure, and habitual physical activity.

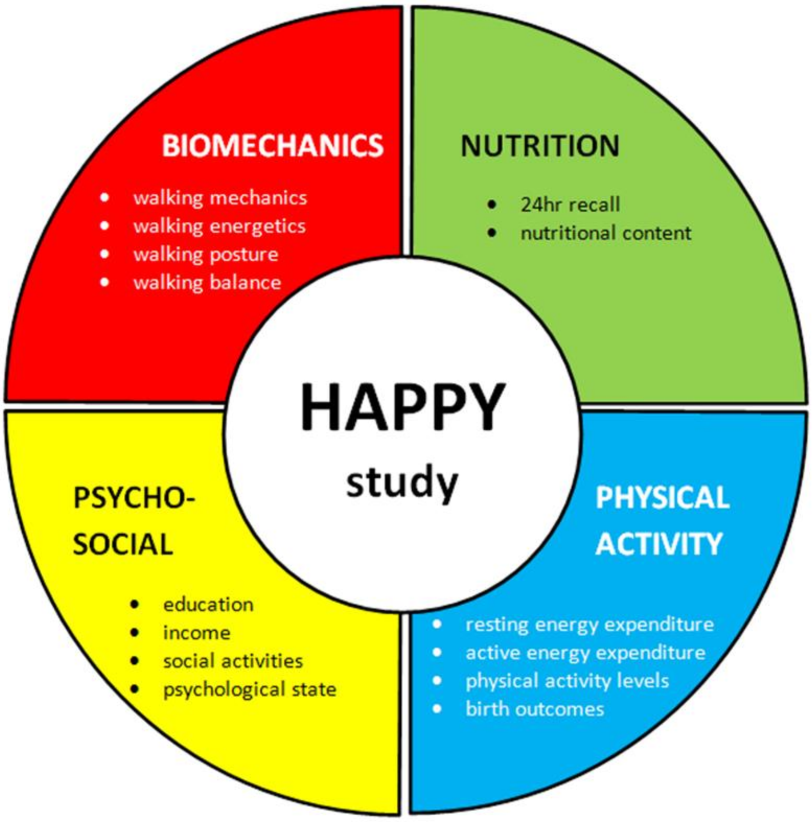

Figure 1.1: Habitual Activity Patterns during PregnancY (HAPPY) study conceptual framework

CHAPTER 2 LITERATURE REVIEW: BIOMECHANICS OF GAIT DURING PREGNANCY

2.1 Introduction

Gait is adapted across the life time and is influenced by various factors, some resulting from the lifestyle changes such as the weight gain or loss, ageing and others as a result of chronic or acute injury to the musculoskeletal system. The pregnancy-induced gait changes are the result of both, weight gain associated with foetal growth and the changes in the body's musculoskeletal system, mimicking different pathologies, varying across individuals. Each pregnant woman responds differently to pregnancy, mostly due to pre-pregnancy physiological and physical differences in individuals. The body possesses numerous mechanisms by which it controls itself to maintain the optimal functioning, and once that homeostasis is challenged, the body utilizes various defence mechanisms which also differ across individuals in type and magnitude by which they act. Therefore, taking into consideration individual differences in women as well as the body's ability to respond differently to various pathologies, it is not surprising that studies continuously address the lack of systematic patterns of responses to the body's various physiological changes, in this case to pregnancy (Jang, Hsiao, & Hsiao-Wecksler, 2008:472; Poppitt, Prentice, Jequier, Schutz, & Whitehead, 1993:363; Prentice, Goldberg, Davies, Murgatroyd, & Scott, 1989:5; Wu, *et al*., 2002:685; Wu, *et al*., 2008:1166).

While walking utilizes mechanisms common to all individuals, there are variations that allow us to identify differences between "normal" vs. "abnormal" walking. Anything beyond the "normal" parameters also bears the assumption of lack of efficiency, since normal functioning is generally considered the optimal in efficiency as well. The efficiency can be measured in different ways and it depends on the goal of the movement. The efficiency can be a single variable such as achieving maximum speed at any cost, or achieving maximum distance at any cost. It can also comprise multiple variables such as achieving maximum distance in the shortest stretch of time, which obviously includes the combination of speed and distance. The trade-off between the two variables is what determines efficiency. In order to understand changes and adaptation in gait, particularly during pregnancy, it is important to understand the trade-off mechanisms that occur during pregnancy in humans, given the variables such as energy cost, avoiding pain, stability, and comfort. Each individual might apply different adaptive trade-off mechanism such as walking at higher energy cost in order to avoid pain, or walking with a wider step to promote stability relative to higher energy cost, due to larger excursions of COM (Saunders, *et al.,* 1953:553)

In order to better understand the gait during pregnancy, the factors comprising the normal gait need to be understood first. Therefore, in the first part of this review, normal gait will be discussed. Since a large number of parameters apply when kinetic and kinematic analysis is conducted on a full body, only the primary gait determinants will be discussed, as their contribution to gait-specific changes and changes in energy expenditure is the greatest. Additional factors that contribute to variability in gait mechanics during pregnancy will be discussed in a section of various musculoskeletal conditions induced by common physiological and physical changes occurring during pregnancy. In addition, while there is a specific section on energy cost and gait during pregnancy, the impact of the primary gait determinants may not be explained efficiently without their relationship to mechanical work and consequently energy expenditure. Therefore gait parameters, and their impact on mechanical work and energy, will be analysed together, while specific energy expenditure analysis will be discussed in a separate section. This will allow for better understanding of the importance of the specific gait determinants. While there are a large number of the musculoskeletal symptoms induced by physiological changes resulting from pregnancy, they are largely reflective by the changes in posture and balance. Hence, the relationship between increased mass, posture, balance and their effect on gait mechanics will be examined together. And lastly, the effect of behavioural modifications during pregnancy on reduction of symptoms of pregnancy on gait walking economy will be considered. While benefits of physical activity are well known, various limitations prevent pregnant women from participation. This section will address the benefits of behavioural changes during pregnancy, and their effect in reducing the symptoms of pregnancy on gait economy.

The purpose of Chapter 2 therefore is to understand the elements involved in normal gait, the adaptations to gait observed during pregnancy due to physical and physiological changes, as well as the role of energy expenditure in the changes observed in gait.

2.2 Normal gait

In layman's terms language, the human gait is a repetitive motion and a primary means of moving from one point to another. In mechanical terms, the aim of walking is to move the centre of mass of the whole body (COM_{wb}) at a constant speed, and with the least amount of expended energy (Chapman, 2008:98). Given the above definition, studying gait and its changes may be analysed using different methods and concepts, which are largely dependent on the parameters to be examined. Kinematic analysis describes the gait (and movement of all body segments) in terms of speed, stride and step length, step width, and frequency, or descriptive parameters, while kinetic analysis examines the internal and external forces affecting the afore-mentioned parameters (e.g. muscle and ground reaction force (GRF) respectively). In addition, the interaction of the internal and external forces causing the body movements produces data relative to the economy of walking, generally examined through concepts of mechanical work, joint and segment moments. With these statistics, changes in energy expenditure while walking can be analysed (i.e. gait energetics). Given the various measures used, it is safe to assume that there are many factors that can affect gait. On a daily basis we observe how body weight fluctuations, changes in posture, injury to upper or lower extremity, even changes in emotions may reflect on the way others walk. For this reason it is easy to recognize a familiar person simply by the way they walk even without seeing their face. While the differences between two types of walking, in terms of some of the more specific gait parameters, may be difficult to distinguish with the "naked eye", other parameters are easy. For example, it is very noticeable that elderly persons walk much slower than younger populations (Oberg, Karsznia, & Oberg, 1993:213), and it is quite easy to notice that professional models place their feet in front of each other, causing very small step width. On the other hand, the differences in walking speed and step length between more and less obese individuals are difficult to notice, yet studies have shown for the gait of these individuals to be significantly different in numerous ways (Freedman, Milner, Thompson, Zhang, & Zhao, 2013:575). Even more difficult for an untrained eye, is to explain the underlying factors responsible for the observed differences. While it is easy to interpret the above findings as an increased weight that has caused the lower walking speed, this conclusion only indicates a symptom of the interaction between the underlying forces causing this effect, and does not explain the interaction of the factors causing it. The function of gait in each of the above examples differs. Modelling gait is for aesthetics, fast gait to save on time, while gait of the obese is to save energy or possibly to increase stability. Using various gait analyses we may understand what factors are manipulated or altered in order to accomplish a specific function.

2.2.1. Gait composition and kinematics

The human gait is a cyclical event and the start of a cycle may begin at different stages in a step. Gait consists of a few distinct phases: heel strike (double support phase), toe off (push-off) of the opposite leg, single leg stance (swing phase), heel strike of the opposite leg). The step may start with the heel strike, at which point both feet are in contact with the ground (i.e. double support phase). At the same time, the back foot is propelling the body forward to counteract the backward reaction force of the ground of the previous heel strike.

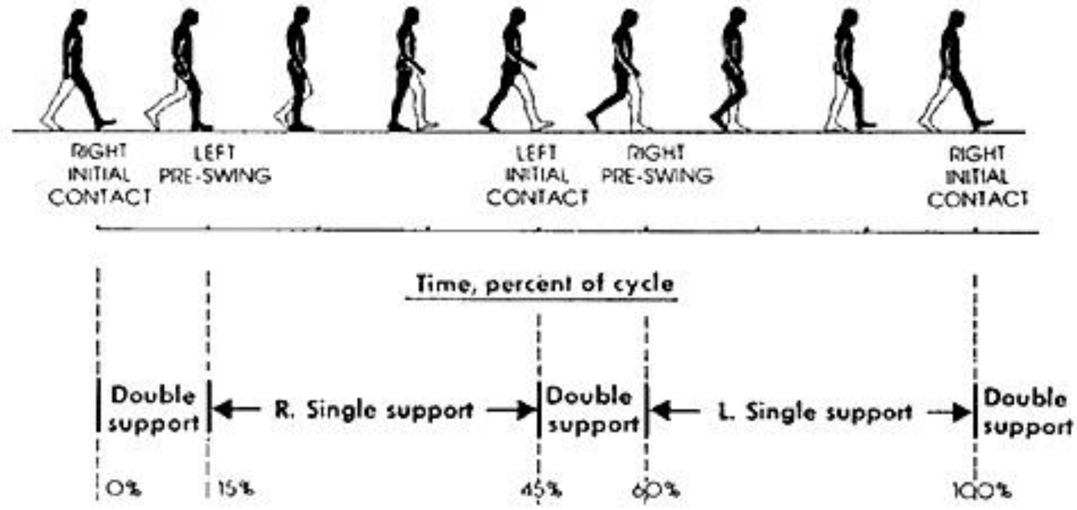

Figure 2.1 Phases of normal walking. Adapted from http://atec.utdallas.edu/midori/Handouts/walkingGraphs.htm

As the leg loses contact with the ground at toe off (i.e. push-off), the step enters the swing phase, during which the trailing leg is swinging forward and prepares for the next heel strike. As seen from Figure 2.1, this phase comprises the majority (80%-90%) of the duration of the step. During the heel contact of the swing foot, the gait enters the next double support phase as both feet are on the ground while the body is moving forward. This phase usually comprises only a small part (10%-20%) of the human walking step. One step is considered to be from the initial heel strike to a heel strike of the opposite leg, while the stride consists of two steps, that is heel strike to heel strike of the same leg. A step length, step width, speed of walking, and step frequency, are commonly used parameters to describe gait. Even in a normal gait, kinematic parameters are affected by factors such as environment, age, and gender. Normal gait speed has been reported to be between 1.1 m/s and 1.6 m/s, and includes gender, age and environment differences (Oberg, *et al*., 1993:212). Women generally walk slower and have smaller step lengths than men, while step frequency depends on a multitude of factors (Oberg, *et al*., 1993:213). Environment may affect walking speed in numerous ways. Walking in a laboratory may be considered inside walking and as a result may be slower than when walking on the street, while walking in a visually stimulating environment such as a shopping mall, may lead to a slower walking speed. As a result, normal walking speed may also be categorised as "slow normal" or "fast normal" so as to address these variations (Oberg, *et al.,* 1993:213).

As may be expected, age has a negative correlation with walking speed, and is a function of step length rather than step frequency (Oberg, *et al.,* 1993:213). While gait description may be used to establish differences in walking, they are a mere effect of an intricate interplay of internal and external forces acting on the body segments causing numerous inter- and intra-segmental interactions. Considering kinematic and kinetic variables of all the extremities and their descriptive parameters, gait analysis yields an enormous amount of data. However, even the early studies without the use of modern technology were able to synthesize gait parameters into the primary determinants of locomotion (Saunders, Inman, & Eberhart, 1953:546).

2.2.2 Basic gait model and the importance of centre of mass

While walking relies on the timely function of all body segments, Saunders, *et al.* (1953:546) have set what they considered underlying gait determinants from which conclusions concerning many types of pathological gait may be deduced. These are pelvic rotation, pelvic tilt, lateral displacement of pelvis, knee flexion in the stance phase, and knee and ankle interaction mechanism. Even though early authors relied mainly on the theoretical models of gait, the importance of these parameters is evident from their use in present studies related to normal and pathological gait (Russell, Bennett, Kerrigan, & Abel, 2007:297; Wu, *et al.,* 2002:680;Wu, *et al.,* 2004:483; Wu, *et al.,* 2008:1163). The individual role of each factor may be evaluated by examining the simple changes in motion of the consequent body segments, while their overall contribution to gait efficiency may be evaluated through changes in energy expenditure by excursions of the COM_{wb}. The simplest approach to understand this interaction is by using the pendulum gait model introduced by the Weber brothers in 1894 (as cited by Haddad, van Emmerik, Whittlesey, & Hamill, 2006:430) and later modified as an inverted pendulum model (Saunders, *et al.*, 1953:548). The inverted pendulum model focuses on the path of the COMwb to explain the effect of various changes in lower segments or the trunk, following the assumption that any change in force during walking will reflect on the path of the COM_{wb} (Bennett, *et al.*, 2005:2190; Donelan, Kram, & Kuo, 2002:3725).

During walking, COM_{wb} follows a smooth oscillatory line (Figure 2.2). The path of the COM_{wb} shows cyclical vertical changes in COM_{wb}, with the highest position occurring during the middle of the single support phase, and the lowest during the double support phase. Given that the motion of the COM_{wb} may be regarded as the summation of all forces that act on the body, the significant portion of the total metabolic cost during walking should be attributed to the work required to move the COM_{wb} along that path (Bennett, *et al.*, 2005:2190; Donelan, Kram, & Kuo, 2002:3725), especially as the weight of the body increases as in pregnancy. Therefore, since

COM_{wb} displacement plays an important role in energy consumption, and is largely influenced by the primary gait determinants, the relationship between the displacement of the COM_{wb} and energy expenditure should be examined first, followed by the effect of the gait parameters on COM_{wb} and the walking economy.

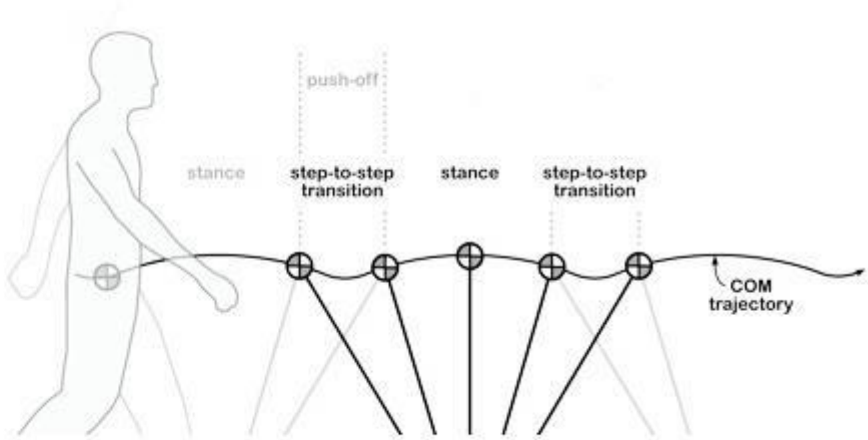

Figure 2.2: Sinusoidal curve represented by a pendulum principle during normal walking (adapted from Saunders, *et al.*, 1953:545)

There are multiple mechanisms through which the effect of the vertical and lateral displacement of the COM_{wb} may be viewed. While studies exist that indicate that lowering the vertical displacement lowers the energy expenditure (Ortega & Farley, 2005:2099; Russell, Bennett, Kerrigan, & Abel, 2007:295; Saunders, *et al.*, 1953:24), other studies show that increased vertical displacement contributes to better energy exchange associated with lower energy expenditure in some types of pathological gait (Bennett, *et al.*, 2005:2191). Therefore, while the optimal goal during walking should be to minimize vertical excursions of the COM_{wb}, in some instance when this is not feasible, vertical excursions may be used as an adaptive mechanism to minimize energy expenditure. In either case, the importance of vertical displacement of COM_{wb} is undeniable. Since the COM_{wb} goes through a motion in all three planes, the forces acting in the direction have a specific role.

2.2.3 Principal gait determinants

Principle determinants of gait have been a topic of many studies since first introduced by Saunders, *et al.* (1953:24). While the early authors were identifying the important gait elements, more modern studies have focused on creating a hierarchical list of most to least important determinants from these elements. While there have been the significant strides in research to establish the order of importance of each of these (Childress & Gard, 1997:161; Gard &

Childress, 1997:236; Gard & Childress, 1999:29; Gard & Childress, 2000; Della, Riley, & Lelas, 2000:83; Hayot, Sakka, & Lacouture, 2013:287), given the various pathologies and their symptoms that may affect the gait, priority attention should be given to identifying importance of each gait parameter to a specific pathology – in this case pregnancy.

The pelvic horizontal rotation allows for the path of the COM_{wb} to "flatten" during the double support phase, causing the COM_{wb} to be higher relative to the ground at this stage (Saunders, *et al.*, 1953:548). This activates two energy-saving mechanisms. While this causes the absolute height of COMwb at this stage to be higher, relative to the height at which COMwb has to be raised during the single support stage, is smaller, minimizing the vertical force needed to raise the COM_{wb}. In addition, changes in potential energy (E_p) are smaller and less abrupt, increasing the exchange of mechanical energy, which minimizes the total muscle work as mentioned earlier. However, a few factors exist that may influence the horizontal trunk rotation. Firstly, during pregnancy, increased weight in the abdomen will increase the moment of inertia of the trunk segment resulting in smaller horizontal trunk rotations (Wu, *et al*., 2008:1161). This might be the reason for the lower walking speed during pregnancy. And, while there is an optimum energy exchange for any walking speed, lower walking speed will still have higher energy cost than the cost occurring at self-selected walking speed. The answer here may lie in analysing segmental coordination and timing of the pelvic and trunk rotations. Even though the speed of walking changes, opposing rotations of the thorax in relation to the pelvis may contribute to the energy saving process if the amplitudes of their rotations are synchronized regardless of the magnitude. This mechanism is further explained in the section on segmental coordination.

Pelvic obliquity is also associated with minimising vertical displacement of the COM_{wb} during its highest point or single leg stance (swing phase) (Saunders *et al.*, 1953:549). However, the significance of it has been in question since its angular displacement is at most 5 degrees (Gard & Childress, 1997:233), causing the reduction of the vertical displacement only between 2-4mm (Della *et al.*, 2001:79). This certainly is not significant as an energy-saving mechanism in normal walking. However, given that pelvic tilt increases significantly during pregnancy (Foti *et al.*, 2000:628), these gait determinants might be more important in pathological rather than normal walking. If the stance leg was rigid, the vertical displacement of COG_{wb} would be the factor of the step length; the longer the step, the greater the vertical displacement. However, during swing phase, pelvic "lateral drop" lowers the height to which COM_{wb} is raised, affecting the magnitude of vertical force needed and minimizing change in E_p. In addition, with greater pelvic tilt, knee flexion also may be greater to allow for the clearance of the swinging foot (although this may also be accomplished with greater hip flexion and/or dorsiflexion). While there is a cost of concentric contraction of the knee flexors, greater knee flexion results in the shortening of the moment arm (lower leg), lowering the moment of inertia needed to swing the leg, also contributing to lowering the energy cost. However, “lateral drop” of the hip is a sign of the weakness of the hip abductors of the stance leg, unable to maintain the hips remaining level. As a result, while the increased flexibility during pregnancy (caused by increased relaxin levels) might cause the weakness in the muscles, energy-saving mechanism is activated in terms of lowering vertical displacement of the COG_{wb}.

The importance of knee flexion in the stance phase is reflected on the knee’s ability to control the height of the COM_{wb} during single leg stance phase mentioned earlier. Allowing flexion during stance, the vertical displacement of the COM_{wb} is lowered further contributing to the horizontal path of the COG_{wb} as a means of conserving energy (Saunders *et al.*, 1953:550). As the single support phase is the longest phase of the human step, the amount of energy conserved during this stage is also potentially the greatest. Therefore, while pelvic rotation increases the height of the COM_{wb} during the double support phase, the consequent pelvic tilt and knee flexion lowers the peak height, overall flattening the pathway of the COM_{wb} throughout the stride. However, weight that the leg has to overcome during the single stance reaches as much as three times body weight. Therefore this mechanism is highly impractical given that knee flexion in the stance phase of walking is a factor of an eccentric contraction, and as a result much work would have to be done to support the knee flexion in stance. Hence this might be a trade-off mechanism, where conservation of energy occurring as a result of the horizontal path of the COG_{wb}, is relative to the muscular work done during knee flexion in stance. The clear evidence for this hypothesis cannot be found in literature, and in contrast, some studies (Gard & Childress, 1997:236; Kerrigan, Della, Marciello, & Riley, 200:1078; Childress & Gild, 1997:161) indicate minimal contribution of the knee flexion in stance to vertical movement of the body, and rather speculate this mechanism’s contribution to the absorption of the GRF. In either case, in pregnancy, knee flexion will be challenged differently than in normal gait. With increased weight later in pregnancy, the energy saving becomes less important as the weight changes become less abrupt and, absorbing force could be a trade-off mechanism. Studies indicating no significant changes in vertical GRF (McCrory, Chambers, Daftary, & Redfern, 2011:527; Lymbery & Gilleard, 2005:251) late in pregnancy might be indicative of this mechanism. Earlier during pregnancy, while the weight gain is still not maximal, control of the vertical displacement rather than shock absorption might be a trade-off in some individuals.

Knee and ankle interaction mechanism is relevant from the moment of heel strike to the push off (toe off) of the opposite leg. While the pendulum model of gait allows for the most energy conservation to occur during swing phase, the transition from one stance to the next does require a certain amount of work (Bennet *et al.*, 2005:2191). Hence, in terms of function, it can be said that knee and ankle interaction complements the horizontal rotation of pelvis as it helps in minimizing the possible abrupt change in vertical displacement during heel strike; that is the transition between kinetic and potential energies. This may occur if the plantar flexion, a result of the initiation of the knee flexion, is faster, causing earlier knee flexion, which in turn would flatten the vertical path of the COM just prior to a change of direction (Figure 2.4). Consequently, at the push-off of the opposite foot, knee flexion would allow for the clearance of the swinging leg without resulting in a raise of the hip. However, pregnancy studies have found weaker plantar flexion during push-off, affecting the gait kinetics in two ways (Foti *et al.*, 2000:629). With lower plantar flexion, the swing phase becomes a factor of the larger knee flexion moment (i.e. more muscular work) (Whittlesey, van Emmerik, & Hamill, 2000:289) and/or greater vertical raise of the COM_{wb} (i.e. larger frontal pelvic tilt). Also, lower plantar flexion moment may cause more abrupt transition of potential (E_p) and kinetic (E_k) energy during this stage; that is, in order to clear the swinging foot a person may have to generate sufficient kinetic energy first in order to raise the COM to its peak (increased potential energy) by using muscle mechanical work; hence increasing total energy expenditure (Donelan *et al.*, 2002:3724).

While Saunders *et al.* (1953:544) consider ankle, knee and hip mechanism together, Kerrigan *et al.* (2000:1079) have demonstrated that heel rise is the actual major contributor to the vertical rise of the COM_{wb}, and the knee flexion and pelvic tilt are consequently least contributors. Given their findings, and the decrease of plantar flexion during pregnancy indicated above, this mechanism could potentially be a major variable to increased energy expenditure in walking during pregnancy. Its relevance is not only reflected on the vertical rise of the COM_{wb}, but also on the internal work of the muscles that would have to supplement the work of weak plantar flexors, and consequent knee flexion, also contributing to increased cost of walking.

Lateral displacement of pelvis may be pictured plainly as a side-to-side sway of a person with impaired balance. This kind of walking is characterised by large lateral displacement of the COM_{wb}. Much like vertical displacement, minimizing lateral displacement (i.e. smoothing out movement of the COM_{wb} in the horizontal plane) is another mechanism of conservation of energy (Figure 2.3). Lateral sway may also be a factor of weak abductors.

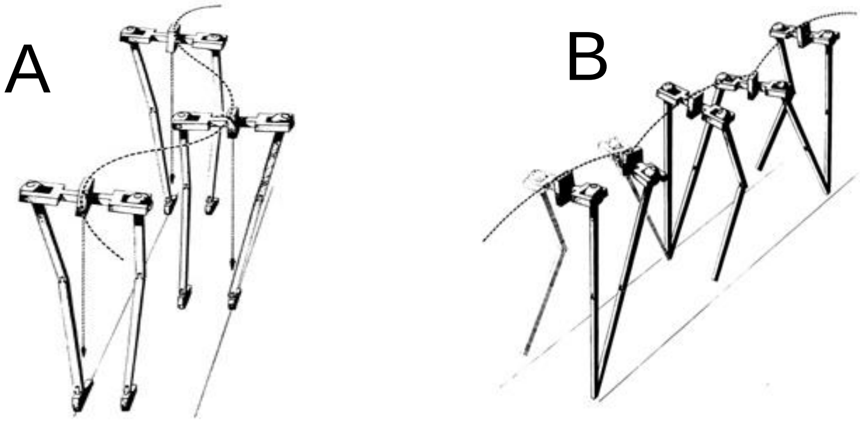

Figure 2.3: Lateral (A) and vertical (B) displacement of the centre of mass depicted by the pendulum gait model (Saunders, *et al.,* 1953:552)

During a single leg stance, COG_{wb} relative to the hip joint creates a moment arm. Adductor muscles' function is to activate in order to keep the pelvis levelled. If the muscles do not provide sufficient support, people demonstrate a tendency to lean towards the supporting leg in order to move the COG_{wb} closer to the joint axis of rotation and over the base of support, shortening the moment arm. When the trunk lean is accompanied by a contralateral pelvic drop, the result is the condition known as Trendelenburg gait (Figure 2.4). Clearly the parameters indicated above all contribute to the overall path of the COM_{wb}, and as a result greatly influence the energy cost of walking. However, walking or any other human activity for that matter consists of a much more complex interaction between all body segments, which also greatly contributes to the changes in the energy cost.

While some add to the energy cost, others minimize it. This occurs by efficient energy transfers between subsequent segments as a result of the intersegment coordination. More recent research on gait has revealed that approximately 66% of the total work is performed by other elements in coordination with the above examined primary determinants of gait (Russell *et al.*, 2006:296).

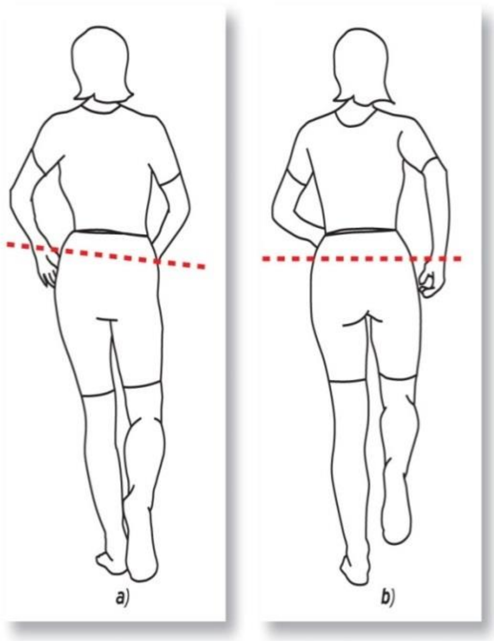

Figure 2.4: Trendelenburg gait characterized by low pelvic stability (A), and normal gait with normal pelvic stability (B). Modified from http://www.flickr.com/photos/sportex/3233234116/galleries/

2.3 Models of mechanical work and energy cost for gait assessment

Vertical displacement of the COM_{wb} is the result of the vertical force, with primary purpose to generate vertical impulse large enough to overcome the force of gravity. Even though this impulse fluctuates with each contact with the ground, its magnitude will depend on the mass of the body (m), acceleration (a) due to gravity (g), and time (t) over which the force (F) is applied, giving the definition of impulse as:

$$\text{Impulse} = m \times a \times t \qquad \text{Equation 2.1}$$

Since *m* and *a* are the derivatives of force, it follows that

$$\text{Impulse} = F \times t \qquad \text{Equation 2.2}$$

In similar fashion forward motion of the COM_{wb} is the result of the "propulsive" force (i.e. momentum generated by the force) applied in the anterior-posterior (AP) direction (Chapman, 2008:100). Therefore forces in the muscles of the hip, knee and ankle need to produce vertical and horizontal impulses, large enough to overcome gravity, yet small enough to minimize energy expenditure and maximize efficiency of walking. Once the muscles generate force and initiate movement, a certain amount of work is done.

The type of work responsible for changes in mechanical energy of the COM_{wb} relative to the surrounding is called external work (W_{ext}), while the mechanical work done by the body segments relative to the COM_{wb} is called internal work (W_{int}) (Massaad, Lejeune, & Detrembleur, 2007:791; Minetti, Ardigo, & Saibene, 1994:213; Schepens et al, 2004:587; Willems, Cavagna & Heglund,1995:379; Winter, 2006:375). Therefore the total work a body does is considered a sum of the external and internal work at each instant of time relative to the surroundings, or

$$E_{tot,wb} = (MgH + \tfrac{1}{2} MV_{cg}^2) + \sum_{i=1}^{N} (1/2 m_i V_i^2 + 1/2 m_i K_i^2 \omega_i^2) \qquad \text{Equation 2.3}$$

where H and V_{cg} are the height (m) and speed (m/s) of the centre mass of the body with a mass M *(kg)*; g is the acceleration (m/s^2) due to gravity; V_i is the velocity (m/s) of the *i*th segment with mass (kg) m_i, with radius of gyration K_i, and angular velocity (deg/sec) ω_i, around its centre of mass (kg) (Willems *et al*., 1995:380). First portion of the Equation 2.3 is the W_{ext} relating to the movement of the COG to the surroundings, while the other part is the W_{int}, or the sum of all segments relative to the centre of mass. Therefore, as a result of mechanical work, any movement of the body will result in the cost of mechanical energy. While there are many forms of energy, in mechanics, and in this study for that matter, the primary concern is with the two basic forms: kinetic energy (E_k) which is energy due to motion or speed, and potential energy (E_p) which is energy due to vertical position or height (Bennett *et al.,* 2005; Chapman, 2008:98; McGinnis, 2005:106). The total work done in an activity is simply a change in total energy spent (McGinnis, 2005:109), or

$$W = \Delta E, \qquad \text{Equation 2.4}$$

from which it follows that total energy spent during an activity is the sum of changes in kinetic and potential energies, or:

$$W = \Delta E_k + \Delta E_p. \qquad \text{Equation 2.5.}$$

The amount of work done to perform a certain action (or activity) will also depend largely on the goal to be accomplished. The goal of each activity might be accomplished at different energy costs. For example, moving an object consisting of many parts may be achieved by taking that object apart and moving each part separately with little or no effort (small energy requirement), but with a longer time requirement. In this case the goal of the activity is to preserve the energy, with time not being relevant. On the other hand, moving the object as a whole would be an option to conserve time, without regard for the effort as a non-relevant factor (large mechanical energy). In walking, the least amount of mechanical energy is spent at self-selected speeds and stride frequency (Bennett *et al.*, 2005:2189). Given that walking consists of repetitive and oscillating motion of the COM_{wb}, the inverted pendulum model represents a continuous exchange of mechanical energy, and its effectiveness is the difference between efficient and increased energy expenditure (Ortega & Farley, 2005:2030). In mechanical terms, minimal energy expenditure occurs when the potential energy (E_p) and kinetic energy (E_k) curves are equal in amplitude and opposite in phase as depicted in Figure 2.5a. When this occurs, recovery of mechanical energy (R) is maximal, which in turn minimizes the amount of muscle work needed (Bennett *et al.*, 2005:2191). In this case, the vertical movement of the COM is advantageous because it allows pendulum-like energy exchange which reduces net external work and reduces metabolic cost in walking.

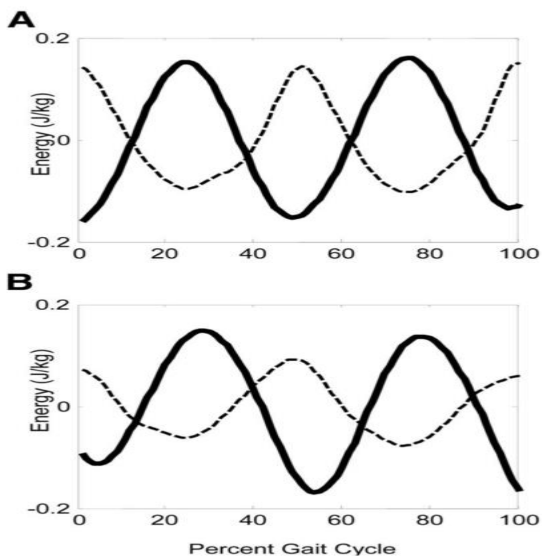

Figure 2.5: The exchange of potential energy (solid line) and kinetic energy (dashed line) for (A) normal gait children and (B) children with pathological gait. The variations in kinetic energy curve contribute to lower energy recovery during walking which is indicative of higher energy cost during walking. (Adapted from Bennett *et al.*, 2005:2191)

The coordination (i.e. timing) of the oscillations of the COM_{wb} is a resulting factor of the multiple segmental coordination, as well as gait kinematics, of which walking speed is the most important factor during pregnancy (Wu *et al.*, 2004). Any changes in walking velocities will cause changes in the timing of the segments. This is a concern, since an additional weight decreases cadence (Haddad *et al.*, 2006:429); hence the slower walking velocities during pregnancy (Wu *et al.*, 2004:486). The most drastic change in weight is experienced in the upper body, therefore the coordination of the thorax and pelvis will be affected most with changes in speed (Wu *et al.*, 2004:485; Wu *et al.*, 2008:1164). With lower walking speed in pregnancy indicated earlier, the magnitudes of the horizontal rotations also decrease, lowering their coordination (Wu *et al.*, 2004:485); that is, these segments become less synchronized. In studies, the term *relative phase* is used to describe the "synchronization" of the segments in the amplitude and magnitude of their relative rotations. This is a concept similar to the exchange of potential and kinetic energies discussed earlier. In pregnancy, however, with lower velocities increased moments of inertia of the thorax and pelvis (due to additional weight), would result in smaller rotational amplitudes, negatively affecting their coordination (Wu *et al.*, 2004:486), all the indicators of the higher energy cost. Wu *et al.* (2004:486) also speculate that while the cause of the lower speed is increased weight, it also gives pregnant women more time to react and control additional balance demands during walking. This certainly compliments the findings of increased step width in pregnancy in response to increased balance demands mentioned earlier. Impact of coordination might increase or decrease with the number of segments involved, each contributing less to the total energy cost. However, resulting improvement in segmental coordination will reflect on the energy recovery resulting from the relation of E_k and E_p of the centre of mass.

The question of segmental coordination gives rise to numerous possibilities of segmental interactions, and the reason for their function. The preference of lower speed of walking (increased energy cost) in exchange for stability (i.e. safety), gives rise to a number of possible adaptation mechanisms relative to the women's needs during pregnancy. Increasing safety in terms of stability, minimizing lower back pain while walking, countering sudden weight gain, are all conditions which can be moderated using various body adjustments and are relative to individual abilities. This compliments numerous studies that indicate a lack of systematic grouping variables and characterization of the typical "pregnancy gait". In addition, physiological differences in women pre-pregnancy will reflect on the physical response to pregnancy. For example, taller women in relation to shorter women will respond differently to the pregnancy if they carry a foetus of similar size and weight. This difference becomes even more drastic if one woman is used to carrying loads (for example, factory worker), and the other was not (for example, office secretary). While there will be a physiologically identical process of pregnancy, their response to the demands would be different and unique. For this reason, adaptive mechanisms might be more subtle and different in some individuals relative to others, as the pregnancy as a trigger of these changes might not manifest the same for all women during pregnancy.

2.4 Impact of pregnancy on gait mechanics

Pregnancy induces numerous physiological and anatomical changes necessary for normal foetal development and birth (Ponnapula & Boberg, 2010:452). These changes dramatically alter body mass, mass distribution, joint laxity, and musculo-tendinous strength during the various stages of pregnancy (Abramson *et al.,* (cited by Butler, Colo, Druzin, & Rose, 2006:1105); Borg-Stein, Dugan, & Gruber, 2005:189; Foti *et al.*, 2000:625; Heckman & Sassard, 1994:1720; Jang *et al.*, 2008:468; Paul, van Dijk, and Frings-Dresen, 1994:156). As a result, the mechanics of gait in pregnant women are often adapted to compensate for the various changes, most commonly those associated with increase in body mass, mass distribution, and balance. In addition, musculoskeletal problems during pregnancy are common and may cause mild discomfort, pain, or even serious disability. Consequently, to manage any discomfort, pregnant women may go through various biomechanical adaptations in posture, and walking patterns, in an attempt to minimize the discomfort and/or pain resulting from these conditions common during pregnancy (Foti *et al.*, 2000:625; Gutke, Östgaard, & Öberg, 2008:304; MacLennan, 1991:7). Given the large number of pathologies induced by pregnancy, and the ways they may affect each individual, a large inter-subject inconsistency exists among postural and gait adaptations during pregnancy (Wu *et al.*, 2002:685).

These variations also stem from inconsistencies in trimester classification during research process. Studies on pregnancy assume that changes during pregnancy occur at the same time of gestation in all women. Hence, most research is based on the trimester classification, which is also inconsistent between studies, or simply studies collect over a long period and consider it “during pregnancy” parameter. For example, Byrne *et al.* (2011:824) analysed gait in all participants between 15 and 30 weeks of gestation, while Wu *et al.* (2004:483) measured average kinematic variables for period between 20-34 weeks of pregnancy. Similarly, Butte *et al.* (2004:1081) determined wide range for each trimester such as 0-9 weeks for the first trimester, 9-22 weeks for second, and 22-36 weeks for third trimester. However, Butler *et al.* (2006:1110) chose the 3^{rd} trimester that is between 36-39 weeks, which is further in pregnancy than any of the previous studies. The large diversity in changes occurring during this time results in high variance within parameters, and in parameters between studies. Due to vast individual responses to pregnancy, all changes during pregnancy could not be expected at the same trimester. Furthermore, between trimesters analysis does not provide clear indication of the relationship between large the number of factors that influence gait mechanics and may impact walking energy consumption. Therefore, musculoskeletal changes during pregnancy occur irrespective of any classifications pregnancy progression, these changes will be discussed relative to relationships between variables, in addition to potential changes between trimesters.

2.4.1 Relationship between posture, balance and gait during pregnancy

The pelvic girdle width significantly increases during pregnancy (Foti *et al.*, 2000:629) in order to accommodate a growing foetus. During this time weight distribution shifts primarily to the anterior of the abdomen placing an increased demand on the lumbar spine and the abdominal muscles, causing an anterior pelvic tilt (Ponnapula & Boberg, 2010:457). Subsequently the anterior pelvic tilt causes the posterior movement of the pubic bone and the tailbone, which consequently increases the arch in the lower back. Because of the dynamic nature of the spine, changes in the pelvic girdle may cause significant adjustment in the upper body such as the posterior upper body tilt (Ponnapula & Boberg, 2010:457), causing the anterior rounding of the shoulders, and resulting collapse of the chest. In response to the increased thoracic curve, the head will move forward to ensure that the centre of gravity of the body is maintained, further contributing to compound spinal alignment problems such as kyphosis, lordosis, or even both.

Due to the specific weight distribution during pregnancy, the COMwb also shifts more to the anterior. In addition, an increase in the width of the pelvic girdle causes an increase in the width of the base of support (Foti, *et al.*, 2000:629) and consequently the increase in the step width during pregnancy (Jang, *et al.*, 2008:469). Increased step width, associated with increased pelvic width throughout pregnancy, decreases proportionally to the decrease in pelvic width post-partum, indicating direct correlation between the two variables (Foti, *et al.* 2000:629). Walking with the large base of support results in large side-to-side excursions of the centre of gravity (COGwb) (Lymbery & Gilleard, 2005:251), which may increase the energy demand as mentioned earlier. However, it is also indicative of the fact that the majority of these adaptations are consistent with the need to promote stability. Increased hip abductor power shown in some studies (Fotti, *et al.*, 2000:631; Lymbery & Gilleard, 2005:251; Wu *et al.*, 2004:481) is consistent with increased use of hip abductor muscles to maintain normal gait with the increased mass. The hip moment and the power in the coronal and sagittal planes are increased by increasing the use of the hip abductor, and the hip extensor muscles. Consequently, hip flexion moment decreases (Dumas & Reid, 1997:4) which requires an increase in the knee moment. The changes in these kinetic parameters place an additional demand on the muscles and joints of the lower extremity, leading to their overuse, directly contributing to knee, hip and lower back pain (Ponnapula & Boberg, 2010:457).

2.4.2 Various musculoskeletal conditions in pregnancy and effect on gait

Gait adaptations induced by changes in the musculoskeletal system have numerous underlying factors which stem from other physiological systems. In pregnancy specifically, hormone secretion increases dramatically in order to increase laxity of muscles, tendons, and ligaments (MacLennan, 1991:7; Calguneri, Bird, & Wright, 1982:126; Ponnapula, & Boberg, 2010:452). Relaxin for example, an oestrogen-dependant hormone, has been reported to exert its influence by triggering the collagenolytic system; thus increasing the water content of connective tissue, and activating fibroblast in the synthesis of new collagen with the simple purpose of allowing for relaxation of the pelvic articulations during child bearing (Ponnapula, & Boberg, 2010:456). A resulting joint hyper mobility of the pelvic bones may lead to altered body mechanics, and given that effects of relaxin hormone are not joint specific, increased mobility of some joints and weakening of surrounding soft tissues may lead to pregnancy-related pain (Ponnapula, & Boberg, 2010:456). Alterations of gait may also occur as a result of secondary, dermatological, vascular and neurological changes that also naturally occur during pregnancy. For example, one of the most common characteristics of pregnancy is oedema, resulting from surge of corticotrophin and oestrogen (Morales, *et al.*, 1995:759; Ponnapula, & Boberg, 2010:456). Oedema may cause changes in a toenail curvature, or increased overall foot size, and even lowering of the longitudinal arch, which may cause pain due to pressure on the nail, or in an inadequate shoe gear. Ponnapula and Boberg (2010:456) explain that to eliminate pressure on feet caused by some of these symptoms, a patient may in turn adjust a stand or a push of phase during walking of that foot to eliminate further compression. Also, there is a significant incidence of reported neuropathies and radiculopathies associated with pregnancy, causing tingling, burning and numbness in feet and/or legs. These symptoms may be significant enough during walking; hence any changes to the gait would be in order to alleviate any of these symptoms. The duration of these symptoms may depend on the time of the onset and may last up to 1 year post-partum (Padua *et al.*, 2001:1949). However, some may persist for as short a period as 4 weeks (Franklin, & Conner-Kerr, 1998:136).

Foot studies have shown an increase in subtalar, and first metatarsal-phalangeal joint range of motion in pregnant women (Ponnapula, & Boberg, 2010:456). Pronated foot type could be a result of lowering of a talar head, caused by ligament laxity combined with weakening of tibialis posterior tendon (Ponnapula, & Boberg, 2010:456). Resulting midfoot pronation, and partial collapse of the longitudinal arch, may create flattening of the pedal architecture. Even though there are possible arch height changes (even though not recorder or studied) any structural pedal changes are the result of fluid retention rather than stretching of plantar ligaments (Ponnapula, & Boberg, 2010:456). Rules of the kinetic chain indicate that increased weight should be absorbed by the lower extremities, whether by kinetic alterations of the lower extremity segments, or structural changes of the segments. Maximum ankle power absorption is a measure of the amount of eccentric muscle work being done by the plantar flexors during stance. Therefore, increased sagittal plane maximum ankle power absorption, and maximum ankle plantar flexion moment during gait are indicators of increased use of these muscles due to increased body weight during pregnancy (Foti, *et al.*, 2000:629). The manifestation and the experience of these symptoms differ in each individual (as seen in differences in plantar flexion moments), possibly due to the physiological condition prior to pregnancy, or the behavioural adaptations in the activities of daily living during pregnancy, although no known research has investigated this relationship.

2.5 Pregnancy and energy expenditure

Similar to irregularity in other physiological parameters, variability in individual adaptations in posture and gait and an ability to perform activities of daily living more efficiently are also expected. This may be a reason for a high inconsistency reported in measuring energy cost of these activities during pregnancy. Changes in activity energy expenditure may be explained by changes in either economy of movement (metabolic) or the overall volume of movement (behavioural) (Byrne, Groves, Mcintyre, & Callaway, 2011:825). Making movement more economical reflects on the energy cost of that activity, and in pregnancy it means the efficiency of the adaptations in performing that activity. Studies that analysed daily total energy expenditure indicate that even in a moderate physical activity setting, a pregnant woman's net daily energy expenditure for physical activity will not necessarily be more than her pre-pregnancy net cost for the same physical activity when adjusted for change in weight (Byrne *et al.*, 2011:825; Forsum, Kabir, Sadurkis, & Westerterp, 1992:338; Lof & Forsum, 2007:301; Meltzer. Schutz, Boulvain, & Kayser, 2009:1189; van Raaij, Schonk, Vermaat-Miedeme, Peek, & Hautvast, 1990:160). This indicates that a pregnant woman will compensate for the extra energy needed to move her heavier body in weight-bearing activities by decreasing her pace so that she works at a more comfortable rate (van Raaij, *et al.*, 1990:161). Walking at a comfortable rate indicates a decrease in walking speed (kinematic adaptation), and assuming the walking economy is lower; hence energy expenditure would remain more or less the same.

In this case, either the gait speed is a compensating factor, or the adaptation in walking is not sufficient to replace lower speed, in which case increase in active energy expenditure (AEE) is expected. A study by Byrne *et al.* (2011:827) suggests that most changes in AEE are the result of increased weight, indicating that already occurring changes in gait during pregnancy are either efficient adaptations to an increased weight, or so miniscule to significantly produce any changes in metabolic cost. In order to assess either theory, it is imperative to monitor the relationship of these changes with changes in gait mechanics, and consequently walking energy expenditure, independently of trimester classification.

With studies reporting wide range of weeks for each trimester, for example 9-22 weeks for second trimester and 20-36 for third trimester (Butte *et al*., 2004:1081; Wu *et al.,* 2004:483), the variance for each trimester may be large and hinder the significant differences between trimesters. If there are kinetic and kinematic parameters of gait that consistently change throughout pregnancy, it should reflect on the metabolic cost of gait irrespective of stage of pregnancy. If the changes in gait are not only relative to weight, then another element has been omitted in current research – irregular change in weight gain during pregnancy. The period of adaptation and learning to cope with the additional weight is longer after the initial weight gain, which will allow for a development of movement efficiency during that time. No significant changes in walking speed, stride length, cadence, and joint angles (Foti *et al.*, 2000:626) in late pregnancy may be indicative of these adaptations. However, in this study, Foti *et al.* (2000:626) have examined the gait kinematics the latest in pregnancy than most studies, between 35 and 40 weeks. In contrast, Forczek, and Staszkiewicz, (2012:115) considered the third trimester at 33 weeks of repugnancy, while Lof and Forsum (2007:298) considered third trimester at 32 weeks of pregnancy. However, these differences in weeks of development have not been examined before, hence the changes in gait during this period are unknown. However, in other study of gait during pregnancy and post-partum, Lymbery and Gilleard (2005:251) explain that pregnant women had residual changes in mass and body dimensions that continued to affect their stance phase parameters post-partum. They add that after birth, women may continue to use patterns learned during the pregnancy which is considered a physiological change. Considering the earlier discussion on principal gait determinants and their potential effect on walking efficiency, no changes in the stance phase may have potential contribution to the energy cost of walking post-partum. However, other studies on gait during pregnancy reported no changes in pregnancy and post-partum (Foti *et al.*, 2000:626) which may demonstrate individualized adaptations warranting further investigation.

2.6 Pregnancy and physical activity

Recently, the role of exercise and physical fitness during pregnancy has gained global popularity. Generally, the amount of physical activity continuously decreases from pre-pregnancy and throughout pregnancy (Borodulin, Evenson, & Herring, 2009:30). However, recently there is a trend of increased participation in pre-natal exercise and fitness programmes around the globe (Heckman & Sassard, 1994:1727). Women increasingly inquire about the pre-natal programmes, and fitness and health centres increasingly offer classes specifically designed for prenatal care. This does not come as a surprise, given the rise of scientific research on the issue and overall positive reports on the impact of exercise on pregnancy-induced changes in the body (Artal, Clapp, & Vigil, 2011; Foti, *et al.*, 2000:625). Earlier in the text, various symptoms and their impact on the body during pregnancy have been addressed. In this section, the potential of general exercise programmes to fully eliminate some, if not all of them, will be discussed.

Foti *et al.* indicated that secondary gait characteristics developed during pregnancy may induce musculoskeletal overuse injuries (2000:625), and that the symptoms of the overload may be improved with participation in a structured exercise and conditioning programme during pregnancy (2000:632). Dynamic exercises that keep joints and muscles moving, as well as static or isometric exercise where no movement occurs, may also address the balance problems (Butler *et al.*, 2006:1107) – a crucial issue especially in the latter stage of pregnancy when balance decline increases. As it was addressed, the changes in pregnancy continually occur throughout pregnancy; hence the postural and muscular changes tend to be self-reinforcing: as the abdomen expands, the postural deviations worsen, which in turn further augment muscular imbalances causing pain. Hence, promoting good posture and practising exercise that address core strength and stability while incorporating the neutral spine position may address these problems (Shim, Leeb, Ohc, & Kim, 2007:19). These exercises focus on back extensor muscle endurance, abdominal and hip extensor muscle strength, overall improvement of muscle functionality and decrease in symptoms of pelvic pain during pregnancy and post-partum (Borg-Stein *et al.*, 2005:182; Gutke *et al.*, 2008:40). In addition to musculoskeletal improvements, studies suggest that exercise during pregnancy and post-partum leads to weight management and diabetes prevention, subsequently reducing the incidence of the related chronic neuropathic pain (Chambliss, *et al.*, 2006:989).

These are but a few related factors affected by participation in a structured exercise programme. Overall impact of exercise is much broader and its effects on human physiology have been well documented. The amount of exercise recommended during pregnancy has evolved drastically due to significant focus of the research on the issue. However, even today, the recommendations for exercise during pregnancy are vague and simply relate to woman's ability to perform exercises (Artal, *et al.*, 2011), indicating that generally exercising is safe for all pregnant women, and that they are encouraged to participate, as long as they adhere to basic exercise guidelines. American College of Sport Medicine indicates that both weight- and non-weight bearing exercises are recommended, as long as such exercises are comfortable (Artal, *et al.*, 2011). Heavy lifting is discouraged due to over straining, as well as exercises that may be affected by balance changes later in the pregnancy. The intensity of exercise also should be related to how hard a woman believes she is working, not exceeding the pre-pregnancy levels, and levels between moderate to hard are deemed safe.

Taking into consideration that overall recommendations are suitable for every individual and the variety of modes of exercise available, the recommendations should be sufficient to help manage and control the effect of the altered body mechanics, and changes associated with other physiological control systems during pregnancy and post-partum (Artal, *et al.*, 2011).

2.7 Summary

The gait during pregnancy is a primary example of how internal and external factors may cause small, but nonetheless relative changes. In pregnancy, anatomical changes and their manifestation are vast and the high inconsistency between subjects does not support the idea of a common optimal motor pattern of gait, but further support the notion of the individual-specific processes. The effects of the primary and the secondary symptoms are not the only factors that should be taken into consideration when examining gait throughout the pregnancy. The initial changes to gait may be altered to accommodate foetal development. However, significant changes to gait occur once the adaptations to internal factors take place, which is later in pregnancy. The efficiency of the adaptations throughout the pregnancy may be evaluated by the energy cost of walking at different stages of pregnancy. The general consensus is that changes in energy cost are mainly due to the additional weight of the foetus. Consequently, variability in weight gain between women will determine at which trimester subsequent changes in gait and posture occur. Considering that studies reviewed in this chapter, used inconsistent weeks of gestation to determine trimesters of pregnancy, it is of interest to examine variables that affect gait energetics outside of the trimester classification. Hence, the relationship between gait, balance, posture and energy expenditure variables adjusted for weeks of pregnancy, may provide a better indication of how physiological and physical changes during pregnancy relate to the alterations in gait mechanics, and their effect on the walking energy expenditure. The relationship between mechanical adaptations and energy cost, if shown to be significant, may offer a better picture of factors that elicit changes in gait mechanics, and consequent changes in walking energy expenditure, which has vast application in clinical gait analysis. This knowledge may further contribute to professionals in health and rehabilitation, clinical and sport settings, in the interaction between musculoskeletal and other body systems, as well as compensations and means by which a body is able to adapt to internal and external factors.

CHAPTER 3 METHODOLOGY

3.1 Introduction

The aim of this study was to examine the relationship between gait mechanics and walking energy expenditure throughout pregnancy. Every woman responds differently to pregnancy, and as a result adapts to physical requirements in her unique way. Studies investigating pregnancy classify women according to trimesters, and often compare the gait results to other trimesters, pre- or post- pregnancy data. This study contributes to the current knowledge by determining the relationship between gait mechanics, postural adaptations, and the effect these changes on energy expenditure during pregnancy. While the normal response is to minimize physical activity as the pregnancy progresses (Byrne, *et al*., 2011:819; Melzer, *et al.,* 2010:494) there are indications that changes in mechanics of gait may increase the energetic cost of walking resulting in an increase in total energy expenditure (TEE). In order to obtain the answers to the research questions posed in Chapter 1, TEE, walking energy cost, and gait mechanics were obtained from participants at different stages (trimesters) of pregnancy. In this chapter, the methodology applied for data collection was described, along with the data analyses, statistical analyses performed, and ethical considerations.

3.2 Study design

This study is a sub-study of the larger **H**abitual **A**ctivity **P**atterns during **P**regnanc**Y** (HAPPY) study, which included data from several disciplines investigating multiple aspects of pregnancy (Figure 1.1). The current study has an observational cross-section design. Participants were recruited at different stages of pregnancy distributed as follows: first trimester (9-12 weeks), second trimester (20-22 weeks), third trimester (28-32 weeks). Weeks of gestation was recorded in conjunction with the trimester of pregnancy. All participants were only measured once.

3.3 Participants

The study recruited pregnant women at different weeks of gestation of pregnancy by advertisements in the local press, the consulting rooms of local gynaecologists and a local health clinic in Potchefstroom, North West Province, South Africa. The following served as inclusion criteria:

- Pregnant women from any ethnic background and socio-economic level.

- Over 18 years of age, but younger than 40 years.

Participants were excluded from the study based on the following exclusion criteria:

- Diagnosed with a mental condition
- Physical limitations that may prevent movement
- Inability to complete the test procedures
- High-risk pregnancy according to ACSM guidelines (ACSM, 2013:195).

3.4 Measurements and instrumentation

3.4.1 Demographics

During the first measurement, a demographic questionnaire was administered to obtain information with regard to the participants' age, home language, ethnicity, marital status, employment status, education level and average household income per annum. The demographic questionnaire was compiled specifically for the HAPPY project, and was used in each ancillary study. However, each study extrapolated only relevant data which complimented the primary objectives. For this study, only ethnicity and socio-economic level were used. The questionnaire can be viewed in Appendix D.

3.4.2 Pregnancy-related information

A questionnaire was administered to collect pregnancy-related data, which included the following: self-reported pre-pregnancy weight (kg), weeks of pregnancy, type of pregnancy (single, twin or triplets), expected date of birth, number of previous pregnancies and number of live births. The questionnaire also collected data regarding risk factors for cardiovascular disease, medicine use, smoking habits, alcohol consumption and drug use in the previous three months (yes/no). A health screen was performed with regard to risk factors for physical activity during pregnancy and cardiovascular disease as indicated by the ACSM (ACSM, 2014:195). At every measurement interval, data were collected on current medicine use, smoking habit, and alcohol consumption.

3.4.3 Anthropometric measurements

At each assessment point, anthropometric measurements were taken: height to the nearest 0.5 cm using stadiometer, weight using an electronic scale (Beurer, Germany) to the nearest 0.1 kg, waist and hip circumferences to the nearest 0.1 cm using the standard procedures for anthropometric assessment described by the International Society for the Advancement of Kinanthropometry (Stewart, *et al*., 2011:8-9). Weight and height were further used to calculate the body mass index (BMI), as weight/height^2.

3.4.4 Resting metabolic rate

Resting metabolic rate (RMR) was assessed using Fitmate (Cosmed, Italy, Figure 3.1), which measured ventilation and analysed the fraction of oxygen in expired gases using standard metabolic formulae, while energy expenditure was calculated using a fixed respiratory quotient (RQ) of 0.85 (Nieman, *et al*., 2006:4). Nieman, *et al*. (2006:6) conclude that the Fitmate gives reproducible (r = 0.94) and accurate RMR (kcals/day) measurements (p = 0.579, r = 0.97). Prior to RMR being measured, participants were requested to lie down for 10 minutes during which blood pressure was taken by means of the Microlife® Semi-Automatic blood pressure monitor (Microlife BP A80, Switzerland). Blood pressure and heart rate measurements were measured twice 5 minutes apart to ensure the resting state, and were reported in millimetre mercury (mmHg).

Following the 10 minutes resting period, RMR gas exchange was collected for 16 minutes per Fitmate RMR protocol as the participants were breathing through a one-way antibacterial-filtered disposable mask. The first minute of the sample was discarded, as it was considered a period of adjusting to the measurement. While there are no specific pre-testing procedures, participants were instructed not to perform any exercise during the 24 hours prior to testing, and to fast for at least 10 hours prior to the RMR measurement.

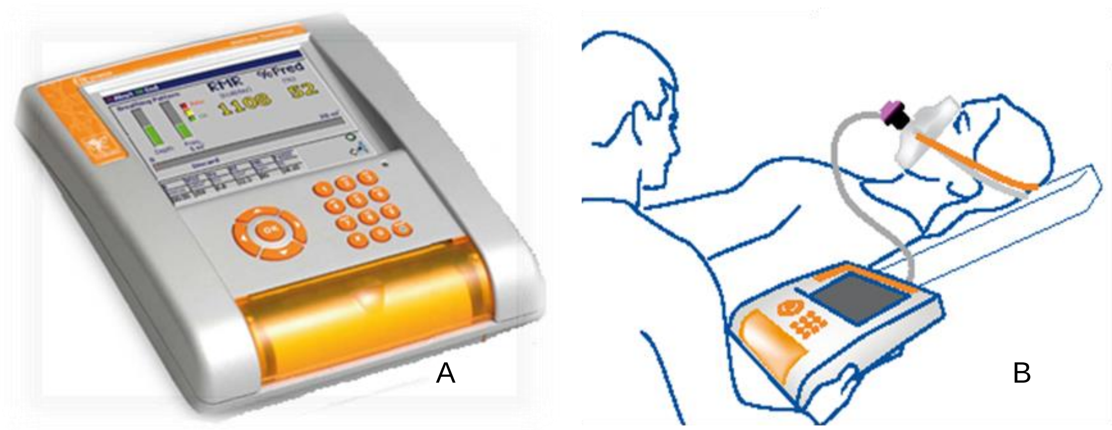

Figure 3.1: Cosmed Fitmate (A), and its application (B)

Sampling was performed every 30 sec for 15 minutes, and the average metabolic rate was reported as an average for the 15 minutes of sampling in kCal/day. A calibration of the Fitmate was done before each participant was subjected to a measurement.

3.4.5 Habitual physical activity measurement

Habitual physical activity was collected by means of objective measurements using the reliable (Brage, *et al*., 2005:561) and validated (Melzer, *et al*., 2012:e9) instrument, namely the Actiheart® (CamNtech, United Kingdom) (Figure 3.2). The Actiheart® uses synchronized measures of accelerometry and heart rate to calculate an objective measurement of activity energy expenditure (Brage, *et al.*, 2005:562) using a 30 second epoch interval. At every measurement interval (i.e. each trimester), habitual physical activity was measured for seven consecutive days. The following parameters were extracted from the data: Activity Energy Expenditure (AEE), Physical Activity Level (PAL), Diet-Induced Thermogenic energy expenditure (DIT) and Total Energy Expenditure (TEE). Activity-, Diet-Induced Thermogenic- and Total Energy Expenditure are expressed in kCal/day.

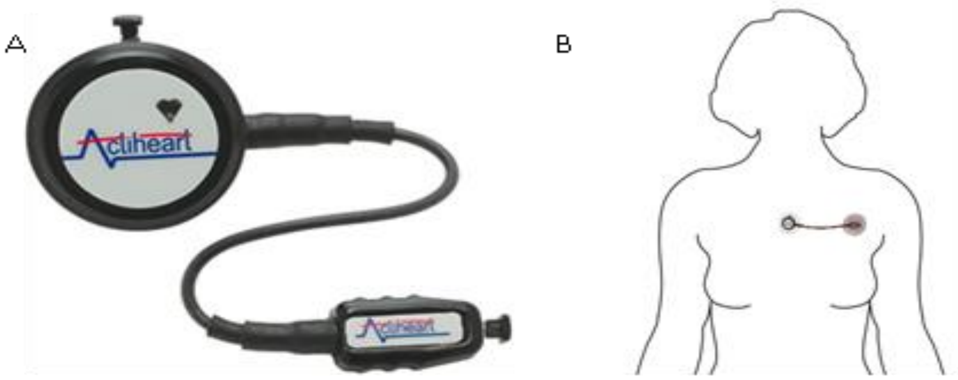

Figure 3.2: The combined heart rate and accelerometry device (Actiheart®) (A) and its placement (B)

Physical activity level (PAL) was calculated by dividing the TEE by resting energy expenditure (REE). While some measures such as PAL, were suggested not to be used with pregnant participants, as the basic metabolic rate is affected (increased) by pregnancy (Prentice, *et al*., 1996:108), there are studies that have shown that PAL models of the Actiheart® may be used with r^2 values exceeding 0.84 (Brage, *et al*., 2005:568). Additional data downloaded from the Actiheart® include sleeping heart rate, mean heart rate, movement counts (cpm), lost minutes (min), time spent in a specific metabolic equivalent of task category (MET), as well as the amount and period of time the Actiheart® was worn in days. During the data analysis, if the device detected a continuous period of 2 or more hours of zero activity, it was indicative of the device not having been worn, in which case the Actiheart® filled the gaps by the average of the day's AEE excluding the gap (Cambridge, 2004:40). The data reflecting that the Actiheart® was not worn for a full day, was discarded, and the average values were computed from the days when the Actiheart® was indeed worn. The combination of movement counts and the heart rate measurements is shown to be accurate in the classification of physical activity rather than the individual measures (Barreira, *et al.*, 2009:67). Movement in counts per minute was grouped into three categories: low activity (< 1952 counts/min), moderate activity (1952-6893 counts/min) and vigorous activity (> 6893 counts per minute) (Freedson, *et al.*, 1998:779; Hendelman, *et al.*, 2000:S445). Barreira, *et al.* (2009:69) indicated that counts/min is more accurate at low or moderate intensities, than at higher intensities. Considering that pregnant women in previous studies mostly participate in low- and moderate physical activity (Melzer, *et al.,* 2010:501), the Actiheart® is a valuable tool for identifying low intensity activities during pregnancy. Time spent in a specific metabolic equivalent of task was divided into the following categories: sedentary activity (MET < 1.5), light activity (1.5 – 2.9 METs), moderate activity (3.0 – 5.9 METs) and vigorous activity (MET ≥ 6.0) in accordance with the ACSM (2014:3).

In order for the Actiheart® to calculate the most accurate AEE, the calibration protocol was conducted, consisting of the eight-minute step test with the box height of 21.5 cm. The calibration by step test was used to calculate the mechanical power rate for each individual, from which linear regression was created from the corresponding HR (Brage, *et al.*, 2005:565). These prediction equations were used in conjunction with a branched equation model described by Brage, *et al*. (2004:348) to estimate AEE (kcals/kg/min) during a 7-day collection period.

3.4.6 Gait motion analysis

Gait analysis consisted of collecting all kinematic and kinetic parameters of all body segments using eight Oqus 300+ cameras from Qualisys Motion Analysis System (Qualisys, Sweden) and filmed at 220 Hz. Before each gait data analysis, a 90-second wand (750 mm) calibration was completed, with a long arm of a L-shaped reference structure indicating "x" axis representing the direction of the walking. While Qualysis software indicates if the calibration is passed or failed, calibration residual of ≤ 1.5 was used. For gait analysis, a participant was dressed in appropriate clothing, cycling shorts and a tank top which would allow marker placement on the skin and minimize any artefacts from clothing motion. A full-body CAST/IK/HH (calibrated anatomical systems technique/Helen-Heyes/ inverse kinematics) gait model (Cappozzo, Catani, Della Croce, & Leardini, 1995:175) was used, requiring 12 mm reflective markers to be applied on the following anatomical landmarks (right and left): heel at the insertion of the Achilles tendon, head of the first, second and fifth metatarsal, medial and lateral malleoli, lower leg (shank) cluster consisting of 4 markers, lateral and medial knee epicondyles, thigh cluster consisting of 4 markers, greater trochanter, anterior and posterior superior iliac spine, inferior angle of scapula, thoracic vertebrae (T10), cervical vertebrae (C7), radial and ulnar styloid processes, humeral lateral epicondyle, humerus, acromion. This full marker set was used for a static trial only, which required the participant to stand still for 5 seconds while filmed in the centre of the calibrated area. Static trials are used to create a dynamic gait model for later analysis. Once the static trial was completed, only dynamic markers were left, therefore the markers on the medial and lateral malleoli, knee epicondyles, and the trochanter were removed.

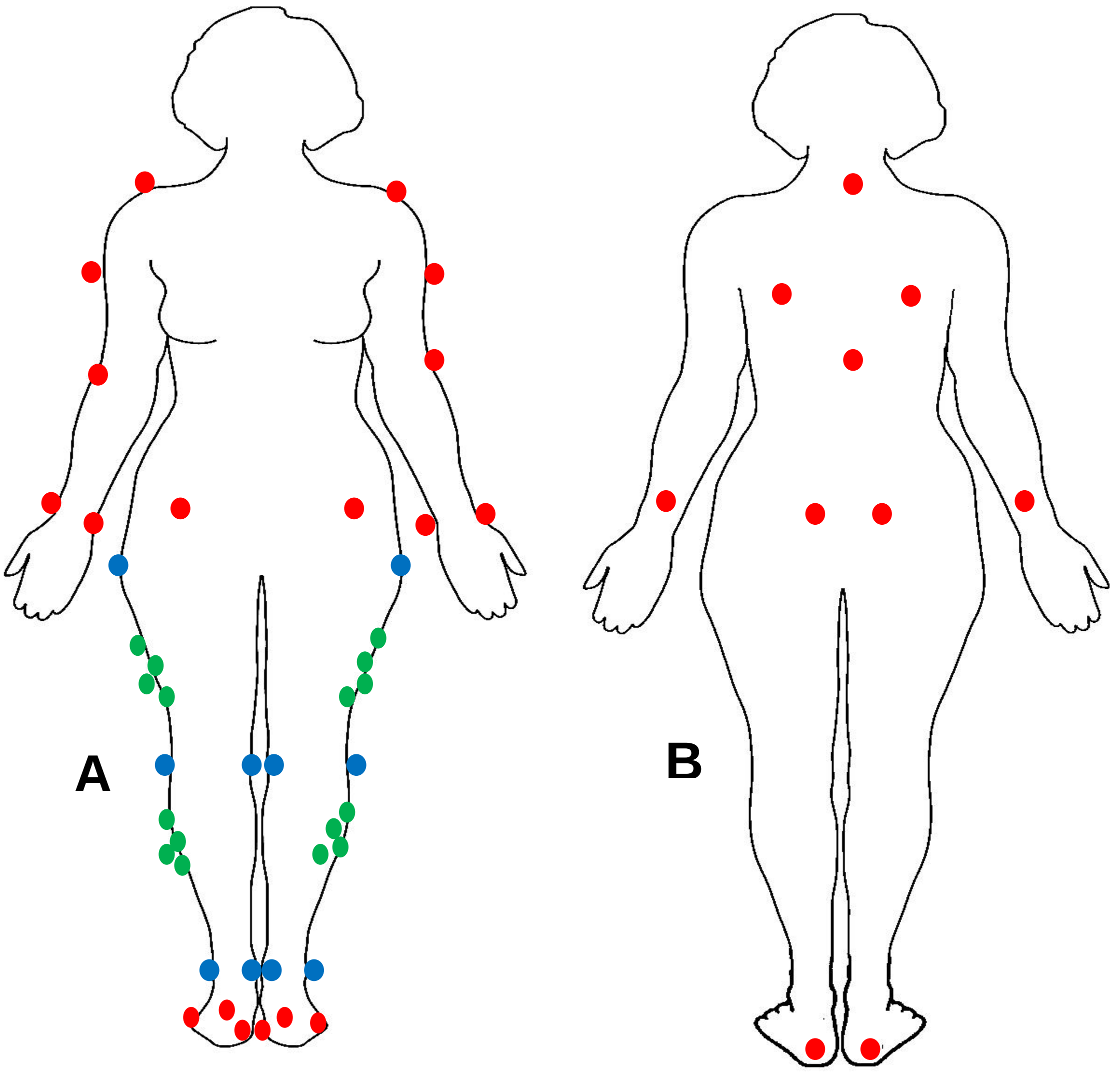

Figure 3.3: Anterior (A) and posterior (B) view of a full body-marker set for gait analysis

3.4.7 Ground reaction forces

During the dynamic gait trials, ground reaction force (GRF) was collected using three AMTI BP400600 force plates (AMTI, MA, USA) in a configuration depicted in Figure 3.4. Video and GRF data were synchronized with an external trigger, and collected simultaneously for five seconds in the middle portion of the 15-meter walkway, allowing each participant to reach normal gait pattern and comfortable walking speed, and provide enough space for slowing down beyond the data collection zone. Once the video data collection was completed it was processed via Visual 3D analysis software (C-Motion, MD, USA). Vertical, anterior/posterior (AP), and medio/lateral (ML) GRFs normalized for current weight were analysed and compared between trimesters.

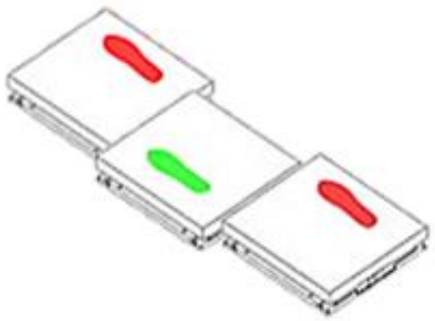

Figure 3.4: Force plate configuration

Figure 3.5: Fitted K4b2 metabolic system for walking analysis

3.4.8 Walking energy expenditure

Walking energy expenditure was completed using a portable oxygen analyser K4b2 telemetry system (Cosmed, Italy) (Figure 3.5). Among the data obtained from the Cosmed are Oxygen (VO_2) and Carbon Dioxide (VCO_2) Pulmonary Gas Exchange, Respiratory Quotient (RQ), Resting Metabolic Rate (RMR), and HR. Room air, gas, and turbine calibrations were completed daily, prior to scheduled data collections, or before each measure if the time between 2 consecutive measures was longer than 3 hours apart. Metabolic energy expenditure is generally reported in terms of O_2 consumption (O_2 rate), the millilitres of O_2 consumed, per kilogram body weight per minute (ml/kg/min). For this study O_2 consumed will be normalized for current bodyweight. However, to demonstrate the physiological work (O_2 cost) for a given task, the physiological equivalent rate was also normalized for speed to express the physiological work per unit distance (ml/kg/m) which was used to depict energy efficiency (Waters & Mulroy, 1999:208). Therefore steady state walking total O_2 cost might be affected by an increase in O_2 rate, or a change in a comfortable walking speed, in which case the participant would not experience any physical differences.

Preparing the participant for the walking oxygen consumption test involved the participant wearing an HR monitor (Polar T31, Polar Electro, Finland), attaching a Rudolph type mask over the subject's nose and mouth, and mounting the K4b2 unit to a harness worn by the participant (Figure 3.5). The participant sat quietly for three minutes to adjust to the equipment, and to achieve comfortable resting steady HR. After the resting period the participant was asked to walk at a self-selected pace on a circular track inside the laboratory (approximate radius of 15 m). Participants walked around the track until they reached the steady state established by steady HR (variation of no more than ±3 bpm), less than 5% variation of RQ (Thomas, *et al*., 2009:616), during which RQ of less than ≤ 0.99 has to be maintained (indicative of still using oxidative system, and not reaching fatigue state) (Schutz, 2004:561).

3.5 Experimental procedure

All participants in the study were requested to complete an informed consent form after the study protocol had been explained to them. As soon as the participants' demographic information was collected the anthropometric and body composition measurements were taken. The participants were then requested to lie on their left side in order to enable measurement of the resting metabolic rate while connected to Cosmed via a one-way antibacterial filtered disposable facemask (Figure 3.1B). After the resting measurements were taken, the participants were equipped with the Actiheart® to perform the calibration procedure. An Actiheart® device was first programmed for the 8-minute step test, and attached to the participant via 2 standard electrocardiograph (ECG) electrodes (Figure 3.2B). During the step test the participants followed the audio cue for an accurate step frequency, which increased each minute. After 8 minutes had expired, participants were asked to sit quietly for 2 minutes. The Actiheart device was then removed from the chest and data downloaded with the accompanying ActiHeart software. From the calibration data Actiheart software calculates lift work rate of the step test, from which linear regression was created to model power rate from the step test HR (Brage, *et al.*, 2005:565). Once the calibration was completed, the Actiheart® was programmed via "Advanced Energy Expenditure" mode using 30s epochs (counts per minute), for a 7-day continuous collection. Starting time was synchronized with a computer clock, and the Actiheart was reattached. Women were advised to take the monitor off when they were bathing or showering and to put it on again immediately afterwards. An extra set of electrodes were given to the participants to replace the device should it become loose. The device was removed after 7 days and the data were downloaded using the accompanying software (Version 2.132, Cambridge Neurotechnology Ltd, Cambridge, UK). Individual estimates of AEE were calculated from the calibration prediction equations which were used in conjunction with the branched equation model described by Brage, *et al*. (2004:348) during the 7-day collection period. Equation models can be found in the Actiheart User Manual (Cambridge Neurotechnology Ltd., 2004).

Gait video analysis and gait energy expenditure were conducted when the participant was scheduled to return the Actiheart® device, 7 days after the initial measurements for demographics. Once the markers were applied (Figures 3.3 and 3.6), the participant was requested to stand in the middle of the calibrated area for 5 seconds for the collection of the static trial. The participants were then asked to walk along a 15-meter walkway embedded with three AMTI force plates. Only trials in which the participants' foot landed entirely on a force plate for three consecutive steps (i.e. full stride), were considered for inclusion in the data set. The participants continued walking until 3 trials of full strides were completed. The participants were instructed to stop and rest as long as necessary, should they feel tired at any stage of the gait analyses. None of the participants requested a rest period during gait measures. Upon completion of the dynamic trials, all of the markers were removed from the body, and participants were prepared for walking energy expenditure analysis.

A B

Figure 3.6: Participant ready for data collection with a full-body marker set (A), and static trial (B)

The participants were fitted with an HR monitor (Polar T31, Polar Electro, Finland), and a harness equipped with the K4b2 unit (Figure 3.5). Participants were connected to the analyser via a Rudolph type mask allowing for a one-way gas exchange. Once equipped, the participant sat quietly for three minutes to adjust to the equipment, and to achieve comfortable resting steady HR. Walking energy analysis was completed once the steady state was reached as described earlier. All participants reached the steady state within 4 minutes of walking, without a need for resting. The average consumption rate during the last minute of steady state walking was used as the walking metabolic rate.

3.6 Data analyses

During walking trials, the data were inspected for gaps in marker trajectories. The default gap-fill function was applied for gaps of no more than 10 frames using non-uniform rational basis (NURB) spline interpolation (Qualisys Track Manager, 2011:177). No walking data trials analysed had gaps larger than 10 frames. No other processing was done via Qualisys software. Once the walking trials were trimmed to include completed strides, the data were exported to Visual 3D motion analysis software for processing, through which segmental and whole body kinetic data and gait kinematic data were calculated. The kinetic and kinematic parameters were low-pass filtered with a bidirectional Butterworth with a 10-Hz cut-off frequency to remove noise from the differentiation process with zero-phase distortion (Olney, *et al.,* 1990:433; Wu, *et al*., 2002:680). Gait kinematics, GRF and COP variables were obtained from this data, while other data were computed separately. The following sections give comprehensive steps for computing variables used in the study.

3.6.1 Gait kinematics

Prior to processing of 3D motion analysis data, raw data were inspected for gaps and, in addition to standard gait kinematics such as walking speed, step length and width the additional kinematics included swing time, double support time, and foot clearance. These parameters were computed as follows:

- **Walking speed** - the time it takes to complete a single stride per unit of time measured in meters per second (m/s)
- **Step length** – the distance between spatial position of reflective markers placed on the Achilles tendon insertion on the calcaneus on the right and left foot measured in meters (m). Step length was also normalized for leg length.

- **Step width** – the distance between left and right foot joint centres determined as the midpoint between lateral and medial malleoli measured/calculated in meters (m). Step width was also normalized for leg length.
- **Swing time** – the time from toe-off to heel strike calculated in seconds (s).
- **Foot clearance** – the highest vertical position of the first metatarsal reflective marker reported in meters (m).
- **Double support time** – the time from heel strike to push of the opposite foot determined in seconds (s).

The step kinematics were measured from heel strike to the subsequent heel strike. Leg length was measured from the great trochanter to the lateral malleoli of the dominant leg. All of these gait parameters are co-dependent to various degrees in terms of metabolic and mechanical walking energy cost, balance, posture and ground reaction forces. The magnitude of this interaction depends on the individual adaptations which were investigated in this study, and revealed by the statistical analysis.

3.6.2 Mechanical work analysis

Mechanical work is derived from the König theorem (Cavagna & Kaneko, 1977:471) that utilizes symmetric limb displacement relative to the whole body COM and is given by equation 2.3 (previously discussed in Chapter 2):

$$E_{tot,wb} = (MgH + ½\,MV_{cg}^2) + \sum_{i=1}^{N} (1/2 m_i V_i^2 + 1/2 m_i K_i^2 \omega_i^2) \qquad \text{Equation 2.3.}$$

The external work (W_{ext}) is given by the algebraic sum of the 1st two terms of the equation 2.3:

$$(MgH + ½\,MV_{cg}^2) \qquad \text{Equation 2.3a.}$$

W_{int} is represented by the second part of equation 2.3, and represents the incremental sum of the segmental energies due to their velocity relative to the COM of the whole body:

$$(\sum_{i=1}^{N} (1/2 m_i V_i^2 + 1/2 m_i K_i^2 \omega_i^2)) \qquad \text{Equation 2.3b.}$$

External and internal work (W_{ext} and W_{int}) and total mechanical energy (E_{tot}) were reported in J/kg/m and correlated with indirect calorimetry. Energy recovery factor, R, an amplitude ratio of potential energy (Ep) to kinetic energy (Ek) was computed from the average of the peak-to-peak values (Figure 3.7).

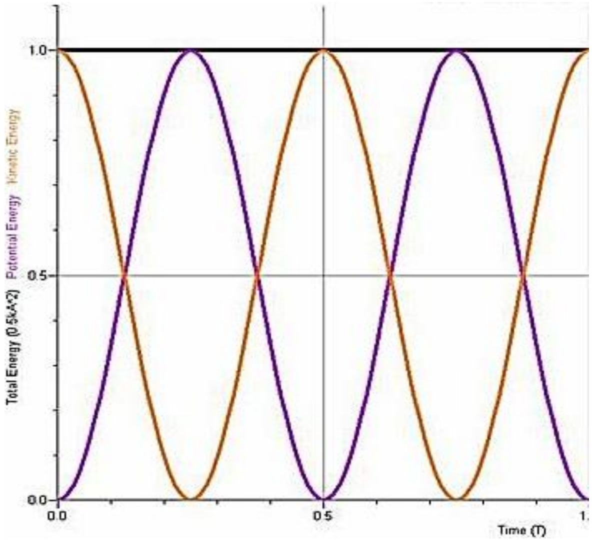

Figure 3.7: Kinetic and potential energy exchange in a system with maximum energy recovery, depicted by equal and opposite amplitudes

3.6.3 Balance

Postural control or balance during unperturbed stance are generally assessed by the centre of pressure measures (COP), computed from the force platform (Pinsault & Vuillerme, 2009:276). Several parameters assessing balance were computed using centre of gravity (COG) and centre of pressure (COP) as:

- **COP_{ML} range** – maximum medio-lateral COP deviation during a step reported in centimetres (cm)
- **COG_{ML} range** – distance COP moved during single support reported/calculated in centimetres (cm)
- **COP/COG inclination angle** - Angle resulting from horizontal distance between COG and COP (Figure 3.9) reported in degrees.

In this study, however, postural control was assessed during dynamic walking conditions, for which a measure of dynamic postural control should also be used. Since the walking mechanics were examined by the principle of inverted pendulum model, the measures that assess postural control using the same principle were also used. Extrapolated centre of mass (xCOM) proposed by Hoff, *et al*., (2005:7), extends the basic concept of static stability, while COM stays within the base of support (BOS) to dynamic conditions.

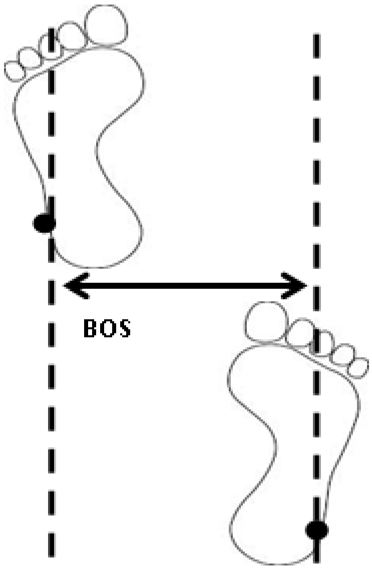

Figure 3.8: Base of support diagram

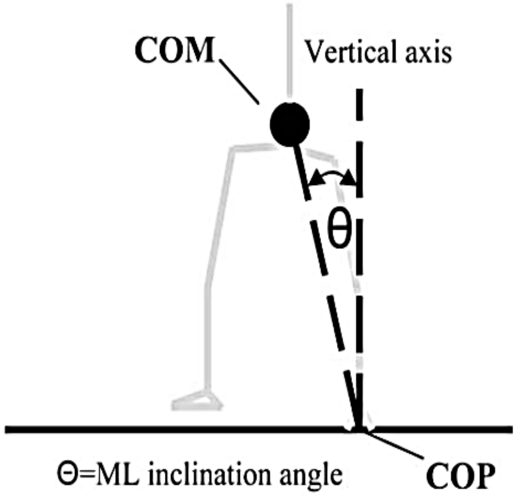

Figure 3.9: Centre of pressure/centre of gravity inclination angle used for balance evaluation

The balance is simply interplay of the COM and the centre of pressure (COP). When the foot is in contact with the ground, gravity acts on the COM through COP. When the COM is not directly over COP (almost never), a destabilizing moment arm is created. Timely alteration of the COP relative to the COM stabilizes the body. Hoff (115:2008) derived and validated a mathematical model based on pendulum gait that utilizes the concept of distance between BOS and the projected COM on the ground. Both these variables are obtained through kinematic parameters and use of force plates. For this calculation Hoff (113:2008) introduced the parameter named extrapolated centre of mass (xCOM) which is derived from the position of the COM and more closely associated with measure of balance. The xCOM is calculated as follows:

$$xCOM = X + \frac{V_{COM}}{\omega_0}, \qquad \text{Equation 3.1.}$$

in which X is a projected position of the COMwb on the ground, V_{COM} is a velocity of the COMwb, and ω_0 eigen frequency of the inverted pendulum model calculated as

$$\omega_0 = \sqrt{\frac{g}{l}},$$ Equation 3.2.

where g represents the acceleration of gravity (9.81 $\frac{m}{s^2}$) and l is equivalent to the pendulum length of the subject. Pendulum length was defined as distance from COM to the middle point between medial and lateral malleoli of the ankle. Then the margin of stability, *b,* was defined as:

b=BOS - xCOM Equation 3.3.

Since position of the BOS coincides with the COP (Bruijn, *et al*., 2013:12), the above equation can be rewritten as:

b=COP - xCOM Equation 3.4

where xCOM is the most lateral position of the xCOM and the COP is the corresponding lateral position of COP, Figure 3.10. Furthermore, width of the BOS was considered to be the distance between lateral malleoli during double stance stage (Forczek & Staszkiewicz, 2012:115).

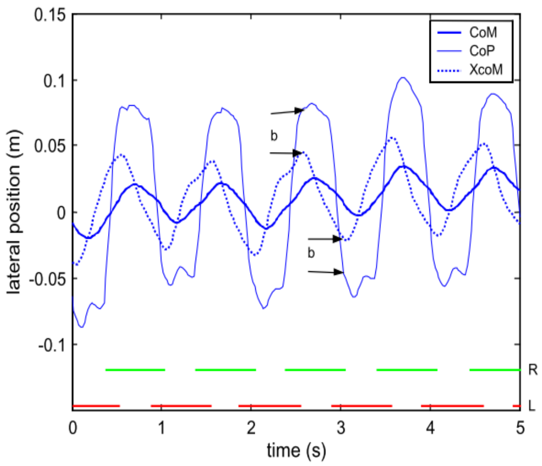

Figure 3.10: Position of the centre of mass, centre of pressure, and extrapolated centre of mass during walking. Margin of stability *b* is marked by arrows during contralateral push-off. Adopted from Hoff, *et al*., 2005:7.

3.6.4 Posture

Assessment of posture during gait is closely related to balance, and simple to analyse. Change in posture during gait was assessed in forward and backward trunk lean, as well as lateral trunk lean during walking, in a projected 2D plane. Inclination angle of the trunk along the sagittal plane was calculated as a front to back deviation of the line connecting acromion to the greater trochanter. Lateral tilt of the trunk and pelvis were analysed by calculating the lateral inclination angle of both segments, and reported in degrees to the nearest 1/10th. Similar to stability inclination angle, lateral trunk tilt inclination angle was calculated as an intersection of the line connecting the left and right acromion process, with an absolute horizontal line (Figure 3.11). Pelvis lateral inclination angle was calculated as an intersection of the line connecting left and right ASIS, and a horizontal line (Figure 3.11).

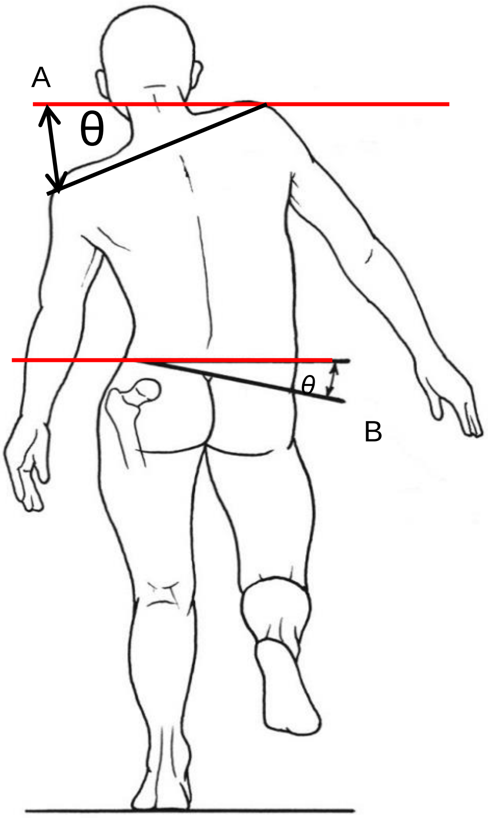

Figure 3.11: Diagram for determining inclination angles of A) lateral trunk lean, and B) lateral pelvic tilt

3.7 Statistical analyses

Statistical analyses were completed using SPSS v. 21.0 (IBM Corp., Armonk, NY). Descriptive data analyses and between trimester analysis were presented for data for comparison with previous research. Mean and standard deviation for each trimester were presented for all gait kinematic and kinetic variables, walking energy expenditure, as well as posture, balance and ground reaction forces. A one-way ANOVA was used to assess the differences between trimesters for all parameters. Significant differences were analysed using LSD post-hoc. Levene's test was used to test differences in variances between trimesters. If there were significant differences in variances between trimesters, Games-Howell post-hoc was conducted. Kruskal-Wallis test for non-parametric data was done to confirm ANOVA due to small sample size. Kruskal-Wallis was not interpreted if the ANOVA-based results are not significant. In a case where ANOVA presents significant differences which are not confirmed with Kruskal-Wallis, both results were presented. Additional analyses, linear regression and correlation, were performed to assess the relationship between changes in participants characteristics primarily weight, and weight gain, on gait kinematics, kinetics, and energy expenditure. Significance level for all tests was set at $p < < 0.05$. Power analysis for all inferential analyses was calculated with G*Power software (v 3.1.9.2, Heinrich-Heine-Universität Düsseldorf, Germany).

For objective one, first, a multiple hierarchical linear regression was used to determine the contribution of REE and net O_2 on gross energy expenditure, followed by a linear regression to determine the relationship between gait kinematics, walking speed and vertical excursion of COG, with net walking energy expenditure. Analyses of variance determined the proportion of variance explained by the predictors. Data presented was standardized coefficients, significance, 95% confidence interval, R, and the adjusted R^2. Additional Pearson correlation (set at $p < 0.05$) was done to measure the level of agreement for those variables found significantly related. Post-hoc power analysis for regression was completed given $\alpha = 0.05$, sample size of 35, effect size computed from the correlation coefficient (R^2) and using 3 predictors.

For objective two, multiple hierarchical linear regressions were conducted to determine the contribution of gait kinematics and weight gain to variation in COG/COP inclination. Data presented was standardized coefficients, significance, 95% confidence interval, R and the adjusted R^2. Additional Pearson correlation (set at $p < 0.05$) was done to measure the level of agreement for those variables found significantly related, and relationship between trunk and pelvic inclination angles with gait kinematics and changes in weight. Post-hoc power analysis for regression was completed given α = 0.05, sample size of 35, effect size computed from the correlation coefficient (R^2) and using 2 predictors.

For objective three, Pearson correlation (set at $p < 0.05$) was also used to evaluate the level of agreement between measures of mechanical work (W_{ext}, W_{int}, and W_{tot}), and the net and gross O_2 consumption and cost. Additional regression prediction equations were calculated for measure of internal, external and total work, with each measure of metabolic energy expenditure.

Lastly, the walking economy is determined from the analyses in objective one, as walking economy is measured by the amount of energy conservation from vertical excursion of COG. Additional Pearson correlation (set at $p < 0.05$) between the measures for gross and net walking energy, and gross and net walking were correlated with walking speed.

3.8 Ethical considerations in data collection and analysis

Pregnancy is a stage of the development of new life, and different cultures have different beliefs concerning privacy related to pregnancy and exposure of the women's body. Except for the gait analyses, none of the measurements were invasive. During extensive data collection several ethical issues arose. During measures, some participants indicated that they felt uncomfortable to be measured by a man, and would have preferred to be measured by a woman. Additionally, during biomechanics laboratory data collection, laboratory access was limited only to authorized staff, to protect participants' privacy. At no point during assessment was the mother or the foetus exposed to any known physical dangers. Some discomfort may have been present while wearing the portable Cosmed unit, or while wearing the motion analysis markers. However, neither represented any physical danger. Even though participants were explained the particulars of each test, they were free to stop at any point in time, but no participant exercised that option. The exposure to the measurements was strange to some of the participants. Due to their level of education and experience, familiarization was performed to ensure they become relaxed or to withdraw from the measurement. Finally, the Ethics Committee of the North-West University approved the study (NWU-00044-10-A1).

3.9 Summary

This chapter presented the measure instruments and measurements that were used to collect the data needed to reach the objectives presented in Chapter 1. Demographic variables, activity energy expenditure, gait kinetics and kinematics and posture and balance measurement were described. The data collection procedures were listed in the order in which they were completed during the study, and will be presented in Chapter 4, the results section. A co-dependence of measures will result in grouping of variables per relevance to the objectives.

CHAPTER 4 RESULTS

4.1 Introduction

Literature on the changes observed in gait during pregnancy are largely equivocal, due to large inter-variability between participations, and the fact that all the studies are relating changes to gestation according to trimester. This study aimed to determine the relationship between gait kinematics, kinetics and walking energy expenditure of pregnant women at different trimesters of pregnancy. The relationships occurring between variables were irrespective of trimester progression, but rather based on weeks of gestation in pregnancy. The results of the study will be presented in the same order as the objectives stated in Chapter 1. Firstly, descriptive data and between trimester differences will be presented for participants' characteristics, gait kinematics and kinetics, dynamic balance and posture, and walking metabolic expenditure, followed by the inferential analyses, the multiple linear regressions and correlations indicating the relationships between the variables presented in the objectives of this study.

4.2 Descriptive results

Total of thirty five (35) women gave informed consent for participation in the study. Recruitment was across all trimesters of pregnancy and according to the inclusion criteria (Chapter 3). All participants were only measured once during their pregnancy at which point weeks of gestation was recorded. Levene's test for homogeneity of variances shows no differences in variance for any of the participants' characteristics across the different trimesters.

4.2.1 Participant demographics

The participant demographics as presented in Table 4.1 are categorised according to trimesters based on the weeks of gestation reported by the participants. The majority of the participants that gave consent for participation were black (75%), while mixed ancestry comprised just over 17% (Table 4.1). The majority of participants (65.1%) had an education level of less than 10th grade, and 79% earned less than R100 000 per annum. The population shows a large range in age, and (self-reported) pre-pregnancy weight. There were no significant differences between trimesters for anthropometric variables, or variance between trimesters. Throughout Chapter 4, the change in weight and weight gain will be considered relative to the self-reported pre-pregnancy weight. Weight gain per trimester was higher for each trimester, but was within the range recommended by the Institute of Medicine (6.7 – 11.2 kg) for the particular BMI category (Institute of Medicine of the National Academies, 2009:2). Participants' pre-pregnancy BMI reveals they were on average borderline overweight with a mean of 25.1 ± 5.5 kg/m^2 (Institute of Medicine of the National Academies, 2009:2).

Table 4.1: Descriptive statistics of the participants with Levene's test of homogeneity of variance and differences between trimesters

Measure	**Average** Mean (SD)	**1st trim** Mean (SD)	**2nd trim** Mean (SD)	**3rd trim** Mean (SD)	Levene's statistic	Sig.
Participants (n)	35	13	12	10	-	-
Age (years)	27.5 (5.8)	28.0 (5.5)	27.0 (6.1)	27.3 (6.6)	0.71	0.90
Gestation (wks)	20.6 (8.2)	12.1 (2.2)	22.3 (2.6)	31.4 (2.6)	0.83	-
Height (cm)	160.8 (6.4)	160.8 (5.9)	160.2 (6.8)	161.4 (7.2)	0.72	0.93
Weight (kg)	70.4 (15.7)	62.7 (10.5)	71.3 (16.6)	78.8 (14.7)	0.12	0.08
BMI (kg/m^2)	27.3 (5.9)	24.3 (4.0)	27.7 (6.2)	29.9 (4.9)	0.26	0.10
W_{gain} (kg)	6.1(6.3)	1.1 (3.1)^{a,c}	5.3 (2.8)^{b,c}	13.8 (7.9)^{a,b}	0.58	≤0.001
PPW (kg)*	64.4 (14.5)	61.6 (10.3)	66.0 (15.9)	65.2 (18.0)	0.35	0.65
PPBMI (kg/m^2)	25.1 (5.5)	23.6 (5.1)	32.8 (7.7)	29.8 (8.3)	0.62	0.66
Ethnicity						
Black	74.3%					
Mixed	17.1%					
White	8.6%					

^{a,b,c} significant difference between relative trimesters; trim = trimester; W_{gain} = weight relative to pre-pregnancy weight; PPW = self-reported pre-pregnancy weight; PPBMI = pre-pregnancy body mass index*

4.2.2 Gait kinematics and kinetics during pregnancy

Stride length, and step length were normalized for leg length, and expressed as a percent of leg length (%ll), which was measured from the greater trochanter to the lateral malleolus of the dominant leg. Hence, through the Results section, when interpreting results, it should be noted that stride length and step width are adjusted values, whereas no absolute values were used. Table 4.2 shows that no significant differences between trimesters were noted for gait kinematics, and Levene's test indicates no significant difference in variance in gait kinematics between trimesters.

Table 4.2: Descriptive gait kinematics with Levene's test for equality of variances and differences between trimesters

	Average Mean (SD)	**1st trim** Mean (SD)	**2nd trim** Mean (SD)	**3rd trim** Mean (SD)	Levene's statistic	Sig.
S (m/s)	1.08 (0.11)	1.09 (0.07)	1.11 (0.11)	1.04 (0.11)	0.09	0.34
Stride length*	0.70 (0.06)	0.69 (0.06)	0.72 (0.06)	0.70 (0.05)	0.94	0.17
Step width*	0.06 (0.02)	0.06 (0.02)	0.07 (0.02)	0.07 (0.02)	0.80	0.30
Foot clearance (m)	0.07 (0.01)	0.07 (0.01)	0.07 (0.01)	0.07 (0.01)	0.22	0.85
DS time (sec)	0.12 (0.04)	0.12 (0.03)	0.12 (0.03)	0.13 (0.06)	0.10	0.53
Swing time (sec)	0.46 (0.02)	0.46 (0.02)	0.45 (0.02)	0.46 (0.03)	0.74	0.49

*S = walking speed; DS = double support; trim = trimester; * = normalized for leg length and expressed as a ratio to leg length*

Centre of gravity vertical and medio-lateral excursions and centre of pressure medio-lateral range are depicted in Table 4.3. Levene's test demonstrates that there were no differences in variance between trimesters in either variable. COG_{ML} continuously increased throughout pregnancy, with 3rd trimester significantly higher than 1st ($p \leq 0.001$) or 2nd trimester ($p \leq 0.01$). Similarly, COP_{ML} range in 3rd trimester was significantly larger than in the 1st ($p \leq 0.01$) or the 2nd trimester ($p \leq 0.01$). The decrease in COP_{ML} from 1st to 2nd trimester was not significant.

Table 4.3: Descriptive centre of gravity and centre of pressure parameters with Levene's test for equality of variance, and differences between trimesters

	Average Mean (SD)	**1st trim** Mean (SD)	**2nd trim** Mean (SD)	**3rd trim** Mean (SD)	Levene's statistic	Sig.
COG_V (cm)	3.41 (0.63)	3.37 (0.56)	3.57 (0.63)	3.24 (0.76)	0.96	0.49
COG_{ML} (cm)	2.44 (0.81)	2.01 (0.42)[a]	2.28 (0.88)[b]	3.28 (0.81)[a,b]	0.10	≤0.001
COP_{ML} (cm)	1.51 (0.59)	1.38 (0.44)[a]	1.25 (0.57)[b]	2.06 (0.49)[a,b]	0.37	≤0.01

[a,b] significant difference between relative trimesters; COGv = vertical excursion of the centre of gravity; COG_{ML} = medio-lateral centre of gravity displacement; COP_{ML} = medio-lateral range of the centre of pressure; trim = trimester

All ground-reaction forces (GRFs) were normalized for body weight. Paired *t*-test determined that there were significant differences between the right and left leg for push-off peak GRF ($p \leq 0.01$), as well as heel-strike peak GRF ($p \leq 0.01$). Therefore, dominant leg GRFs will be used for all parameters (all participants reported "right" as their dominant side). Table 4.4 shows descriptive data for ground reaction forces and no significant differences in variance between trimesters. Although one-way ANOVA demonstrates no significant differences between trimesters in vertical reaction forces during toe-off (GRF_{TO}), Kruskal-Wallis test for non-parametric data shows significant differences between trimesters ($p = 0.04$). Shapirro-Wilk test showed that residuals were normally distributed. The LSD post-hoc determined that the significant difference was depicted between the 1st and 3rd trimester ($p = 0.02$). However, both ANOVA and Kruskal-Wallis tests show that in 3rd trimester vertical reaction forces in loading stage were significantly lower relative to 1st ($p \leq 0.001$ and 2nd trimesters ($p \leq 0.001$).

Table 4.4: Descriptive vertical ground-reaction forces, with Levene's test for equality of variance, and differences between trimesters

	Average Mean (SD)	**1st trim** Mean (SD)	**2nd trim** Mean (SD)	**3rd trim** Mean (SD)	Levene's statistic	Sig.
GRF_{HS} (BWs)	1.06 (0.06)	1.06 (0.05)	1.08 (0.07)	1.03 (0.06)	0.64	0.14
GRF_{TO} (BWs)	1.08 (0.06)	1.11 (0.05)	1.08 (0.05)	1.05 (0.07)	0.56	0.07*
GRF_{MS} (BWs)	0.87 (0.09)	0.90 (0.04)^{a}	0.94 (0.06)^{b}	0.74 (0.03)^{a,b}	0.25	≤0.01

**significance for Kruskal-Wallis test (p=0.04); ^{a,b} significant difference between relative trimesters; GRF_{HS} = heel-strike peak ground-reaction force; GRF_{TO} = toe-off/push-off peak ground-reaction force; GRF_{MS} = mid-stance/loading/passive peak ground-reaction force; BWs = body weights; trim = trimester*

4.2.3 Dynamic balance and posture during pregnancy

Postural changes were assessed via pelvis and trunk inclination angles during standing (static) and walking (dynamic). Intra-subject variability for these variables was assessed with the coefficient of variation (CV) between 10 walking trials. CV is independent of the units of measurement, and presents the variation of the variable in proportion to the mean, accounting for differences in the magnitude of variation between each walk. Results (Table 4.5) show that the dynamic trunk inclination angles exhibited slightly higher CV than the static trunk conditions, or the pelvic inclination angles.

Table 4.5: Coefficient of variability for pelvic and trunk inclination angles during walking of participants categorised for each trimester

	1st trim CV (%)	**2nd trim** CV (%)	**3rd trim** CV (%)	**Average** Mean (SD)
Pelvic θ_{FT} (deg)	5.3	5.7	5.6	5.5 (0.2)
Trunk θ_{FT} (deg)	7.4	8.9	7.8	8.0 (0.8)
Trunk $\theta_{SG\ static}$ (deg)	4.2	3.8	4.8	4.3 (0.5)
Trunk $\theta_{SG\ walking}$ (deg)	7.4	8.9	8.5	8.3 (0.8)

Pelvic θ_{FT} = Pelvic inclination angle in frontal plane; Trunk θ_{FT} = Trunk inclination angle in frontal plane; Trunk $\theta_{SG\ static}$ – trunk lean angle changes in sagittal plane during quiet standing; Trunk $\theta_{SG\ walking}$ – trunk lean angle in sagittal plane during walking; trim = trimester

Table 4.6 depicts the descriptive data and differences between trimesters for posture and balance as functions of COG/COP inclination angle, medio-lateral deviations of the COG, as well as medio-lateral range of the COP. Levene's test indicates that there was no variance among variables between trimesters. Trunk hyperextension (Trunk$\theta_{SG,static}$) increased 104% from 1st to 2nd trimester ($p = 0.03$), and 66% from 2nd to 3rd trimester ($p = 0.02$). Similarly, the COG/COP inclination angle was significantly higher in the 3rd trimester, relative to 1st ($p \leq 0.01$) or 2nd ($p= 0.03$) trimesters.

Table 4.6: Descriptive balance and postural parameters, with Levene's test for equality of variance and differences between trimesters

	Average Mean (SD)	**1st trim** Mean (SD)	**2nd trim** Mean (SD)	**3rd trim** Mean (SD)	Levene's statistic	Sig.
Pelvicθ_{FT} (deg)	8.19 (1.92)	8.66 (1.88)	8.03 (1.74)	7.66 (2.23)	0.94	0.46
Trunkθ_{FT} (deg)	5.97 (2.32)	5.33 (1.85)	6.23 (2.78)	6.61 (2.31)	0.20	0.40
Trunk$\theta_{SG,static}$(deg)	6.06 (4.60)	3.07 (2.83)^{a,b}	6.29 (3.87)^{b,c}	10.41 (4.40)^{a,c}	0.26	0.00
Trunk$\theta_{SG,walking}$(deg)	1.37 (0.58)	1.29 (0.54)	1.43 (0.68)	1.41 (0.54)	0.48	0.81
COG/COP θ_{FT} (deg)	3.89 (0.34)	4.09 (0.57)^{a}	4.63 (0.66)^{b}	4.97 (0.74)^{a,b}	0.29	0.01
b	5.18 (1.79	5.17 (1.43)	4.60 (2.08)	5.99 (1.78)	0.49	0.21

^{a,b,c} significant differences between relative trimesters with similar symbols; Pelvic θ_{FT} = Pelvic inclination angle in frontal plane; Trunk θ_{FT} = Trunk inclination angle in frontal plane; COG/COP θ_{FT} = centre of gravity/centre of pressure inclination angle in frontal plane; Trunk θ_{SG} static – trunk lean angle changes in sagittal plane during quiet standing; Trunk θ_{SG} walking – trunk lean angle in sagittal plane during walking; b = margin of stability; trim = trimester

4.2.4 Walking and resting energy expenditure during pregnancy

Descriptive walking energy expenditure parameters are given in Table 4.7. Levene's test indicated that there was no significant difference in variances between trimesters in any walking energy expenditure variables. One-way ANOVA demonstrates that there were no significant changes in walking energy expenditure between trimesters. However, Kruskal-Wallis test determined that there was a significant difference in respiratory quotient ($p = 0.04$), with post-hoc indicating that RQ significantly increased from 2nd to 3rd trimester ($p = 0.05$). Similarly, one-way ANOVA found no significant differences in gross O_2 cost, while Kruskal-Wallis test found significant difference ($p = 0.04$) between trimesters. Specifically, gross O_2 cost decreased significantly from 1st to 2nd trimester ($p = 0.04$). Shapiro-Wilk test determined that the data was normally distributed. Although mean respiratory quotient (RQ) remained below 1.0, in the 3rd trimester RQ significantly increased ($p = 0.05$) which indicates a potential change in metabolic process.

Table 4.7: Descriptive data for active and resting energy expenditure and cost, with the Levene's test for equality of variances and differences between trimesters

	Average Mean (SD)	**1st trim** Mean (SD)	**2nd trim** Mean (SD)	**3rd trim** Mean (SD)	Levene's statistic	Sig.
REE (kcal/kg/day)	21.8 (2.5)	22.7 (2.6)	21.4 (2.2)	21.0 (2.3)	0.77	0.78
Gross O_2 (ml/kg/min)	10.23 (2.12)	10.93 (2.47)	9.32 (1.35)	10.38 (2.13)	0.18	0.15
Gross O_2 (ml/kg/m)	0.16 (0.03)	0.17 (0.04)	0.14 (0.02)	0.17 (0.03)	0.32	0.06*
Net O_2 (ml/kg/min)	8.54 (3.20)	9.15 (3.26)	7.76 (2.65)	8.64 (3.89)	0.42	0.56
Net O_2 (ml/kg/m)	0.13 (0.04)	0.14 (0.05)	0.12 (0.03)	0.13 (0.04)	0.31	0.35
RQ	0.91 (0.08)	0.90 (0.10)	0.90 (0.06)[a]	0.97 (0.08)[a]	0.06	0.09*
Activity counts (cpm)	27.93 (10.67)	28.47 (6.87)	28.31 (10.24)	26.66 (16.13)	0.93	0.46

*[a] significant difference between relative trimesters with similar symbols; *significant differences found with Kruskal-Wallis test; O_2 = walking volume of oxygen; RQ = respiratory quotient; Net O_2 = energy expenditure only necessary for walking (TEE_{gait}-REE); trim = trimester; cpm = counts per minute*

4.3 Inferential analyses

Inferential analyses will investigate the relationships in order to address the objectives stated in Chapter 1.

4.3.1 Relationship between gait kinematics and gait kinetics during pregnancy

Results from the multiple regression that is presented in Table 4.8 to predict walking speed from stride length, step width and double support time indicated that stride length and double support time statistically significantly predicted walking speed $F(3, 31) = 8.788$, $p < 0.001$, adjusted $R^2 = 0.41$. Shapiro-Wilk test showed normal distribution for standardized residuals (p = 0.78), and there was no interaction between predictor variables. The stride length, step width, and double support time, accounted for 41% percent of variation in walking speed during pregnancy.

Table 4.8: Multiple linear regression analysis of walking speed with stride length, step with and double support time as predictive gait parameters

Speed (m/s)	Standardized coefficients, β	Sig.	95.0% Confidence interval*	R	Adjusted R^2
Constant		≤0.001	0.17 - 1.03		
Stride length (m)	0.42	≤0.001	0.28 - 1.39	0.68[a]	0.41
Step width (m)	0.14	0.30	-0.78 – 2.43		
Double support time (s)	-0.46	≤0.001	-2.07 - -0.49		

a. Predictors: Double support time, Stride length, Step width

* unstandardized coefficient

Partial correlation analyses controlling for weeks of pregnancy shows that the changes in walking speed during pregnancy have a strong significant relationship with the stride length (r = 0.52, p ≤ 0.01), while increase in time spent in double support stage of a stride was significantly associated with decrease in speed (r = -0.53, p ≤ 0.01) (Table 4.9). The increase in double support stance time however, was significantly associated with the increase in weight gain during pregnancy (r = 0.37, p = 0.03). Similarly, increases in weight had moderate, but significant relationship with decrease in walking speed (r = -0.38, p ≤ 0.03). The post-hoc power analysis with effect size of 0.69 (determined from adjusted $R^2 = 0.41$), at α = 0.05, and 3 predictors was 0.98.

Table 4.9: Relationship between gait kinematics during pregnancy represented by partial correlation and controlled for weeks of pregnancy

	W_{gain} (kg)	Weight (kg)	DS time (sec)	Stride length (% ll)
S (m/s)	r = -0.26 p = 0.13	r = -0.38* p = 0.03	r = -0.51** p ≤ 0.01	r = 0.52** p ≤ 0.01
Stride length (% ll)	r = -0.30 p = 0.08	r = -0.03 p = 0.86	r = -0.23 p = 0.18	
DS time (sec)	r = 0.37* p = 0.03	r = 0.13 p = 0.46		
Weight (kg)	r = 0.22 p = 0.22			

S = speed; DS = double support; W_{gain} *= weight gain relative to pre-pregnancy weight*

A partial correlation (Table 4.10) was run to determine the relationship between vertical ground reaction forces during heel strike (GRF_{HS}), toe-off (GRF_{TO}), and mid-stance (GRF_{MS}), and participants' gait kinematics (walking speed, double support time, stride width and length), whilst controlling for weeks of gestation. There was a significant, moderate, positive partial correlation between GRF_{HS} and walking speed, r = 0.45, n=35, p ≤ 0.01, and a significant, moderate, negative partial correlation with double support time r = -0.38, n=35, p ≤ 0.05, and stride width r = -0.34, n=35, p ≤ 0.05. Similarly, there was a significant, moderate positive relationship of GRF_{TO} with walking speed, r = 0.34, n=35, p ≤ 0.05, and significant, moderate negative relationship with double support time, r = -0.39, n=35, p ≤ 0.05.

Table 4.10: Partial correlation between gait kinematics and vertical ground reaction forces during pregnancy adjusted for weeks of gestation

	GRF_{HS} (BWs)	GRF_{TO} (BWs)	GRF_{MS} (BWs)
S (m/s)	r = 0.45, p ≤ 0.01**	r = 0.34, p = 0.05*	r = 0.34, p = 0.05*
DS time (sec)	r = -0.40, p = 0.02*	r = -0.39, p = 0.02*	r = -0.29, p = 0.09
Stride width (% ll)	r = -0.35, p = 0.04*	r = -0.14, p = 0.41	r = -0.28, p = 0.11
Stride length (% ll)	r = 0.31, p = 0.07	r = -0.11, p = 0.52	r = 0.33, p = 0.05*

S = speed; DS = double support; GRF_{HS} *= heel-strike peak ground-reaction force;* GRF_{TO} *= toe-off/push-off peak ground-reaction force;* GRF_{MS} *= mid-stance/loading/passive peak ground-reaction force; BWs = body weights*

4.3.2 The effect of gait kinematics on energy expenditure and walking efficiency during pregnancy

Shapiro-Wilk test showed normal distribution for standardized residual (p = 0.55), and there was no interaction between predictor variables. Results presented in Table 4.11 indicate that resting energy expenditure and net O_2 are significant predictors of gross O_2 $F(2, 32)$ = 44.47, $p < 0.001$, adjusted R^2 = 0.74. The resting energy expenditure and net O_2 accounted for 72% of variation in gross O_2. The post-hoc power analysis with effect size of 2.57 (determined from adjusted R^2 = 0.72), at α = 0.05, and 2 predictors was 1.0.

Table 4.11: Multiple linear regression analysis of gross energy expenditure with resting energy expenditure, and walking speed as predictors

Gross O_2 (ml/kg/min)	Standardized coefficients, β	Sig.	95.0% Confidence interval*	R	Adjusted R^2
Constant		0.000	-799.46 - -255.27		
Net O_2 (ml/kg/min)	0.76	0.000	677.40 - 1137.05	0.86[a]	0.72
REE (kcal/day)	0.64	0.000	25.20 - 45.79		

a. Predictors: Net O_2, REE

* unstandardized coefficient

However, a partial correlation depicted in Table 4.12, shows that weight showed strong, positive correlation with resting energy expenditure r = 0.82, n=35, p ≤ 0.01. In addition, there was a significant positive partial correlation between walking speed and net O_2 r = 0.70, n=35, p ≤ 0.001, in contrast to gross O_2 rate or cost.

Table 4.12: Partial correlation between walking speed, resting energy expenditure (REE) and weight with walking energy expenditure, adjusted for weeks of pregnancy

	Speed (m/s)	REE (kcal/day)	Weight (kg)	Δ Weight (kg)
Gross O_2 (ml/min)	r = -0.04 p = 0.84	r = 0.56 p ≤ 0.01	r = 0.65 p ≤ 0.001	r = 0.23 p = 0.20
Gross O_2 (ml/kg/min)	r = 0.20 p = 0.10	r = -0.10 p = 0.59	-	-
Net O_2 (ml/kg/min)	r = 0.70 p ≤ 0.001	r = -0.19 p = 0.27	-	-
REE (kcal/day)	-	-	r = 0.82 p ≤ 0.01	r = 0.26 p = 0.14

Linear regression in Figure 4.1 demonstrates that net O_2, rate rather than the gross O_2 rate, has a significant correlation with walking speed ($p \leq 0.001$). When considering the energy cost per distance walked (Figure 2), gross O_2 cost demonstrates negative, although non-significant correlation with walking speed. Net O_2 cost was positively associated with walking speed, although the strength of the relationship was lower (R^2 = 0.29), relative to net O_2 rate (R^2 = 0.49).

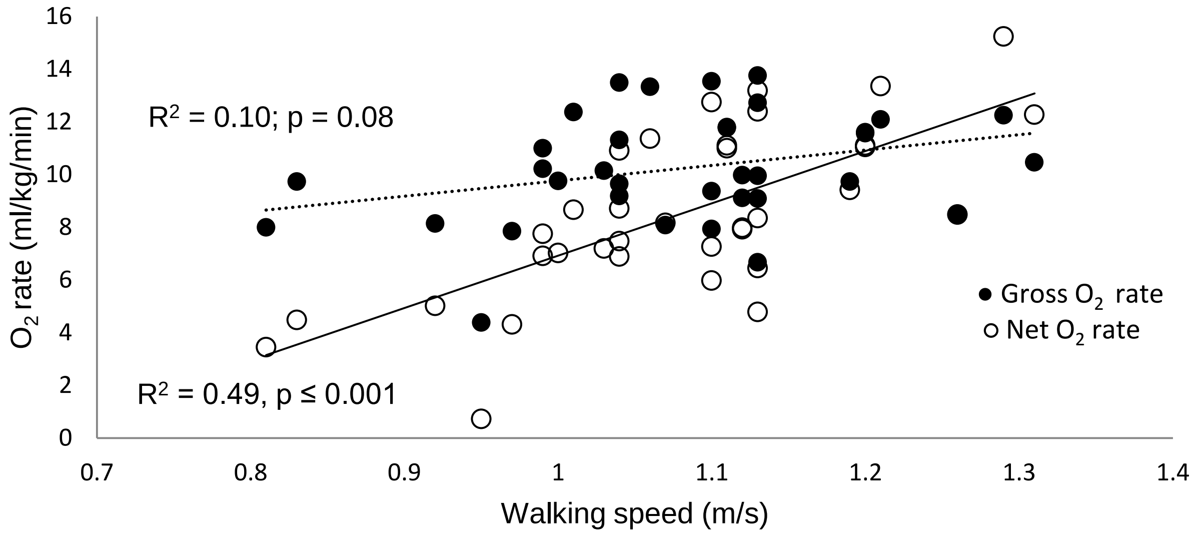

Figure 4.1: The changes in gross and net energy (O_2) rate (ml/kg/min) relative to changes in walking speed (m/s) during pregnancy

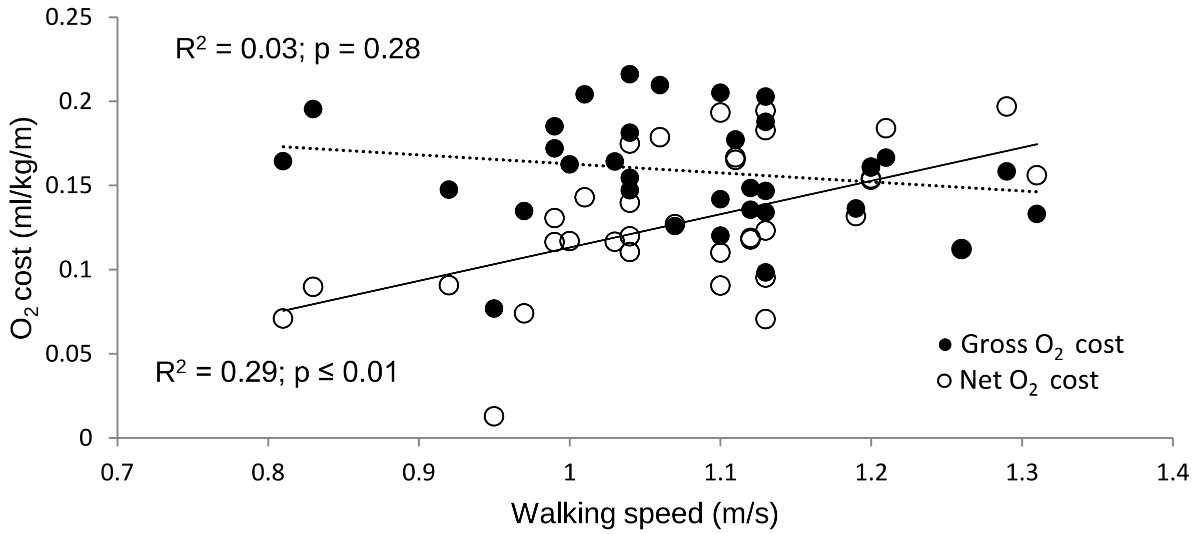

Figure 4.2: Gross and net energy (O_2) cost (ml/kg/m) relative to walking speed (m/s) during pregnancy

4.3.3 Mechanical work and indirect calorimetry

The computations for the internal, external and total work were explained in detail in the Methodology chapter, section 3.6.2. Metabolic energy expenditure is presented in O_2 rate, and O_2 cost, in gross and net energy expenditure (Table 4.13). Prediction equations for external work (W_{ext}), internal work (W_{int}) and total work (W_{tot}) depict weak, but positive, significant relationship with net energy expenditure of walking during pregnancy (p =0.04, p =0.04 and p = 0.02, respectively), Figure 4.3.

Table 4.13: Regression equations for metabolic energy expenditure and mechanical work

	W_{ext} (J/kg/min)	**W_{int} (J/kg/min)**	**W_{tot} (J/kg/min)**
Net $O_{2\ cost}$ (ml/kg/m)	$1.1646O_2 + 0.7314$	$0.889O_2 + 0.2807$	$1.2374O_2 + 1.0803$
Net $O_{2\ rate}$ (ml/kg/min)	$0.7221O_2 + 0.7671$	$0.5154O_2 + 0.3132$	$0.012O_2 + 1.1381$
Gross $O_{2\ cost}$ (ml/kg/m)	$0.9977O_2 + 0.7025$	$10.736O_2 + 0.2098$	$2.0713O_2 + 0.9123$
Gross $O_{2\ rate}$ (ml/kg/min)	$0.0134O_2 + 0.7233$	$0.0134O_2 + 0.2431$	$0.0268O_2 + 1.9664$

W_{ext} = external mechanical work; W_{int} = internal mechanical work; W_{tot} = total work

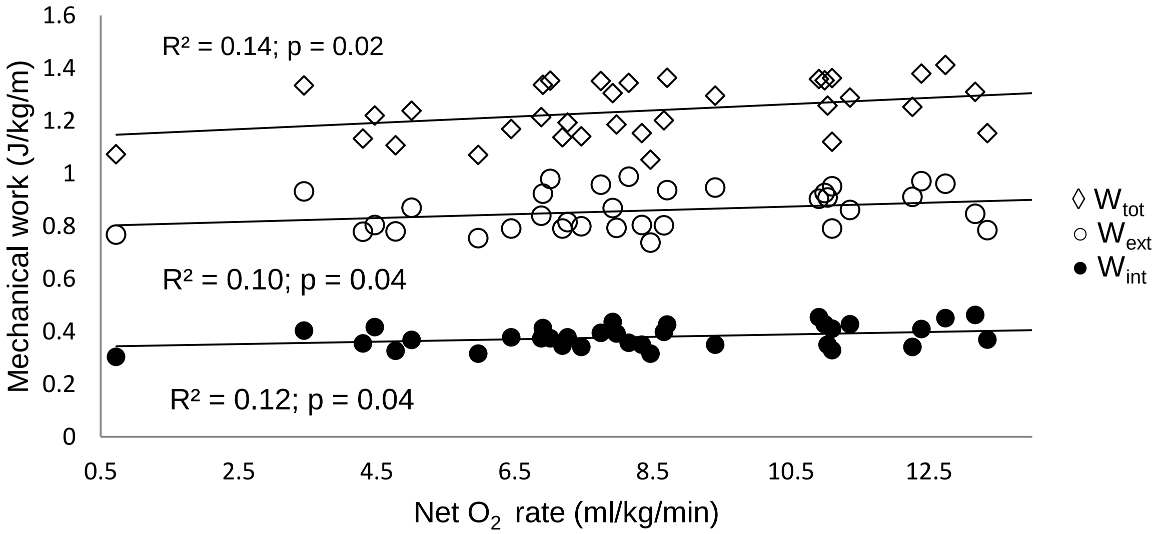

Figure 4.3: Relationship between net energy expenditure and mechanical work during pregnancy

However, once normalised for speed to express energy efficiency (net O_2 cost) (Figure 4.4), prediction equations showed moderate-to-strong, significant relationship for external work (W_{ext}) ($p \leq 0.01$), internal work (W_{int}) (, $p \leq 0.01$), and total work (W_{tot}) ($p \leq 0.01$). Relative to external work, internal work demonstrated stronger relationship, an indication of energy transfer between segments contributing to an important contribution in energy expenditure evaluation.

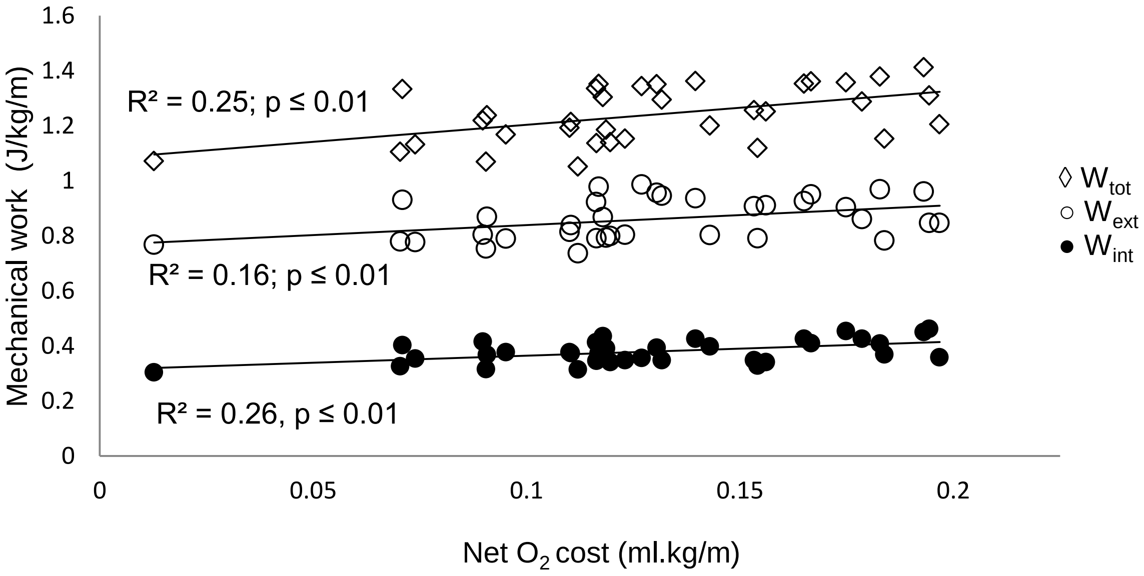

Figure 4.4: Relationship between net energy cost of walking and mechanical work during pregnancy

Figures 4.5 and 4.6 demonstrate the significance of the contribution of REE to total walking expenditure. Adding REE to energy expenditure resulted in a strong, positive, significant relationship to mechanical work. Gross energy expenditure during walking demonstrated a moderate significant relationship to W_{ext} ($p \leq 0.01$), and W_{tot} ($p \leq 0.001$) and a strong positive relationship with W_{int} ($p \leq 0.001$), (Figure 4.5).

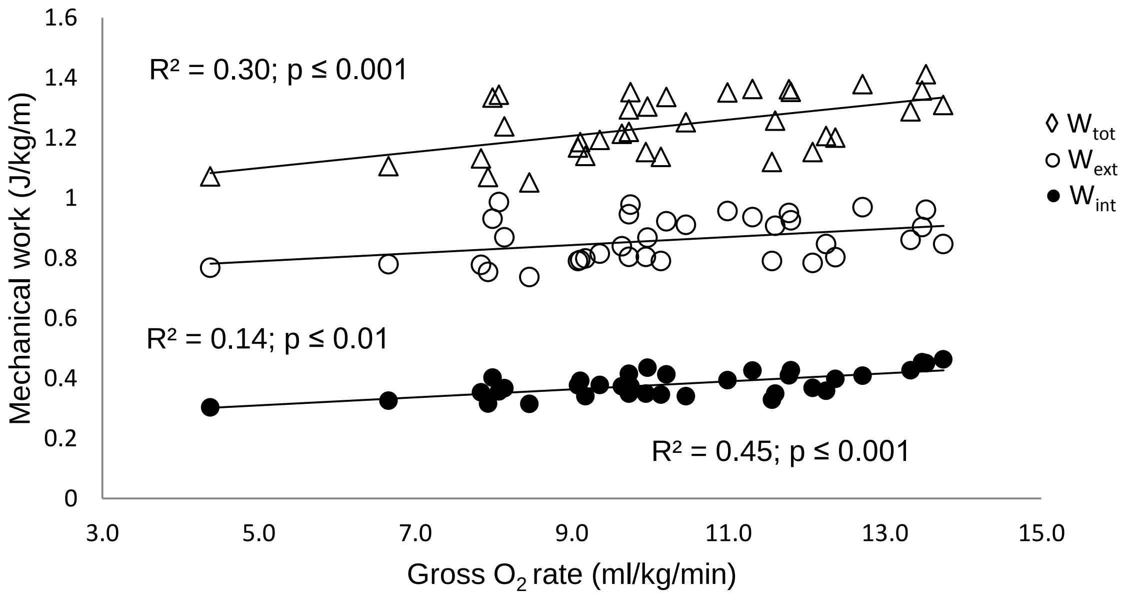

Figure 4.5: Relationship between gross energy expenditure of walking and mechanical work during pregnancy

In terms of walking economy, adding resting energy expenditure to net O_2 cost, also demonstrated strong positive relationship of gross O_2 cost with external work ($p \leq 0.01$), internal work ($p \leq 0.001$), and total work ($p \leq 0.001$) (Figure 4.6).

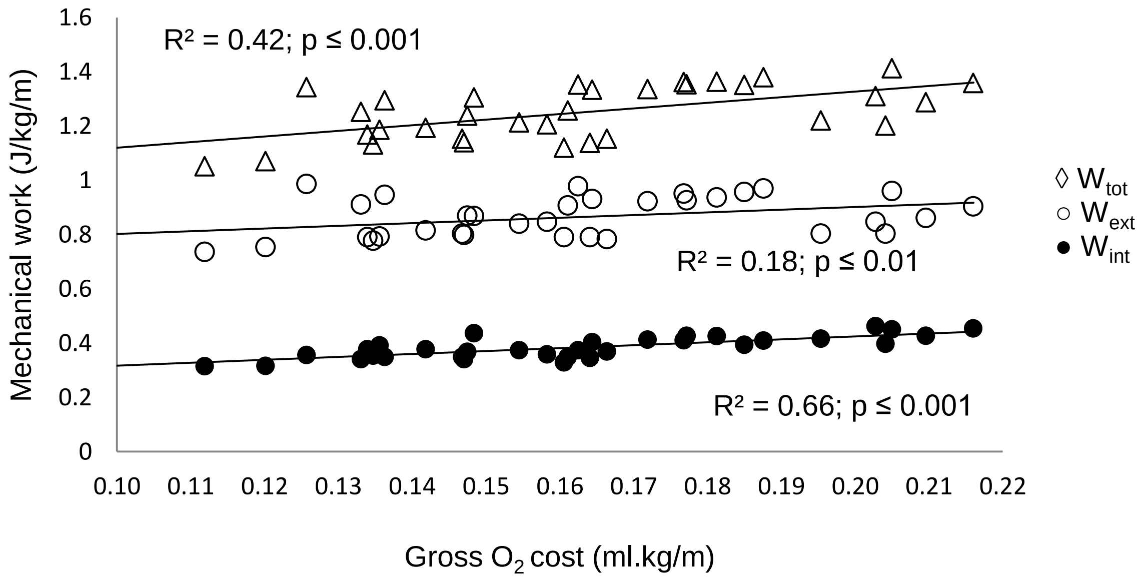

Figure 4.6: Relationship between gross energy cost of walking and mechanical work during pregnancy

4.3.4. Energy recovery and implications of vertical movement of centre of mass and speed

Energy recovery (R) is discussed in Chapter 2, and demonstrates the efficiency of motion through energy recovery using the body's own momentum. Energy recovery factor (R) for the pregnant population in this study was 56.9 ± 3.2%. The exchange of potential and kinetic energies, a determining factor for energy recovery, was largely affected by speed of walking. Figure 4.7 demonstrates a significant relationship between walking speed and energy recovery ($r = 0.61$, $p \leq 0.001$), indicating that during pregnancy energy recovered may be improved with an increase in speed.

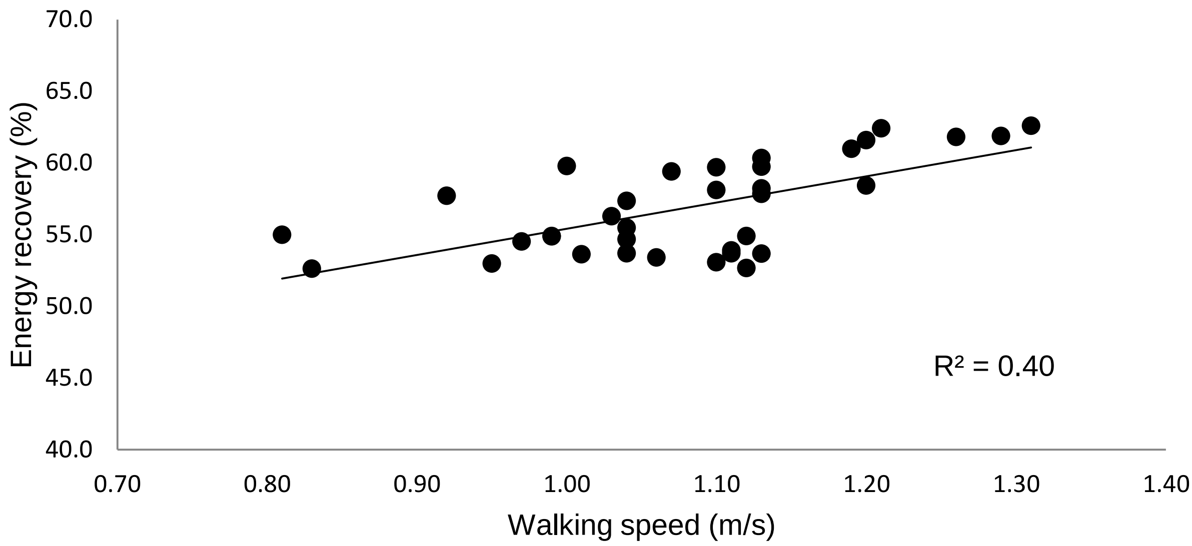

Figure 4.7: Relationship between mechanical energy recovery and walking speed during pregnancy

Given that horizontal velocity is a function of kinetic energy, vertical excursion of COM potential is a function of potential energy. Figure 4.8 demonstrates that as the speed increases so does the vertical deviation of the centre of gravity ($r = 0.70$, $p \leq 0.001$), which aides in energy exchange, since kinetic energy also increases with the increase of speed. The sample of this exchange is depicted in Figure 4.9.

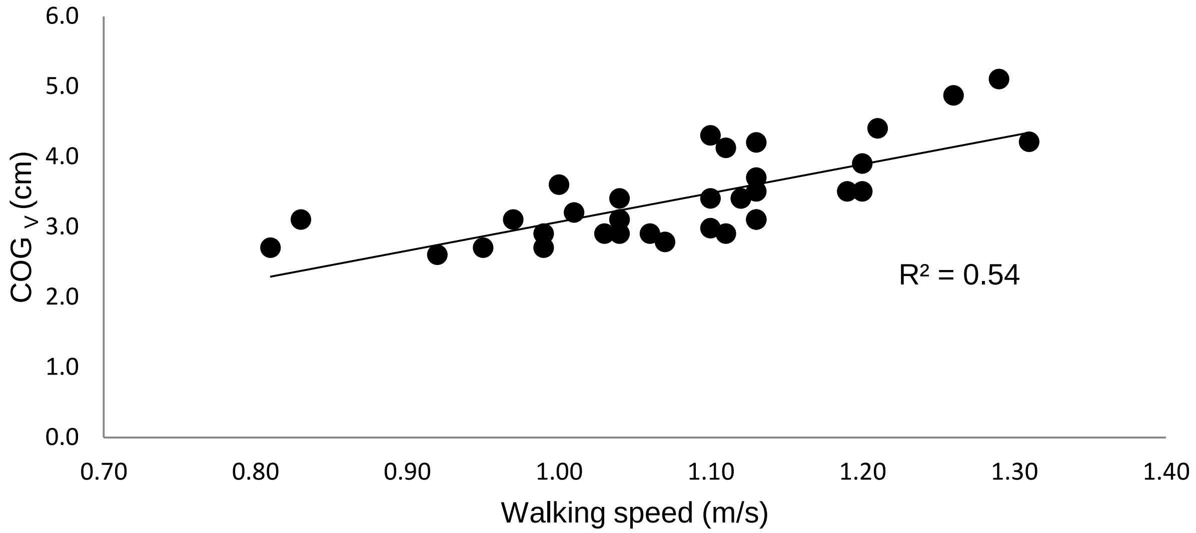

Figure 4.8: Relationship between vertical excursions of centre of gravity (cm) and speed (m/s)

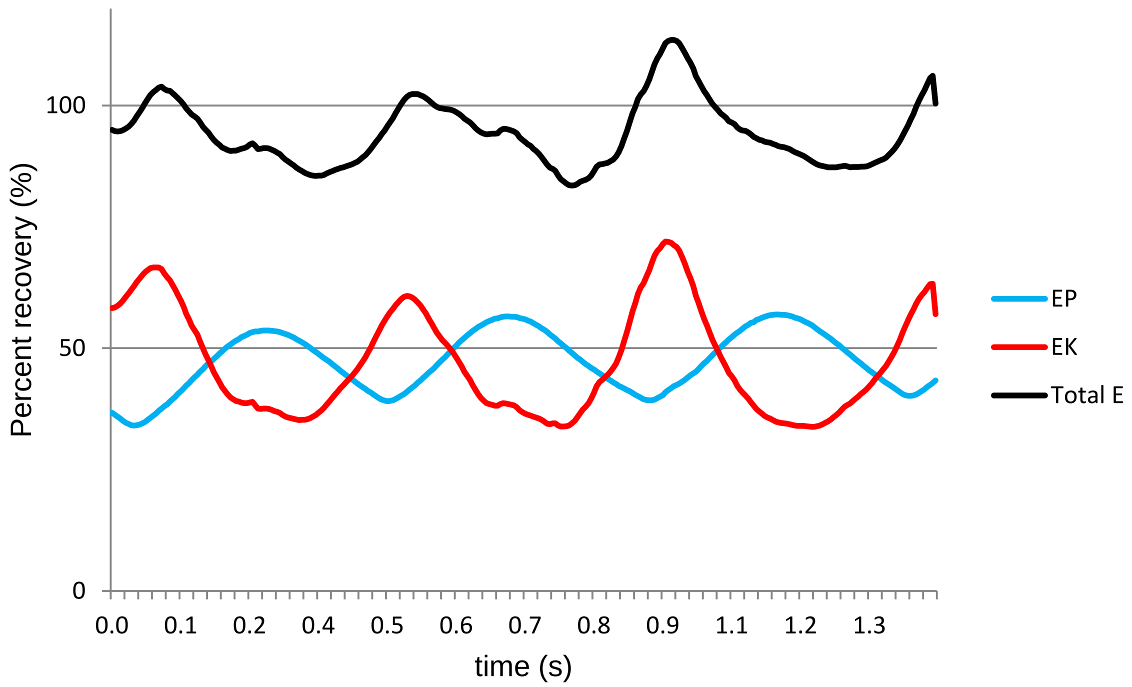

Figure 4.9: Kinetic (E_K) and potential (E_P) energy exchange during the 3rd trimester resulting in an average recovery factor R = 55.9 ± 4.1%

4.3.5 The relationship between gait kinematics with postural deviations and balance during walking in pregnancy

Results from the multiple regression to predict COP/COG inclination angle from step width, step length, and relative weight gain (Table 4.14), indicates that these variables statistically significantly predicted gross COP/COG inclination angle $F(2, 32) = 9.267$, $p < 0.001$, $R^2 = 0.47$. Shapiro-Wilk test showed normal distribution for standardized residual ($p = 0.64$), and there was no interaction between predictor variables. The step length, step width, and relative weight gain, accounted for 47% of variation in COP/COG inclination angle. The post-hoc power analysis with effect size of 0.89 (determined from adjusted $R^2 = 0.47$), at $\alpha = 0.05$, and 3 predictors was 1.0.

Table 4.14: The result of multiple linear regression analysis of COP/COG medio-lateral inclination angle with weight gain, step length and step width as predictors

COG/COP θ_{FT} (deg)	**Standardized Coefficients, β**	**Sig.**	**95.0% Confidence Interval***	**R**	**Adjusted R^2**
Constant		0.000	3.36 - 7.21		
Step width (% ll)	0.12	0.38	-4.40 - 11.16	0.69[a]	0.47
Stride length (% ll)	-0.25	0.07	-5.01 – 0.25		
Δ W (kg)	0.52	0.001	0.02 – 0.08		

a. Predictors: Step width, Stride length, Δ W

* unstandardized coefficient

Table 4.15 demonstrates the partial correlations between gait kinematics and posture and balance adjusted for the weeks of pregnancy. Similarly to COP/COG_{ML}, hyperextension of the back (Trunk $\theta_{SG\ static}$) had a strong significant correlation with the changes in weight ($r = 0.87$, $p \leq 0.001$). In contrast, controlling for weeks of pregnancy yields no significant relationship between anterior-posterior trunk lean and the absolute weight ($r = 0.24$, $p = 0.46$). Additional, analysis of variance showed that the significant portion of variance in COG_{ML} is explained by weight gain ($r = 0.53$, $p \leq 0.01$), rather than the absolute weight.

A partial correlation between stride length, step width and COP/COG inclination whilst controlling for weeks of gestation shows significant, moderate, but negative relationship between COP/COG and stride length $r = -0.44$, $n=35$, $p \leq 0.01$, and no significant relationship was noted between COP/COG and step width. Zero-order correlations show that weeks of gestation did not have significant influence between the relationships. However, partial correlation demonstrates that step width and trunk lateral lean showed strong positive relationship ($r = 0.61$, $p \leq 0.001$). Relationship of margin of stability (*b*) examined via partial correlation showed negative, moderate, but statistically significant relationship ($r = -0.33$, $p \leq 0.05$).

Table 4.15: Partial correlation analyses between posture and balance parameters, and gait kinematics and weight, adjusted for weeks of gestation

	Pelvis θ_{FT} (deg)	**Trunk θ_{FT} (deg)**	**COG/COP θ_{FT} (deg)**	***b***	**Trunk $\theta_{SG\ static}$ (deg)**
V (m/s)	r = 0.25 p = 0.15	r = 0.17 p = 0.34	r = -0.23 p = 0.18	r = -0.03 p = 0.87	This is a static condition, hence no relationship to walking
Stride length (% ll)	r = -0.02 p = 0.91	r = 0.06 p = 0.72	r = -0.44 p ≤ 0.01	r = -0.33 p ≤ 0.05	
Step width (% ll)	r = -0.16 p = 0.37	r = 0.61 p ≤ 0.001	r = 0.26 p = 0.13	r = -0.01 p = 0.98	
DS time (s)	r = -0.64 p ≤ 0.001	r = -0.20 p = 0.26	r = 0.17 p = 0.34	r = -0.19 p =0.27	
Weight (kg)	r = 0.05 p = 0.79	r = 0.24 p = 0.17	r = 0.16 p = 0.37	r = 0.25 p = 0.20	r = 0.13 p = 0.46
Δ W (kg)	r = -0.29 p = 0.10	r = 0.15 p = 0.39	r = 0.53 p ≤ 0.01	r = 0.07 p= 0.70	r = 0.87 p ≤ 0.001

Pelvic θ_{FT} = Pelvic inclination angle in frontal plane; Trunk θ_{FT} =Trunk inclination angle in frontal plane; COG/COP θ_{FT} = centre of gravity/centre of pressure inclination angle in frontal plane; Trunk θ_{SG} static = trunk lean angle changes in sagittal plane during quiet standing; V = speed of walking; ΔW – weight gain throughout pregnancy

4.4. Summary

In summary, the results of this chapter indicate that the participants were generally overweight and borderline obese in early pregnancy. Linear regression analyses and correlation analyses revealed that the rate of weight gain rather than the absolute weight had significant impact in changes in gait kinematics, energy expenditure, and balance and posture.

Changes in gait kinematics were not significantly different between trimesters, while ground reaction forces during mid stance decreased late in pregnancy. However, while the changes in gait kinematics between trimesters were not significant, inferential analyses demonstrate that the changes in gait kinematics, specifically walking speed, may have a significant role in conserving walking energy expenditure during pregnancy via recovery factor, which depicts the increase in exchange of kinetic and potential energies with an increase in walking speed. Walking speed was also a significant factor in changes in vertical ground reaction forces.

As indicated earlier, weight gain rather than the absolute weight has a more significant impact on balance and posture during pregnancy. Expectedly, during walking step width and stride length have a significant effect on walking balance, while velocity was not related to posture or balance.

Consequently, mechanical prediction equations showed a stronger overall relationship with indirect calorimetry when REE is part of the total energy cost, although net walking cost was the strongest individual parameter associated with mechanical work.

Since REE is largely affected by the changes in metabolism and physiology of the mother during pregnancy, removing REE from gross walking energy expenditure, allows for a measurement of walking energy expenditure and cost of walking. While during pregnancy absolute energy expenditure increase, energy cost of walking decreases.

Hence, these results demonstrate the despite the lack of statistical significance in change between trimesters in majority of gait mechanics parameters as well as walking energy expenditure, there was a significant relationships between gait parameters and energy expenditure.

The results in this chapter will be discussed against the background of the current literature in Chapter 5.

CHAPTER 5 DISCUSSION

5.1 Introduction

The limited research on the changes in gait during pregnancy and the relationship between gait kinematics, kinetics, walking energy and balance and posture, provoked this study on gait in pregnancy across all trimesters. This chapter will discuss the results from the findings based on the following objectives as presented in Chapter 1: 1) to determine the relationship between gait kinematics and kinetics with walking energy expenditure during pregnancy, 2) to determine the relationship between gait kinematics, dynamic balance and posture, during pregnancy, 3) to determine the relationship between mechanical work prediction equations and indirect calorimetry in assessing changes in gait economy during pregnancy, and 4) to determine the relationship between gait energy expenditure and walking economy during pregnancy.

This is the first know study to determine comprehensive relationships between gait mechanics and walking energy expenditure, dynamic balance and posture during pregnancy, irrespective of trimester classification. The findings from this study contribute to the gap in the current literature on walking biomechanics and energy expenditure during pregnancy in a South African population, offer a new approach to analysing changes during pregnancy by considering relationships between parameters normalized for weeks of pregnancy, rather than between trimester analyses as considered in numerous previous studies, and include a comprehensive approach to examining correlations between walking, balance, and posture in pregnancy.

The aim of this Chapter is to discuss the main findings of the results in the view of the presented objectives. The baseline variables and participant demographics were discussed first, followed by the inferential analyses in the order of the objectives presented in Chapter 1. Some repetitions might occur due to the interlinking of factors obtained for the different objectives and the parameter co-dependence.

5.2 Participant characteristics

Participants' characteristics in this study closely resemble those of overall population characteristics of South Africa. In this study 74.3% of the participants were Black African, 8.6% white and 17.1% coloured. According to Statistics South Africa (2014:2.1), approximately 78.2% of women in South Africa are Black African, 10.3% white, and 9.0% coloured. Similarly, 65.1%

of the participants in this study reported to have completed grade 10 or less , while 67.5% of the female population of South Africa has completed grade 10 or less (Statistics South Africa, 2014:2.12)..

Self-reported pre-pregnancy BMI for participants in this study was 25.1 ± 5.5 kg/m^2, which according to the South African National Health and Nutrition Examination Survey (2013:140) closely resembles a national average of 26.2 kg/m^2 for women between 25 and 34 years. This could be due to a generally sedentary lifestyle of South African women, as 68.5% percent of women in South Africa are considered physically inactive with an additional 18.6% "minimally active" (South Africa Demographic and Health Survey, 2007:293). For the North West Province this percentage increases, as 74.6% of women are considered inactive with an additional 19.7% considered minimally active (South Africa Demographic and Health Survey, 2007:293). Table 4.2 indicates that there were no differences in counts per minute between trimesters; hence, the participants in this study were predominantly sedentary throughout pregnancy. A longitudinal study stemming from HAPPY project on changes in habitual physical activity throughout pregnancy shows that South African women generally have a sedentary lifestyle that does not change throughout pregnancy (van Oort, 2015:57)

While there are no known statistics on weight gain throughout pregnancy in South African population, in this study the weight gain of participants throughout pregnancy of 0.35 ± 0.2 kg/week was considered normal and within recommended international norms (Institute of Medicine of the National Academies, 2009:2). Large standard deviation in weight gain demonstrates the large variability in responses to pregnancy, at least when it comes to weight, and supports the notion of large between subject variability in studies on pregnancy (Foti *et al.,* 2000:628; Poppitt, *et al.,* 1993:353; Prentice, *et al.,* 1989:5; Wu, *et al*., 2008:1160). In this study the weight gain was not associated with the pre-pregnancy weight, nor age, but rather height of the participants. This is in agreement with more recent study by Schlaff *et al.* (2014:1128) who also found no significant relationship between pre-pregnancy weight and gestational weight gain, while the relationship with the height was not assessed. Although it may be possible that self-reported weight was not close to the actual weight, it is likely that the large variation in weight gait stems from individual differences in lifestyle, and individualized responses to pregnancy. The individual response to the rate of weight gain reflects on the women's ability to adapt to the large weight gain in a short amount of time. For example, during the third trimester, two women might have an identical weight, but a different weight gain will result in different body changes throughout pregnancy. Considering that the pre-pregnancy physical and physiological characteristics differ between women, this is the most likely source of large inter-subject variability in gait parameters during pregnancy reported across various studies. Similar weight gain between women with normal BMI compared to overweight/obese women will result in different physiological and musculoskeletal changes between women as found in this study. For example, the relative weight gain, while considered within recommended norms, has significant relationships with changes in walking kinematics, posture and balance, in contrast to the absolute weight, as it will be demonstrated later in discussion. Hence, weight gain may be a more relevant parameter than the absolute weight when examining biomechanical changes throughout pregnancy.

5.2.1 Physical activity levels and resting energy expenditure during pregnancy

The results in this study show that physical activity level was low and did not significantly change during pregnancy, 28.48 ± 6.87 counts per minute (cpm), 28.31 ± 10.24 cpm, and 26.66 ± 16.13 cpm, for the 1st, 2nd and 3rd trimester respectively. However, the physical activity level in this study is higher than that in a study by Melzer *et al*. (2009:1188) who reported 21.4 ± 10.0 cpm, for women in late 3rd trimester from Switzerland. Considering that a study by Melzer *et al*. (2009:1188) was conducted on participants in an industrialized country with predominantly Caucasian pregnant women, the larger PAL of more than 24% in the third trimester, may result from the differences between the studies' ethnic make-up of the participants (Lovejoy *et al.* 2001: 92). While differences in socio-economic status between participants in these two studies cannot be compared since Melzer *et al.* (2009:1188) did not collect socio-economic data, the differences in PAL are likely not to be related to the potential socio-economic differences between the participants (Dugas *et al.* 2011: 435), but potentially lifestyle and/or cultural differences which were not collected in this study.

Currently in literature there are no clear indications of the trend of physical activity during pregnancy, especially for this particular population. Findings in this study show that during pregnancy participants in this study were already sedentary, which is similar to the generally sedentary lifestyle of South African women (South Africa Demographic and Health Survey, 2007:293). More specifically, a longitudinal study stemming from the HAPPY-study on longitudinal changes in habitual physical activity throughout pregnancy shows that South African women generally have a sedentary lifestyle throughout pregnancy (van Oort, 2015:57). Hence, it is unlikely that any training effect took place during this study that might have induced any significant changes to the gait patterns or the metabolic energy expenditure of the participants. In addition, while counts/min have been shown to be an accurate measure of activity, especially at low or moderate intensities, compared to higher intensities (Barreira *et al*., 2009:69), any changes in physical activity while maintaining overall sedentary lifestyle, would not be significant enough to explain any changes on metabolic or musculoskeletal system (Kopp-Hoolihan, Loan, Wong, King,1999:703).

In this study, changes in resting energy expenditure was directly related to a continuous increase in weight as it accounted for 51.8% variance in REE, lower than that reported by Melzer *et al*. (2009:1185) who found that weight accounted for 70% variance in REE. However, the participants in a study by Melzer *et al*. (2009:1187) had lower pre-pregnancy BMI (21.8 kg/m^2) and were predominantly white. A study by Poppitt *et al*. (1993:363) demonstrated that African women have natural energy-sparing adaptations during pregnancy that manifests through lowering of basal metabolic rate (BMR). These findings indicate that other than weight, women have the capacity to compensate for large changes in metabolism during pregnancies that are independent of the changes in active energy expenditure (Kopp-Hoolihan *et al.,* 1999:703). These could be attributed to changes in dietary intake, pre-pregnancy malnutrition, or energy cost to synthesize new placental tissue (Byrne *et al.,* 2011:819). However, no recent studies have been found to corroborate these findings, or those specific to South African population. In this study however, although REE decreased slightly between trimesters, the difference was not statistically significant when accounted by the weight. Therefore, the changes in resting metabolism may not be large enough to reflect through changes in REE. On the other hand, resulting changes in metabolism may be reflecting on the metabolic variables such as respiratory quotient. In this study, respiratory quotient reached close to 1.0 later in pregnancy, which was a significant increase from 2nd trimester ($p = 0.05$). While this result might indicate a higher level of exertion while walking, Melzer *et al.* (2014:7) show that especially during pregnancy, the respiratory quotient is largely affected by the multiple metabolic changes in the body related to pregnancy that may not accurately reflect on the exertion level.

Hence, the percentage of variation in REE attributed to weight still leaves significant portion of variability attributed to changes in metabolic system that are not related to any gait mechanics or musculoskeletal changes as in changes in posture. Therefore, normalization of walking energy expenditure for REE should remove variability not associated with walking energy expenditure. This will be discussed in the section on walking energy expenditure.

5.3 Gait kinematics during pregnancy of South African women

Overall, the self-selected walking speed did not significantly change during pregnancy in this study, and was lower compared to the majority of studies examining energy expenditure during pregnancy, with ranges between 1.2 m/s in Foti *et al.* (2000:626) and 1.5 m/s in Byrne *et al.* (2011:822), even though one study reported walking speed as low as 0.83 m/s (Wu *et al*., 2008:1163). However, participants in these studies were predominantly Caucasian. A study by

Falola *et al*. (2009:48), reports much lower walking speed in rural African population ranging from 0.58 m/s ± 0.09 m/s in the 1st trimester, to 0.41 ± 0.08 m/s in late pregnancy. In contrast to the earlier studies, the population studied in Falola *et al*. (2009:49) are African women, living in very rural areas of underdeveloped Africa. Slow speeds of walking cannot be attributed to weight, since this population had significantly lower weight throughout pregnancy relative to the South African participants in this study, although their BMI was similar to this study ranging from 22.7± 2.2 m/kg^2 in the first trimester, to 30.7 ± 2.3 m/kg^2 in late pregnancy. Therefore, lower speeds may not be a result of the malnutrition, and are likely the result of lower stature of women studied and consequent lower stride length resulting in slower walking speed, although these parameters were not reported in the study. Additionally, this study used a pedometer for measuring gait speed, which are not valid instruments particularly at lower walking speeds (Schneider *et al.,* 2003:1782).

Changes in walking speed during pregnancy are strongly associated with the changes in stride length ($r = 0.52$, $p \leq 0.01$). These findings are similar to those found by Foti *et al*. (2000:626) and Lymbery *et al*. (2005:249) and in contrast to those by Falola *et al*. (2009:48), although discrepancy in their results can be assigned to the differences in instrumentation used to measure gait kinematics. The studies by Foti *et al*. (2000:626) and Lymbery *et al.* (2005:249) used video motion analysis systems as in this study (Vicon, Oxford Metrics Limited, Oxford, England, and Expert Vision System, Motion Analysis Corp, Santa Rosa, California, respectively), while in study by Falola *et al*. (2009:48) a simple pedometer Dista F100 Basic (Lille, France) was used which was not validated for scientific measurements. Once normalized for weeks of pregnancy, weight gain was not significantly associated with the decrease in speed. However, the decrease in walking speed during pregnancy was negatively related with the increase in weight during pregnancy($r = -0.38$, $p = 0.03$). This is most likely the result of the need for greater balance later in pregnancy by increasing the time spent in double-support stage (Carpes *et al.,* 2008:35; Lymbery *et al.,* 2005:249), which was also the case in this study ($r = -0.51$, $p \leq 0.01$). Overall, the average double support time in this study was 0.12 ± 0.04 s and did not change between trimesters. This is lower for each of the respective trimesters than the study by Carpes *et al.* (2008:35) who measured 2nd (0.14 s) and 3rd (0.15 s) trimesters. The difference is likely due to the lower weight gain later in pregnancy: in a study by Carpes *et al.* (2008:35) there was a weight loss of 11.63 kg between 2nd and 3rd trimester, whereas in this study, there was a significant ($p \leq 0.001$) weight gain of 8.5 kg between the 2nd and 3rd trimesters.

As discussed in Chapter 2, increase in weight during pregnancy changes the moment of inertia of upper body affecting balance, which would initiate the need for a more stable environment (Wu *et al.*, 2004:486). In this case women would achieve more stability by increasing double-support time, increase the step width, or both, in order to create a larger base of support (BOS). In this study, step width between trimesters was not significant; however, it has significant correlation with the posture and dynamic balance, as will be discussed later. The most likely reason for lack of increase in step width is the amount of relative weight gain, which was not sufficient to induce consequent changes in step width. That is, already overweight participants adapted to the relative weight gain.

These findings demonstrate significant relationships between kinematic variables during pregnancy that exist when relationships are determined based on the weeks of gestation and not the traditional trimesters. Previous studies that have investigated changes in gait kinematics during pregnancy are characterized by equivocal results that do not contribute to further understanding of changes in gait in this population. For example, a study by Lymbery *et al*. (2005:250) found no changes in step length or walking speed between trimesters, while Foti *et al.* (2000:630) found no changes between pregnancy and post-partum of the same parameters. On the other hand Carpes *et al.* (2008:28) found changes in step length and speed between the 1st and 2nd trimesters, but not between the 1st and 3rd or, 2nd and 3rd trimesters. The high variability in the data and previously reported studies (Foti *et al.,* 2000:628; Poppitt, *et al.,* 1993:353; Prentice, *et al.,* 1989:5; Wu, *et al.,* 2008:1160) demonstrate that these differences are more likely due to vast individual responses to pregnancy by women that should be investigated via different analyses and classification of pregnancy development. Hence, regression and correlation as used in this study, along with normalization for weeks of pregnancy rather than trimester, provide more insightful information on how changes during pregnancy reflect on walking kinematics. In addition, with large between individual difference ni gait kinemtics regression analysis using smaller sample size as in this study, was able to detect moderate to larger effect (f^2 = 0.69) with the large achieved power (0.98). Potential effect of these changes on walking energy expenditure, balance and posture is discussed next.

5.4 Walking energy expenditure during pregnancy in South African women

5.4.1 Walking energy expenditure and economy during pregnancy

While there were no significant changes between trimesters in gross and net energy expenditure, gross O_2 walking rate was significantly related to weight ($r = 0.65$, $p \leq 0.001$) and analysis of variance shows that weight accounted for 33.3% of variance in gross O_2 rate, and 10.0% by walking speed, complimenting previous studies investigating metabolic energy expenditure (Byrne *et al.*, 2011:825; Forsum, Kabir, Sadurkis, & Westerterp, 1992:338; Lof & Forsum, 2007:301; Meltzer. Schutz, Boulvain, & Kayser, 2009:1189; Van Raaij, Schonk, Vermaat-Miedeme, Peek, & Hautvast, 1990:160). However, for assessment of energy required for walking, resting energy assessment must be subtracted from the gross O_2 energy expenditure (Massaad *et al.*, 2007:791; Schwartz, 2007:494) since variation in REE especially during pregnancy, may contribute to significant unexplained variation in walking energy expenditure. The results show that REE and net O_2 energy expenditure explain over 70% of variability in gross O_2, while change in weight explained almost 52% of REE. The effect size for this analysis was also large, $f^2 = 2.57$ with the power achieved of 1.0. Therefore, almost 25% of variation in gross O_2 walking energy expenditure is accounted by variables that are not related to walking mechanics, but rather some metabolic changes occurring during pregnancy. Consequently, contribution of walking speed to walking energy expenditure during pregnancy increased from 10% to 26.1% once gross O_2 was adjusted from REE. Therefore, net O_2 expenditure, rather than gross O_2 should have more significant association with changes in gait kinematics.

Overall net and gross O_2 walking rate show positive linear relation with speed (Figure 4.1), which is independent of trimesters - metabolic walking expenditure increased with the increase in speed of walking. However, only net O_2 rate relationship with walking speed was significant, while gross O_2 was not. Reflecting on the previous discussion, lack of significance in gross O_2 most likely stems from the variability in resting energy expenditure, which is part of gross energy expenditure, and consists of various metabolic changes that cannot be attributed to the walking mechanics. However, once energy expenditure was normalized to express the walking economy, that is, the amount of energy required per distance covered (Waters & Mulroy, 1999:211), gross energy expenditure showed negative relationship with speed, indicating that there might be a related decrease in energetic cost of walking. However, this relationship with speed was not significant. In contrast, while relationship of net O_2 rate was significant with walking speed already, normalizing for distance covered resulted in an increased strength of the significance with the walking speed. This demonstrates that net O_2 relative to the gross O_2, as a measure of walking energy economy and expenditure is more resilient to changes not associated with walking mechanics. Considering that changes in walking speed throughout pregnancy are still equivocal as discussed earlier in section 5.3, lack of walking efficiency with change in speed may be attributed to the slow self-selected walking speed of participants in this study.

While this study demonstrates linear relationship of walking energy expenditure and cost with speed, several studies have found the curvilinear relation of energy expenditure with speed (Abe *et al.,* 2008:395; Baker *et al,* 2001:205; Waters & Mulroy, 1999:211). The study by Abe *et al.* (2008:395) related to load carrying (on the back) participants, and found that walking energy expenditure lowers with increases in speed, and reaches lowest walking energy at 1.17 m/s after which energy expenditure increases with increase in speed. On the other hand, studies by Baker *et al.* (2001:205) and Waters and Mulroy (1999:211) found that in normal populations, this transition occurs at much higher velocities of 1.67 m/s, whereas below these speeds, linear relationship shows significantly better fit (Baker *et al,* 2001:205; Waters & Mulroy, 1999:211). Other studies have also reported reduction in walking speed during pregnancy ranging between 5.6% (Lymbery *et al.,* 2005:250) and as much as 11% (Forczek, & Staszkiewicz, 2012:113). Therefore, linear fit in this study is possibly the result of generally lower walking speeds than those in studies mentioned, although those studies have been conducted on non-pregnant population, and included males. In addition, considering that highest walking speeds in this study was during second trimester of 1.11± 0.11 m/s, it is still lower than that reported of Abe *et al.* (2008:395) that showed increase in walking efficiency at 1.17 m/s.

The ability to increase walking efficiency indicates that there is a conservation of mechanical energy during walking that is maximized at certain speeds, which, relative to previous studies, participants in this study did not reach. The principle of conservation of energy is based on vertical displacement of COM as the primary factor, and as discussed in Chapter 2, allows for the exchange of E_k and E_p that COM possesses as it follows the sinusoidal curve during walking. According to the earlier studies, minimizing vertical displacement of COM preserved energy cost due to less muscular work needed to lift the COM (Saunders *et al.,* 1953:550, Waters & Mulroy, 1999:208). But, an alternative view demonstrates that while increasing the vertical displacement increases muscular work, exchange of energy proposed by the inverted pendulum gait model allows conservation of energy which is considerably larger than the increased cost of the muscular work (Ortega & Farley, 2005:2105; Massaad *et al.,* 2007:797; Tesio, *et al.*, 1998:80; Willems *et al.,* 1995:388). That is, larger the vertical displacement of the COG, greater the recovery of mechanical energy.

In this study, speed is strongly correlated with the vertical displacement of COG (r = 64, $p \leq 0.001$) (Figure 4.8), which allows for greater energy exchange, resulting in a greater energy recovery (Figure 4.7) (Cavagna & Kaneko, 1977:475, Ortega & Farley, 2005:2105, Tesio *et al.*, 1998:80, Willems *et al.,* 1995:388). Energy recovery in this study was 56.90 ± 3.24%, at an average speed of 1.08 ± 0.12 m/s, while maximum practical energy recovery is above 60% and has been shown to occur at velocities of 1.4 m/s and higher, relative to participants investigated (Cavagna & Kaneko, 1977:475; Detrembleur, *et al.*, 2003:49; Massaad, *et al.,* 2007:792; Ortega & Farley, 2005:2105). Therefore, while women during pregnancy may reduce mechanical energy cost by improving on energy recovery with an increase in speed of walking, this would also result in the increased gross metabolic cost. However, due to general high inter-subject variability during pregnancy, women may also achieve "individualized" pendulum-like mechanism by varying patterns of motion of body segments (Detrembleuer *et al.,* 2003:54). Cavagna *et al.* (2002:3421) have demonstrated that African women exploit the pendulum-type exchange better than the European women, and while not present in pregnancy, efficient utilization of this model has been shown in African women with the tradition of carrying head loads (Heglund, *et al.,* 1995:52). It seems that pregnancy is characterized by a more "valuable load", and as such efficiency has to be combined with safety, and while it may increase the mechanical energy, women may tend to find a strategy that helps them maintain the rate of energy expenditure at a level that could be sustained for a long time, which is also a strategy adopted by pathological walking (Detremblauer *et al.,* 2003:54).

5.4.2 Dynamic balance, posture and walking energy expenditure during pregnancy

Much like comfortable step length or speed, people also have preferred step width which is also related to minimizing metabolic energy cost (Donelan *et al.,* 2001:1985; Kuo, 1999:918), as anything outside of the preferred step width would result in increase of metabolic energy cost (Donelan *et al.,* 2001:1990). In pregnancy however, the increase in preferred step width in late pregnancy is to promote balance (Jang *et al*., 2008:469; Lymbery *et al.*, 2005:250; McCrory *et al*., 2011:526). In this study, as the step width increased so did the COP/COG inclination angle ($r = 0.36$, $p \leq 0.05$), which is a result of the increased medio-lateral foot placement (Donelan *et al*., 2004:834), in order to stabilize the lateral movement of the COM. While pelvic width increases throughout pregnancy as a result of foetal growth, inclination angle is a reflection of the balance control mechanism (Kuo, 1999:924). Step width was simply measured during double-support stage, while balance control occurs during single stance, where inclination angle, ground-reaction force during loading (GRF_{MS}), and centre of pressure may be used to assess the balance control. However, this strategy of promoting balance may lead to the increased energy rate of walking (Wu *et al*., 2004:486).

First, the work of the active movement of the legs to adjust the medio-lateral foot placement (Donelan *et al*., 2001:1989), and second, the mechanical work to redirect the COM between steps, per step-to-step transition cost principle (Donelan, *et al.*, 2002:3725). The work to adjust the medio-lateral foot placement has already been demonstrated earlier in discussion – the step width increased was significantly related to the COP/COG inclination angle ($r = 0.36$, $p \leq 0.05$), while lateral trunk deviation during walking was also significantly related to the step width ($r = 0.61$, $p \leq 0.001$). Hence, step width has a multidimensional effect, and during pregnancy it is affected by pelvic width, and the inclination angle (Kuo, 1999:924) and is an indication of changes in balance, which is widely documented in pregnancy (Foti *et al.*, 2000:628; Jang *et al*., 2008:474; Lymbery *et al.*, 2005:250; McCrory *et al*., 2011:526).

Second, the step-to-step transition increases metabolic cost as this requires muscular work to vertically redirect the COM at the end of the double-support stage (Donelan *et al.,* 2002:3725). This was also shown earlier in discussion as walking velocity and energy recovery were significantly related to the vertical excursion of the COM. Therefore, the same muscular work should be considered to redirect the COM in a medio-lateral direction (Donelan *et al.,* 2001:1991), which is directly related to the step width, as demonstrated in this study. Hence, if the goal of pregnancy was to minimize the energy cost via reduction of active energy cost, the trade-off between minimizing the cost to redirect the COM and the cost of the lateral balance may determine the preferred step width during pregnancy that would reduce the energy cost.

Furthermore, the results in this study also show that the majority of variance in COG/COP inclination angle during walking was accounted for by weight gain during pregnancy ($p \leq 0.001$). That is, women with relatively larger weight gain relied on a larger BOS during walking, which, as discussed previously leads to an increase in mechanical work. In frontal plane, pelvic tilt relies on the adductor muscle, of which the moment arm is the distance of COG to the hip joint centre. Hence, when the upper body moment increases due to increase in weight and specific weight distribution as in late pregnancy, a larger demand is placed on the adductor muscles to prevent pelvic collapse. If the musculature is unable to support the additional load, the compensatory mechanism includes trunk lateral lean towards the supporting leg in order to move the COG closer to the joint axis of rotation, and over the base of support, shortening the moment arm of the adductor muscle (Hoff, 2008:113). In this study, this effect is demonstrated by the increase in lateral deviation of centre of gravity (COG_{ML}) by means of increase in the lateral trunk lean, as the COG/COP inclination angle increases - women during pregnancy tend to lean towards the supportive leg in order to minimize the moment arm, which would affect lateral postural deviations. This would in turn contribute to larger side-to-side movements of the COG, resulting in the increase in the energy cost as discussed earlier. The resulting effect is most likely instigated by the step width as indicated earlier. As the step width increased to promote stability, COG/COP inclination angle increased as well ($r = 0.36$, $p \leq 0.05$), which resulted in related frontal trunk deviations ($r = 0.62$, $p \leq 0.001$) (Table 4.14). Considering that the area of BOS is a function of step length and step width, it is expected for step length and step width to be significantly correlated with the COP/COG inclination angle as demonstrated in this study ($r = -0.44$, $p \leq 0.01$ and $r = 0.36$, $p \leq 0.05$, respectively).

The dynamic assessment of balance and postural control examined in this study has not been documented before in South African women. However, in similar studies balance during pregnancy has been largely examined by means of anterior-posterior and medio-lateral postural sway during steady quiet standing (Butler *et al.,* 2006:1104; Inanir et al., 2014:1122; Jang *et al.,* 2008:468; McCrory *et al.* 2010:2434; Okanishi *et al.*, 2012:856; Ponnapula & Boberg, 2010:456; Ribas & Guirro, 2007:391). While these studies agree on the need for increased balance during pregnancy, no further conclusion can be drawn on the balance adaptations during walking, and the metabolic cost at which this can be accomplished. Also, in the study of McCrory *et al.* (2010:2435) stability is assessed by varying stability of the platform via the resistance force applied to the platform, which would provide more specific information on the ankle joint movements. In this case, anterior-posterior trunk deviations would largely impact ability to balance, while during walking this is not the case. Hence, standing balance assessment may not address all the means by which stability may be attained in dynamic conditions such as walking, as changes in gait kinematics may also be used to provide stable environment. The results in this study are the first known to address this relationship, and offer insight into the potential preferred trade-off mechanisms during pregnancy. Further normalization for balance improvement may also determine what increase in step-width results in increased balance at the minimal energy cost. .

All of the changes discussed earlier demonstrate postural adaptations resulting from pelvic and trunk deviations in sagittal plane. Previous research based on general postural changes during pregnancy identified consistent presence of lumbar lordosis, thoracic kyphosis, upper body tilt, and sagittal pelvic tilt throughout pregnancy though in different magnitudes and with large inter-subject variability (Bullock *et al.,*1987:16; Foti *et al.*, 2000:632; Okanishi *et al.*, 2012:856; Ponnapula & Boberg, 2010:457). In this study, results are similar and demonstrate that weight gain rather than the weight were strongly associated with the trunk inclination angle in the frontal plane ($r = 0.87$, $p \leq 0.001$), which may lead to kyphosis or lordosis. Therefore, women with larger weight may have already adapted their gait to their respective weight; hence, normal weight gain during pregnancy may not be large enough to induce any postural changes. Since weight does not change due to external conditions, postural changes may not be influenced by changes in gait kinematics, and there is no evidence to indicate that body perturbations adjust during walking (Okanishi *et al.*, 2012:856). Additional analyses conducted in this study revealed that trunk inclination angle in sagittal plane does not change during walking, and has no significant correlation with any gait kinematics during walking.

Hence, while lordosis and kyphosis may remain permanent changes during the period of pregnancy, the dynamic changes in trunk and pelvis frontal rotations shown in this study demonstrate an adaptive strategy that results in more balance gait, at the cost of potentially larger energetic cost of walking. In addition, postural deviations, and balance problems also may be enhanced by the low muscle strength linked to the sedentary lifestyle and low physical activity levels reported in this study (Borg-Stein *et al.*, 2005:182; Butler *et al.*, 2006:1107; Chambliss, *et al.*, 2006:989; Foti *et al.* 2000:632; Gutke *et al.*, 2008:40; Shim, *et al.*, 2007:19). These findings also demonstrate that dynamic stability measured by translational perturbation of the surface while participants stand still as in the study of McCrory *et al.* (2010:2435), relative to walking as a dynamic condition used in this study, utilizes two different methods of maintaining stability.

Overall, gait kinematics, balance and posture during pregnancy, have all been shown to be integrated into a systematic relationship that may be assessed via multifactorial relationship. All of the above discussed changes in gait kinematics and posture result in mechanical adaptations during gait that may affect the overall metabolic energy expenditure as demonstrated by the change in speed, and the relationship with vertical excursions of the COM. However, these changes may directly be assessed via measures of mechanical work, that is changes in internal (W_{int}) and external work (W_{ext}). Hence, the relationship between mechanical work during walking and metabolic energy expenditure may reveal if mechanical changes during gait are associated with the metabolic energy expenditure.

5.4.3 Mechanical and metabolic energy cost of gait during pregnancy

Principle of energy conservation that improves with an increase in speed, and results in an energy economical gait, implies a relationship between walking mechanical energy and walking metabolic energy expenditure. The principles of mechanical work may be used to measure the energy cost of segmental changes during walking, and specifically identify largest contribution to energy expenditure as a result of changes in gait during pregnancy.

To address possible variations in gait kinematics of body segments, the mechanical work in this study was analysed with gross and net O_2 energy expenditure, and also normalized for speed, to determine the relationship with walking efficiency (Water & Mulroy, 1999:208), as mentioned earlier. All three measures of mechanical work significantly correlated with metabolic energy expenditure, in different capacities though. Notably, the gross metabolic rate showed strongest correlation with W_{int}, while the relationship with W_{ext} is significant, but somewhat weaker (Figure 4.5). Net O_2 rate also demonstrate strong positive relationship with W_{int} and W_{ext} (Figure 4.3), although it was relatively weaker than that of gross O_2. However, once the absolute energy expenditure was normalized for distance covered to express energy cost and the indication of walking efficiency (Schwartz *et al.,* 2006:16, Water & Mulroy, 1999:208), the correlation improved (R^2 = 0.25; p ≤ 0.01) for W_{tot}, (R^2 = 0.16; p ≤ 0.01) W_{ext}, and (R^2 = 0.26, p ≤ 0.01)116.7% for W_{int}. This suggests that the normalization for resting energy expenditure, as suggested by Baker *et al.* (2001:208) and Waters and Mulroy (1999:208), does not reduce the internal consistency of data (Thomas *et al.,* 2009:619), and eliminates most of the metabolic variability due to resting energy expenditure, improving the relationship with the mechanical energy expenditure. Also significant improvement in W_{ext} is likely related to the pendulum like exchange of E_k and $E_{P,}$ since external work represents the mechanical work performed to lift the COG relative to the environment (Mian *et al.,* 2006:134).

In addition, several studies have shown that a non-linear relationship exists between step width and metabolic load (Donelan, *et al.,*2001:1991; IJmker *et al*., 2013:2109; Kuo, 1999:918) as a result of which, for the same average step width, variability in medio-lateral foot placement will increase the average step-to-step transition cost (Donelan, *et al.*, 2004:8280). Consequently this will have the largest impact in populations that prefer wider steps, as in pregnancy or clinical gait, resulting in misleading estimates of mechanical work and recovery. Considering that step width was not associated with metabolic load or mechanical work during walking in this study, it could lead to misleading estimates of mechanical work.

This is an inherent limitation of a two-limb model for estimating external work (Cavagna, 1975:176), as an increase in positive and decrease in negative work occurs simultaneously during the double-stance phase which is not accounted for in the external work (Donelan, *et al.,* 2001:1991). Hence this variability will add to the metabolic, but not mechanical, external or total work (IJmker *et al.*, 2013:2109). It is well documented that the co-contractions contribute to the energy cost of the pathological gait, as in cerebral palsy of hemiparatic walking (Olney *et al.,* 1990:433; Schwartz, 2001:264; Unnithan *et al*., 1996:1502), and when performed against static load do not result in mechanical work (Olney *et al*., 1990:433), resulting in the underestimation of the true cost. A study by Mian *et al.* (2006:135) has also expanded the findings onto the older populations. While classification of gait during pregnancy as clinical gait has not been investigated, the findings of previous studies, and gait alterations occurring during pregnancy reported in this and previous studies, may warrant a more investigative look into this notion.

Further, when considering step-to-step transition cost as reported in the study of Donelan *et al*. (2002:3724), muscle work necessary to support the body weight, or muscle work necessary to control stability, both contribute to the metabolic costs, but are not accounted for in the mechanical model. On the other hand, Byrne *et al.* (2011:819) indicate that during pregnancy most metabolic measures also do not account for changes in dietary intake, pre-pregnancy malnutrition, or energy cost to synthesize new placental tissue. Therefore, while mechanical work shows significant relationship to metabolic energy cost, the moderate relationship with the net energy expenditure indicates that it is only true as a result of dominant biomechanical principles underlying the relationship between metabolic cost and mechanical work, common to general gait.

5.5 Ground-reaction forces during pregnancy

The link between gait kinematics, balance, and energy expenditure can further be expanded from the dynamic interactions between the legs and the ground. Diminished balance later in pregnancy is a result of unique weight gain and weight distribution during pregnancy (Jang *et al*., 2008:469; Lymbery *et al.*, 2005:250; McCrory *et al*., 2011:526). With an increase in weight, the ground-reaction force would also proportionally increase given that gait mechanics remain unchanged (Castro *et al.,* 2013:506, Simpson *et al.* 2012:484). This would reflect on the larger reaction impulses transferring to the body. When normalized for weight, vertical ground-reaction forces in this study were similar to that previously reported (McCrory *et al.,* 2011:527) for the 2nd trimester of 1.08 ± 0.07 BWs for $GRF_{HS,}$ 1.08 ± 0.05 BWs for GRF_{TO}, and 0.94 ± 0.06 BWs for GRF_{MS}; and for the 3rd trimester (Lymbery, *et al*., 2005:250; McCrory *et al.,* 2011:527) of 1.03 ± 0.06 BWs for GRF_{HS}, 1.05 ± 0.07 BWs for GRF_{TO}, and 0.74 ± 0.03 BWs for GRF_{MS}.

In this study our results indicated that women tend to minimize the impact of GRFs by slowing walking speed although the differences between trimesters were not statistically significant. Lower walking speed may result in "softer landing" during heel strike - $GRF_{HS,}$ and GRF_{MS} were significantly lowered (4.7% and 21.3 % respectively) later in pregnancy, even after the largest weight gain. Reduction in vertical GRF in walking may be obtained by lowering speed by virtue of relationship of force to velocity and mass, or by knee-ankle mechanism: faster plantar flexion during heel strike would result in the earlier knee flexion, absorbing the peak force with negative muscular work (Derrick, 2004:835; Gard & Childress, 2001:65; McCrory *et al.*, 2011:527; Lymbery & Gilleard, 2005:251; Saunders *et al.,* 1953:551; Waters & Mulroy, 1999:215). The results in this study show that both methods might have been used by the participants in this study. Speed had a significant correlation with the vertical reaction force during heel strike ($r = 0.49$, $p \leq 0.01$), mid-stance ($r = 0.34$, $p \leq 0.05$), and during toe-off ($r = 0.34$, $p \leq 0.05$). These results are partially in agreement with those of McCrory *et al.* (2011:527) who also found the speed to be a covariate in breaking ground-reaction peaks. Hence, lowering velocity in the late trimester would result in lowering the reaction forces to the body, but moderate relationship shows possibility of additional mechanism for absorbing the peak reaction forces, or the significant contribution of the large inter-subject variability.

Ground reaction forces may also demonstrate the relationship with the vertical excursion of the COM, which, as discussed earlier, is a determinant of energy recovery during walking. The reduction of vertical COM resulting in “flatter” path would reduce the energy recovered, decreasing walking economy and consequently increasing walking energy expenditure. The results of this study demonstrate that the vertical deviation of the COM significantly correlated with GRF_{HS} peak ($r = 0.50$, $p \leq 0.01$), the vertical GRF during toe-off ($r = 0.37$, $p \leq 0.05$) and the vertical reaction force during loading stage ($r = 0.38$, $p \leq 0.05$). While these results demonstrate association of vertical ground reaction forces with changes in COM, it is not likely that women use this strategy as is the primary mechanism for energy conservation, but rather than the result of the changes with walking speed which has been demonstrated earlier. Changing vertical excursion of COM would require negative muscle work without the momentum, which would significantly contribute to the energetic cost (Neptune *et al*., 2004:823). Therefore this mechanism is highly impractical given that knee flexion in the stance phase of walking is a factor of an eccentric contraction, and as a result much work would have to be done to support the knee flexion in stance. Hence this might be a trade-off mechanism, where conservation of energy occurring as a result of the horizontal path of the COGwb, is relative to the muscular work done during knee flexion in stance. The clear evidence for this hypothesis cannot be found in literature, and in contrast, some studies (Gard & Childress, 1997:236; Kerrigan, Della, Marciello, & Riley, 200:1078; Childress & Gild, 1997:161) indicate minimal contribution of the knee flexion in stance to vertical movement of the body, and rather speculate this mechanism’s contribution to the absorption of the GRF. In addition, multiple studies have demonstrated no differences in knee flexion during stance phase in late pregnancy and post-partum (Forczek & Staszkiewicz, 2012:117; Foti *et al.,* 2000:627). In addition, Kim and Park (2012:331) demonstrate that the balance between push-off and heel-strike energies is a better indicator of the efficient oscillatory behaviour of the COM. In this study, this relationship has also been demonstrated - vertical GRF_{HS} was significantly associated with the changes in push-off vertical peak (GRF_{TO}) ($r = 0.35$, $p \leq 0.05$). With increased weight later in pregnancy, the energy saving becomes less important as the weight changes become less abrupt and, absorbing force could be a trade-off mechanism. Studies indicating no significant changes in vertical GRF (McCrory, Chambers, Daftary, & Redfern, 2011:527; Lymbery & Gilleard, 2005:251) late in pregnancy might be indicative of this mechanism. Earlier during pregnancy, while the weight gain is still not maximal, control of the vertical displacement rather than shock absorption might be a trade-off in some individuals. Therefore, lowering velocity is a common kinematic change in an attempt to minimize walking effort during walking, and is a more likely method to reduce the reaction forces, while knee flexion during heel strike and single support would rely on significant muscular work, which during pregnancy is very unlikely.

5.6 Summary

An interlink between gait kinematics, balance, energy expenditure and posture exist. Based on the results weight gain during pregnancy, rather than absolute weight had a significant impact on gait kinematics, balance, and posture, and contribute significantly to variation in energy expenditure. Although no significant changes between trimesters were found in majority of gait kinematic parameters, significant relationships were found when adjusting for weeks of pregnancy. These results demonstrate that onset of changes in parameters investigated during pregnancy resulting from relative weight gain may not occur at the specific trimester classification, but rather at an individual level and should be investigated with larger frequency. This is most likely the reason for large inter-subject variability in studies on pregnancy. As a result of weight gain, there is a decrease in walking speed, and increase in step width, which is required for increased stability. Adjusting step width for more stable and controlled gait, results in consequent lateral and vertical deviation of the COM. As discussed, changes in vertical and lateral deviations lead to changes in energy exchange via principle of energy conservation. The changes in walking mechanics are addressed with changes in mechanical work which is significantly correlated with the metabolic energy expenditure in pregnancy.

The final conclusion of the study based on the results and the discussion, will be presented in Chapter 6.

CHAPTER 6 SUMMARY, CONCLUSION, LIMITATIONS AND RECOMMENDATIONS

6.1 Summary

During pregnancy, women undergo significant physiological changes that manifest in the form of biomechanical and metabolic adaptations. The specific adaptations are relative to the individual's ability to adapt to an energy-efficient movement and limiting the risk of falling. While the majority of current pregnancy-related research investigates topics such as energy expenditure, physical activity, posture, and gait, independently, the above adaptations occurring during pregnancy are closely linked to each other and should be investigated in relationship to each other. This is the first known study to investigate the comprehensive relationship between gait mechanics, dynamic balance and posture, and walking energy expenditure during pregnancy in South African women. In Chapter 1 of the thesis the problem statement introduced the lack of research concerning the interrelationship between gait parameters during pregnancy in the face of continuous weight gain. This resulted in the following research question to be answered by this study: What is the relationship between various gait biomechanical parameters and energy expenditure during pregnancy? Based on the research question the objectives and hypotheses for the research was developed and presented, together with the conceptualisation of the study with regards to the larger HAPPY-study.

In Chapter 2, the literature review on gait during pregnancy demonstrated that gait adaptations during pregnancy are biomechanical changes for improved balance, and general comfort, which may however, result in an increase in walking energy expenditure. Considering, that mechanical changes in gait may reflect on the measures of internal and external work, analysing the relationship between mechanical work and metabolic energy expenditure during walking, may provide an understanding of potential energy conservation mechanisms during walking in pregnancy. However, during pregnancy, physical changes and their manifestation are vast, and with high inter-subject variability. Studies on pregnancy assume that changes during pregnancy occur at the same phase of pregnancy in all women, and consequently base their research methodology on the trimester classification. Trimester of pregnancy is considered as categorical data in many studies, rather than continuous data. This may result in exclusion of changes during pregnancy occurring before or after the trimester classification, which is likely to miss individual responses to pregnancy.

Investigating patterns of change in gait biomechanics and energy expenditure, via relationship to numerous physiological and physical changes occurring during pregnancy may assist medical practitioners and researchers in determining how physiological changes, not only in pregnancy but also in clinical populations, affect gait biomechanics, and consequently alter the total energy expenditure during walking.

Chapter 3 described the research methodology behind the observational cross-section design, and the measurements performed during the study to answer the above research question. Thirty-five predominantly black South African women, averaging 27.5 years of age, volunteered for the study. Their measures were taken in each trimester of pregnancy distributed as follows: first trimester (9-12 weeks), second trimester (20-22 weeks), third trimester (28-32 weeks) and three months postpartum. Weeks of gestation was recorded in conjunction with the trimester of pregnancy. All participants were only measured once. Gait analysis was assessed using 3-D motion analysis, gait energy expenditure with indirect calorimetry, while habitual daily activity patterns were assessed with combined heart rate and accelerometry (Actiheart®).

The results in Chapter 4 based on the methods, firstly present the descriptive data for each of the parameters measured, starting with anthropometric parameters, followed by gait mechanics, dynamic balance and posture, and walking energy expenditure. Section on inferential analyses, presents the relationships directly related to the objectives of the study.

Discussion presented in Chapter 5 demonstrates that women during pregnancy prefer a gait pattern that can be sustained the longest, rather than to conserve walking energy expenditure. The gait pattern changes are individualized and mostly independent of trimester progress. As a result, mechanical work prediction equations that showed significant, moderate-to-strong correlation with the metabolic energy expenditure indicate that mechanical work may be used for analysing changes in gait during pregnancy.

6.2 Conclusion

Based on the results obtained in this study the conclusion will be presented based on the hypotheses presented in Chapter 1:

Hypothesis 1:

A significant positive relationship will exist between gait kinematics and kinetics with walking energy expenditure during pregnancy in South African women.

Gross walking energy expenditure did not show a significant relationship with walking speed ($r = -0.04$, $p = 0.84$). However, when normalized for REE, net walking energy rate and net walking energy cost demonstrated strong positive relationship with walking speed ($r = 0.70$, $p \leq 0.001$ and $r = 0.53$, $p \leq 0.001$, respectively). Vertical displacement of COG (COG_v) showed significant positive correlation with net O_2 rate ($r = 0.45$, $p \leq 0.01$), and a significant inverse relationship with the internal work ($r = -0.34$, $p \leq 0.05$). While no other gait kinematic variables demonstrated significant relationship with walking energy expenditure, walking speed and COG_v demonstrated significant relationships that warrant further investigation. Therefore, this hypothesis is **partially accepted.**

***Hypothesis 2*:**

A significant positive relationship will exist between gait kinematics and dynamic balance and posture during pregnancy in South African women.

Step length, and step width, adjusted for leg length, significantly accounted for 47% of variation in COP/COG angle variability, however, only step length was significantly correlated with the COP/COG inclination angle $r(32) = -0.44$, n=35, $p \leq 0.01$. However, step width showed strong significant positive correlation with lateral trunk lean ($r = 0.61$, $p \leq 0.001$) during walking. Margin of stability (*b*) demonstrated significant inverse relationship with stride length ($r = -0.33$, $p \leq 0.05$). Therefore, from these results it can be stated that the gait kinematics do have a significant relationship with dynamic balance and posture. Hence, this hypothesis is ***accepted.***

Hypothesis 3:

A significant positive relationship will exist between mechanical work prediction equations and indirect calorimetry of gait economy during pregnancy in South African women.

Prediction equations for net walking energy expenditure during pregnancy depict weak, but positive, significant relationship with external work (W_{ext}) $r(32) = 0.35$, n=35, $p \leq 0.05$, internal work (W_{int}) $r(32) = 0.35$, n=35, $p \leq 0.05$,and total work (W_{tot}) $r(32) = 0.40$, n=35, $p \leq 0.05$, when controlled for weeks of gestation. Normalizing net energy expenditure for distance covered improved the correlation to moderate-to-strong with external work (W_{ext}) $r(32) = 0.44$, n=35, $p \leq 0.01$,, internal work (W_{int}) $r(32) = 0.51$, n=35, $p \leq 0.01$, and total work (W_{tot}) $r(32) = 0.53$, n=35, $p \leq 0.001$.

However, gross walking energy expenditure demonstrated strong positive correlation with W_{ext} r(32) = 0.48, n=35, p ≤ 0.01, W_{int} r(32) = 0.67, n=35, p ≤ 0.001, and W_{tot} r(32) = 0.60, n=35, p ≤ 0.001. Yet, the strongest relationship was demonstrated when gross O_2 was normalized for distance covered, and related to W_{int} r(32) = 0.82, n=35, p ≤ 0.001, although strong positive relationship was also demonstrated with W_{ext} r(32) = 0.47, n=35, p ≤ 0.01, and W_{tot} r(32) = 0.67, n=35, p ≤ 0.001. Based on these results, this hypothesis is ***accepted***.

Hypothesis 4:

A significant negative relationship will exist between gait energy expenditure and walking economy during pregnancy in South African women.

The gross and net O_2 rate demonstrated strong, significant positive correlation with gross and net O_2 cost, r(32) = 0.87, n=35, p ≤ 0.001, and r(32) = 0.97, n=35, p ≤ 0.001 respectively. Furthermore, while no significant correlation was noted between gross O_2 rate and cost with walking speed, net O_2 rate showed strong, significant positive correlation with walking speed, r(32) = 0.70, n=35, p ≤ 0.001, which was not influenced by weeks of gestation. While walking economy may improve at higher walking speed where energy recovery is greater, walking speed during pregnancy is not fast enough to induce that mechanism. Based on the above findings, the hypothesis is ***rejected***.

Overall, weight gait during pregnancy seem to be a leading cause to changes in gait kinematics and dynamic posture, which are reflected on the ground reaction forces. Changes in reaction forces manifest through relationship with changes in posture and subsequently changes in anterior-posterior and vertical movement of the COG. Relationship of excursions of COG has also been demonstrated to affect energy recovery mechanism, which has the potential to improve the walking efficiency, however, at the speeds that are generally not seen during pregnancy. The effect of these changes on gait expenditure is evident through the relationship of mechanical work and indirect calorimetry. Changes in gait kinematics and kinetics are assessed via internal and external work, which is shown to significantly correlate with the metabolic energy expenditure. Therefore, there are significant relationships that occur during pregnancy between, gait kinematics, kinetics, and dynamic posture and balance that result in increased walking energy expenditure.

As a result of these findings, the answer(s) to the research question(s) presented in Chapter 1 may be presented as follows.

Changes in gait kinematics during pregnancy, primarily the walking speed, increase in step width, and excursions of COG, were adaptations directly associated with the changes in weight, and the weight distribution. However, since the rate of weight gain is different between participants, the change in gait kinematics resulted from two distinct variables – relative weight gain and the consequent change in pelvic, and trunk lateral tilt as measures posture during walking, as well anterior-posterior trunk tilt during quiet standing. Hence, women who were not accustomed to larger weight displayed more drastic changes in posture than those with a smaller percentage of weight gained.

Lateral trunk movement was more prominent during walking. In dynamic conditions (walking), lateral trunk tilt was initiated in order to improve balance. Movement of the trunk towards the support leg, reduces the moment arm between COG and COP, and improves stability. Therefore, while the step width improves stability during double-support stage of walking, stability during single stance, a much longer stage was accomplished by utilizing increased moment of inertia of the upper body to reduce the distance between the base of support and the COG. Subsequently, any postural deviations during walking were associated with excursions of the COG.

Resulting kinematic changes in gait and upper body segments are assessed primarily with mechanical work. Economy of gait may be assessed via changes in vertical excursions of COG, as it directly relates to the conservation of energy. However, walking speed during pregnancy is slow, and does not create large amplitude in vertical excursions of the COG to induce energy conservation. Hence walking economy during pregnancy may be low due to low walking speed.

Significant correlation between mechanical work and indirect calorimetry demonstrates that these mechanical changes reflect on walking metabolic energy, and mechanical work may be used to assess how potential changes during pregnancy may lead to altered gait, posture, balance and consequent energy expenditure.

This is the first known study on pregnancy, and in South African women in particular, to comprehensively investigate the changes in gait, balance, posture and energy expenditure during pregnancy. These findings have significant practical, and research applications. Firstly, medical practitioners, physical therapists may use the information from this study to critically assess their clients during pregnancy, identify changes occurring, and predict potential outcomes. These resources may be used preventatively to educate new mothers on changes that may occur as a result of their pregnancy, and steps that may be taken to counteract any negative effects. For example, if the relative weight gain during pregnancy seems large, according to the results of this study, the large relative weight gain might induce large changes in posture, leading to large side to side movement of trunk during walking, increasing overall energy expenditure. Consequently, a physician or a qualified therapist may prescribe specific exercises to strengthen the core and postural muscles, reducing the effect of a relatively large weight gain. From the research stand point, this study demonstrates that relationships outside of the trimester classification should be used first to determine primary factors of change in pregnancy, from which focused longitudinal studies may be designed. In addition weeks of pregnancy may be used to assess changes throughout pregnancy, rather than trimester classification which allows for large gaps in development to go unnoticed. This is also the only known study to assess the relationship of mechanical work and indirect calorimetry during pregnancy. Hence, effect of medical and rehabilitative interventions in clinical gait analyses, may be analysed via indirect calorimetry or mechanical work to express the effect of the respective intervention on the movement economy.

6.3 Limitations and recommendations

The following limitations should be noted when interpreting the results of this study:

- Small sample size. Although the study examines the relationships based on correlation and linear regression, for between trimester analyses larger sample size is required. Based on a *priori* sample size calculation for the kinematic variables ($\alpha = 0.05$, effect size = 0.50), and a variability from this data, a minimum of 49 participants per trimesters are needed for between trimester analyses. However, the post-hoc power analyses determined the sample size in this study was sufficient for regression analysis to detect the moderate-to-large effect size, with power achieved at 0.98 and higher. For a smaller effect size of $f^2 = 0.30$, and the power achieved of at least 0.80 with 2 predictors the sample size should have been 36, while for 3 predictors the sample size increase to 41.
- The study had large withdrawal rate, which did not allow for longitudinal tracking. Longitudinal data would allow identification of the most common changes occurring during pregnancy in the parameters investigated.
- Pre-pregnancy weight was self-reported, which is known to be under-estimated at the times. Since the self-reported weight was used to determine the weight gain in the rest of the analysis, this difference might have influenced the relationships determined. A recommendation is to use the official pre-pregnancy reports from which a better estimate of pre-pregnancy weight may be derived.

- Due to limited finding post-partum data was not collected. While the aim of the study was to investigate the changes during pregnancy, post-partum data would provide a more comprehensive outlook of the effect of pregnancy on the parameters investigated based on the time it would take to return to pre-pregnancy state.
- While there are various normalization methods for energy expenditure, only those used and validated in the studies reviewed were used in this study – REE and speed of walking. There is a significant contribution of variability in energy cost of placental development, changes in DIT, as well as differences between REE in standing vs lying down, all contributing to the variation in the gross and net O_2. Since there are no known methods for normalization of energy cost for participants during pregnancy, future studies should examine the variability in O_2 consumption due to these parameters, and determine the most reliable normalization method.

6.4 Future research

The findings from this study demonstrate various correlations between walking kinematics, energy expenditure, and postural changes that are independent of differences between the trimesters. The future studies on pregnancy, should investigate if the onset of physiological changes occurs at the same time in all women, and what factors may serve as predictors. Effect of exercise on gait mechanics should also be investigates to determine if more stability can be gained during walking, that would improve walking economy. Low back pain is common during pregnancy and may lead to altered gait. While participants in this study did not report any pain during walking, future studies should investigate how low back pain may affect gait mechanics during pregnancy, and vice versa.

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RESEARCH ARTICLE Open Access

Correlating mechanical work with energy consumption during gait throughout pregnancy

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Abstract

Background: Measures of mechanical work may be useful in evaluating efficiency of walking during pregnancy. Various adaptations in the body during pregnancy lead to altered gait, consequently contributing to the total energy cost of walking. Measures of metabolic energy expenditure may not be reliable for measuring energetic cost of gait during pregnancy as pregnancy results in numerous metabolic changes resulting from foetal development. Therefore, the aim of this study is to determine if mechanical work prediction equations correlate with the metabolic energy cost of gait during pregnancy.

Methods: Thirty-five (35) women (27.5 ± 6.1 years) gave informed consent for participation in the study at different weeks of gestation pregnancy. Gas exchange and gait data were recorded while walking at a fixed self-selected walking speed. External (W_{ext}) work was estimated assuming no energy transfer between segments, while internal work (W_{int}) assumed energy transfer between segments. Hence total energy of the body (W_{tot}) was calculated based on the segmental changes relative to the surrounding, and relative to the centre of mass of the whole body. Equations for mechanical work were correlated with net and gross O_2 rate, and O_2 cost.

Results: External, internal and total mechanical energy showed significant positive relationship with gross O_2 rate ($r = 0.48$, $r = 0.35$; and $r = 0.49$ respectively), and gross O_2 cost ($r = 0.42$; $r = 0.70$, and $r = 0.62$, respectively). In contrast, external, internal and total mechanical energy had no significant relationship with net O_2 rate ($r = 0.19$, $r = 0.24$, and $r = 0.24$, respectively). Net O_2 cost was significant related W_{ext} ($r = 0.49$) W_{int} ($r = 0.66$) and W_{tot} ($r = 0.62$). Energy recovery improved with increase in gait speed.

Conclusions: Measures of mechanical work, when adjusted for resting energy expenditure, and walking speed may be useful in comparing metabolic energy consumption between women during pregnancy, or assessment or gait changes of the same individual throughout pregnancy.

Keywords: Gait, Pregnancy, Energy expenditure, Metabolic energy, Mechanical work

Background

During pregnancy energy required for walking may increase significantly due to an increase in weight [1–3]. Hence walking, as a common activity of daily living, may contribute to an increase in total energy expenditure during pregnancy. Previous studies indicate high variability in gait during pregnancy due to pregnancy-related physical and physiological changes [4], which may result in an increase in mechanical work. The ability to predict changes in mechanical energy based on pregnancy-related adaptations to gait may provide a better understanding of energy balance during pregnancy.

Current research in pregnancy is largely focused on increased energy demands stemming from foetal development, hormonal changes, and changes in physical activity [2, 5–7]. Any increase in energy expenditure during pregnancy has been attributed largely to an increase in resting metabolic rate (RMR) [2], while any increase in the active energy expenditure (AEE) has been attributed primarily to the mass gain during pregnancy

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[1–3]. This indicates that no other factors have currently been identified that contribute to the energy cost, and that relative to mass, AEE remains unchanged throughout pregnancy. In addition, difficulties in metabolic analysis of gait during pregnancy stem mostly from the large inter-subject variability in physiological changes resulting from pregnancy [4]. These include changes in dietary-induced thermogenesis, pre-pregnancy malnutrition, or energy cost to synthesize new placental tissue.

However, studies examining gait biomechanics during pregnancy report that walking speed lowers significantly throughout pregnancy [1, 4], a behavioural change indicating that women during pregnancy are more comfortable at lower velocities. At lower velocities vertical excursions of the centre of gravity (COG) decrease, which contributes to the increase in energy expenditure [8–11]. In addition, step width tends to increase with pregnancy, a change consistent with the need for an increased balance, also an emphasis on safety, which is characterized by the change in path of the COG [12–17]. This seems to indicate a trade-off mechanism for gait during pregnancy, where women would choose to walk slower with wider steps that may result in an increase in walking energy expenditure, contributing to AEE. This notion contradicts the inherent nature of energy sparing during pregnancy [1, 18, 19]. Hence, the use of mechanical work measures would permit simplified evaluation of changes in walking patterns during pregnancy that may reduce the energy expenditure in walking during pregnancy. However, measures of mechanical work have an inherent weakness stemming from assumptions of energy transfers, relative metabolic cost of positive and negative work, stored elastic energy, captivation of antagonist muscles, and isometric work [20]. As a result, the use of mechanical power output in clinical populations tends to be equivocal. Furthermore, the application of mechanical power output on self-paced walking during pregnancy is also lacking.

Therefore, the purpose of this study was to examine the ability of total body mechanical power to explain the variability in the metabolic energy cost of self-paced walking during pregnancy in a South African cohort of women.

Methods

This study is ancillary to a larger Habitual Activity Patterns during Pregnancy (HAPPY)-study that investigated the influence of objectively determined physical activity patterns on various pregnancy parameters. Thirty-five (35) pregnant South African women at different stages of pregnancy, mean age 27 years (S.D. = 6.1) were recruited, by advertisements in the local press, the consulting rooms of local gynaecologists, and a local health clinic in Potchefstroom, North West Province, South Africa. For participation in the study, women had to be healthy, between ages 18 and 40 years, without mental or physical disability, and able to complete the test protocol. Participants were excluded from the study, if they presented with physical limitations that may prevent movement, the inability to complete test procedures, or were considered high-risk pregnancy according to ACSM guidelines [21]. The study was approved by the Human Research Ethics committee of the North-West University (NWU-0044-10-A1). Participants gave written consent for participation in the study before data collection. A translator was available in the case of language barriers. Participants were informed that they are free to withdraw from the study at any point. In addition, at the day of motion analyses testing participants were free to withdraw from this specific protocol. An opportunity to ask questions was also given.

Participants RMR was assessed using the fraction of oxygen in expired gases (Cosmed Fitmate, Italy), applying standard metabolic formulas, while energy expenditure was calculated using a fixed respiratory quotient (RQ) of 0.85 [22]. Before the Fitmate was attached, participants were laying still for 5 min on their left side, to ensure resting state. Prior to gas collection, participants were connected to the Fitmate for no longer than two (2) minutes to ensure that all dead space and any other gases are flushed prior to data collection. Following the initial 2 min preparation period, RMR gas exchange is collected for 16 min per Fitmate RMR protocol. Participants were instructed not to perform any exercise 24 h prior to testing, and fast for at least 10 h prior to the measurement. A calibration of the Fitmate was done before each participant was subjected to a measurement.

Walking energy expenditure was measured using portable $K4b^2$ (Cosmed, Italy) system. Prior to each measure, the system was calibrated for O_2 concentration, gas volume and delay, according to the manufacturer's recommendations. Participants walked at a self-selected pace along a 30-m oval track in the laboratory until steady state was reached. Steady state was considered by HR variation of being no more than ±3 bpm, and less than 5 % variation of RQ [23], during which RQ of less than ≤ 0.99 has to be maintained (indicative of still using oxidative system, and not reaching fatigue state) [24]. Walking metabolic rate was averaged for the full minute the steady state was reached. Although participants were instructed to rest at any point if they felt tired before reaching steady state, no participant exercised this option. All the parameters were collected at 2-s intervals. The following parameters were extracted: walking volume of oxygen (VO_2), respiratory quotient (RQ), resting metabolic rate (RMR) (kcal/day), heart rate (HR)(bpm), and gross energy expenditure during walking per minute (GEE_w).

Three dimensional (3-D) gait analysis was collected using eight Oqus 300+ cameras from Qualisys Motion Analysis System (Qualisys, Sweden) and filmed at 220 Hz. Before each gait data analysis, a 90-s wand (750 mm) calibration was completed, with a long arm of a L-shaped reference structure. Participants were dressed in appropriate clothing, cycling shorts and a tank top which would allow marker placement on the skin and minimize any artefacts from clothing movement. A full-body CAST/IK/HH gait model was used, requiring 12-mm self-adhesive reflective markers to be applied on the following anatomical landmarks (right and left): heel at the insertion of the Achilles tendon, head of the first, second and fifth metatarsal, medial and lateral malleoli, lower leg (shank) cluster consisting of 4 markers, lateral and medial knee epicondyles, thigh cluster consisting of 4 markers, greater trochanter, anterior and posterior superior iliac spine, inferior angle of scapula, thoracic vertebrae (T10), cervical vertebrae (C7), radial and ulnar styloid processes, humeral lateral epicondyle, humerus, acromion. This full marker set was used for a static trial only, which required the participant to stand still for 5 s while filmed in the centre of the calibrated area. Static trials were used to create a dynamic model for gait analysis. Once the static trial was completed, only dynamic markers were left, hence the markers on the medial and lateral malleoli, knee epicondyles, and the trochanter were removed.

During the dynamic trials, each participant was instructed to walk in a straight line at a self-selected pace along a 15-m laboratory walkway embedded with 4 AMTI BP400600 force plates (AMTI, MA, USA). Video and ground reaction force data were collected simultaneously for five seconds in the middle portion of the runway. Only trials in which the participant's foot landed entirely on a force plate for three consecutive steps (i.e. full stride), were considered for inclusion in the data set. The participants continued walking until 3 trials of full strides were completed. The participants were instructed to stop and rest as long as necessary, should they feel tired at any stage of the gait analyses. None of the participants requested a rest period during gait measures.

Data analysis

During walking trials, the data were inspected for gaps in marker trajectories. The default gap-fill function was applied for gaps of no more than 10 frames using NURB spline interpolation. No walking data trials analysed had gaps larger than 10 frames. Once the walking trials were trimmed to include completed strides, the data were exported to Visual 3D-motion analysis software for processing, through which segmental and whole-body kinetic data and gait kinematic data were calculated. The kinetic and kinematic parameters were low-pass filtered with a bidirectional Butterworth with a 10-Hz cut-off frequency to remove noise from the differentiation process with zero-phase distortion [13, 25].

Metabolic energy expenditure is generally reported in terms of O_2 consumption (O_2 rate), the millilitres of O_2 consumed, per kilogram body mass per minute (ml/kg/min). However, to demonstrate the physiological work (O_2 cost) for a given task, the physiological equivalent rate will also be normalized for speed to express the physiological work per unit distance (ml/kg/m) which is used to depict energy efficiency [10]. Therefore steady state walking total O_2 cost might be affected by an increase in O_2 rate, or a change in a walking speed, in which case the participant would not experience any physical differences. To reduce the impact of changes in resting metabolic rate (RMR), a non-dimensional parameter (NN) was used as it deduces the resting energy expenditure from gross or total energy expenditure during walking, leaving only energy cost required for walking and non- dimensional scaling to account for stature [26]. The net O_2 cost may also be less sensitive to changes in walking speed [11]. While this method theoretically accounts for the pregnancy induced changes there are no articles addressing this normalization for gait in pregnancy.

Mechanical work and total energy expenditure were explained in detail in Bennett et al. [16], and Willems et al. [27], hence only a brief summary will be provided in this study. Internal (W_{int}) and external work (W_{ext}), were calculated from COM excursion considering energy exchange as

$$W_{ext} = \sum_{i-1}^{N} (|\Delta Ep| + |\Delta Ek|), \quad (1)$$

and with no energy exchange as

$$W_{int} = \sum_{i-1}^{N} (|\Delta Ep| + |\Delta Ek|), \quad (2)$$

where ΔEp and ΔEk are changes in potential and kinetic energy, respectively [16]. Then, the energy recovery factor (R) representing the percentage of mechanical energy recovered via exchange between kinetic and potential energy in the COM movement is computed as [16]:

$$R = 100 \times \frac{(W_{int} - W_{ext})}{W_{int}} \quad (3)$$

Further, total energy of the whole body based on the segmental movement relative to COMwb at any instant in time as

Table 1 Descriptive statistics of the participants by trimesters

Measure	Total Mean ± SD	1st trim Mean ± SD	2nd trim Mean ± SD	3rd trim Mean ± SD	Sig. (p)
Participants (n)	35[b]	14	20	10	
Age	27.5 ± 6.1	28.1 ± 5.5	27.1 ± 6.1	26.6 ± 6.6	0.83
Height (cm)	160.8 ± 6.4	160.8 ± 5.9	160.2 ± 6.8	161.4 ± 7.2	0.89
Mass (kg)	70.4 ± 15.7	62.7 ± 10.5	71.3 ± 16.6	78.8 ± 14.7	0.08
BMI (kg/m^2)	27.3 ± 5.9	24.3 ± 4.0	27.7 ± 6.2	29.9 ± 4.9	0.08
M_{gain} (kg)	6.1 ± 6.3	1.09 ± 3.1	5.27 ± 2.8	13.81 ± 7.9	0.00
PPM (kg)[a]	64.4 ± 14.5				
PPBMI (kg/m^2)	25.1 ± 5.5				
Ethnicity	74.3 % black				
	17.1 % mixed ancestry				
	8.6 % white				

M_{gain} mass gain from pre-pregnancy (i.e. total mass gain), *PPM* pre-pregnancy mass; [a]Self-reported; *PPBMI* pre-pregnancy body mass index; trim trimester; [b]Several participants were measured in multiple stages

$$E_{tot,wb} = MgH + \frac{1}{2}MV_{cg}^2 + \sum_{i=1}^{N}\left(\frac{1}{2}m_i v_i^2 + \frac{1}{2}m_i K_i^2 \omega_i^2\right), \quad (4)$$

where M is the total body mass; g the acceleration due to gravity; H is height of the COM; V_{cg} the velocity of the COG; m_i and v_i are mass and velocity of the ith segment relative to the surrounding; ω_i and K_i are the angular velocity and the radius of gyration of the ith segment around its centre of mass [27].

Statistical analysis

A one-way ANOVA was used to assess differences between trimesters for descriptive participants' parameters. Simple linear regression was used to calculate the relationship between metabolic energy and mechanical work. All analyses were performed using SPSS v.21.0 (IBM Corp., Armonk, NY), and significance set at p <0.05.

Results

The participant demographics by trimester are given in Table 1. Some of the participants completed analysis at multiple trimesters totalling 44 measures during the total period of pregnancy. There were no differences in age and height between participants in each trimester, although mass gain was significantly increased throughout pregnancy as the foetus grew.

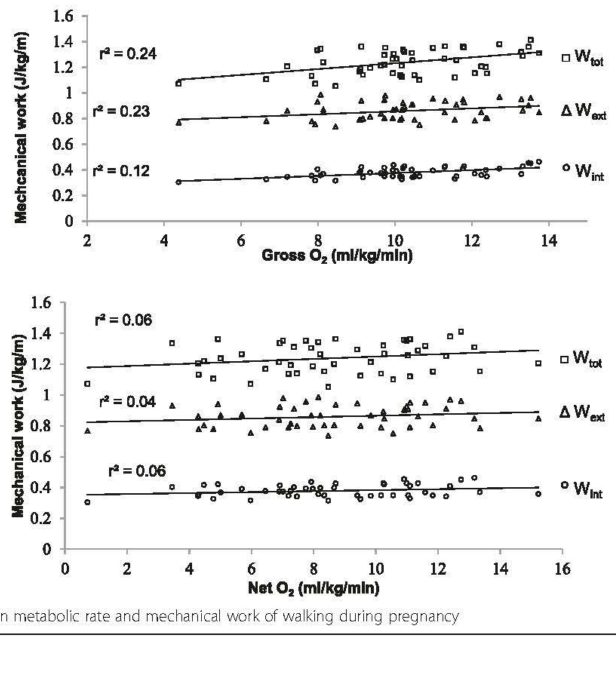

Fig. 1 Relationship between metabolic rate and mechanical work of walking during pregnancy

Prediction equations for external (W_{ext}), internal work (W_{int}) and total work (W_{tot}) depict no significant relationship with net O_2 expenditure of walking during pregnancy (p =0.19, p =0.10 and $p = 0.11$, respectively), Fig. 1. However, once normalized for speed to express energy efficiency (net O_2 cost) (Fig. 2), prediction equations (Table 2) show moderate, but significant relationship for external work (W_{ext}) ($r = 0.49$, $p \leq 0.01$), internal work (W_{int}) ($r = 0.66$, $p \leq 0.00$), and total work (W_{tot}) ($r = 0.63$, $p \leq 0.01$). Although net O_2 expenditure did not demonstrate a significant relationship to mechanical work, adding REE resulted in a significant relationship to mechanical work. Gross O_2 expenditure during walking shows a weak to moderate, but significant relationship to W_{int} ($r = 0.60$, $p \leq 0.01$), moderate with W_{ext} ($r =$ 0. 42, $p \leq 0.01$), as well as with W_{tot} ($r = .71$, $p \leq 0.01$). When considering REE in walking energy cost, the relationship with mechanical work as demonstrated in Fig. 2, did not change significantly. The mass is also the most significant ($r = 0.79$, $p \leq 0.01$) contributor in variance of gross O_2 consumption (VO_2) with 33.3 %, next to walking speed (10.0 %, $p \leq 0.05$). However, once normalized for REE, walking speed explained 26.1 % of the net energy expenditure ($p \leq 0.01$). Energy recovery factor (R) for the pregnant population in this study was 58.1 ± 3.2 %. The exchange of potential and kinetic energies, a determining factor for energy recovery, was largely affected by speed of walking. Figure 3 demonstrates a significant relationship between speed and energy recovery ($r =$ 0.61, $p \leq 0.01$), indicating that during pregnancy energy recovered may be improved with an increase in speed. However, in this study pregnant women decrease their walking speed later in pregnancy. The changes observed are an indication of an increase in walking economy with an increase in walking speed.

Discussion

This study addressed the relationship between metabolic energy expenditure and mechanical work measures of gait throughout pregnancy. With significant findings in studies on gait in pregnancy, as well as energy expenditure during pregnancy, researchers may be able to determine whether changes in gait during pregnancy may contribute to the overall energy expenditure, and whether changes in gait may be used as an energy-sparing strategy during pregnancy.

The study finds significant relationship between W_{int}, W_{ext}, and W_{tot}, and net O_2 and gross O_2 energy cost, and gross O_2 rate, but not for net O_2 rate. The significance between parameters, however, was of different magnitudes and was relevant to the resting energy expenditure, and the normalization for the walking speed. The changes in metabolic system due to foetal development will affect the resting energy expenditure, and consequently the total energy expenditure during pregnancy. This change cannot be accounted for by mechanical work measures, and metabolic changes in resting energy expenditure are also generally based on the estimates. In this study normalizing gross O_2 cost for resting energy expenditure, resulted in a stronger correlation, which suggests that normalization for resting energy expenditure does not decrease the internal consistency of data [23], and reduces the variability of the metabolic changes from foetal development.

Measuring metabolic energy consumption relative to distance or time travelled, may also affect the strength of the correlation [10, 26, 28]. Burdet et al. [28] found that the correlation of mechanical work with metabolic energy consumption per meter walked (ml/kg/m) weaker than when metabolic consumption was measured per time (ml/kg/s). However, Schwartz et al. [26] and Waters and Mulroy [10] demonstrate that normalizing for walking speed would give a better indication of walking efficiency. In this study, once the metabolic energy consumption was normalized for speed, the correlation improved 62.5 % for W_{tot}, 4.3 % for W_{ext}, and more than doubled for W_{int}. This increase may be rooted in the relationship between energy recovery (i.e. energy transfer) and walking speed.

Optimized energy transfer during walking would be inversely related to metabolic cost [29]. The results of this are indicative of this notion. There was a significant positive relationship between the percentage of energy recovered and walking speed (Fig. 3). In addition, women in this study had walking speed significantly lower than that of reported optimal walking efficiency where energy recovery is the highest [10, 11, 30]. Furthermore, as energy transfer demonstrated significant

Table 2 Regression equation for metabolic energy expenditure and mechanical work

	W_{ext} (J/kg/min)	W_{int} (J/kg/min)	W_{tot} (J/kg/min)
Net $O_{2\ cost}$ (ml/kg/m)	$1.1646O_2 + 0.7314$	$0.889O_2 + 0.2807$	$2.0536O_2 + 1.0121$
Net $O_{2\ rate}$ (ml/kg/min)	$0.0045O_2 + 0.8211$	$0.0032O_2 + 0.3514$	$0.0077O_2 + 1.1724$
Gross $O_{2\ cost}$ (ml/kg/m)	$0.9865O_2 + 0.7032$	$0.9384O_2 + 0.2299$	$1.925O_2 + 0.9331$
Gross $O_{2\ rate}$ (ml/kg/min)	$0.0115O_2 + 0.742$	$0.0113O_2 + 0.2624$	$0.0228O_2 + 1.0044$

W_{ext} external mechanical work, W_{int} internal mechanical work, W_{tot} total work

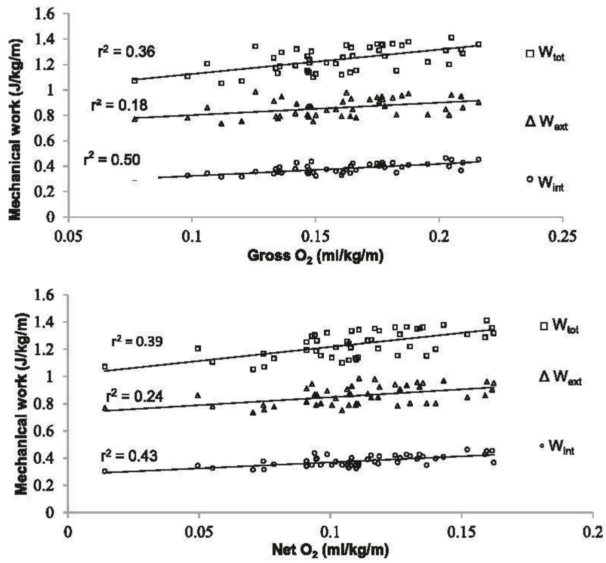

Fig. 2 Relationship between metabolic cost and mechanical work of walking during pregnancy

inverse correlation with the measures of gross O_2 cost ($r = -0.44$, $p = 0.002$) and net O_2 cost ($r = -.328$, $p = .023$). These results are in agreement with previous findings of Willems et al. [27] and Olney et al. [25].

Conclusion

Therefore, measures of mechanical work, when adjusted for resting energy expenditure and walking speed, may be useful in comparing metabolic energy consumption of gait between women during pregnancy, or longitudinal assessment of the same individual throughout pregnancy. Although mechanical work may not account for the variability in metabolic cost stemming from the foetal development, normalizing for REE and speed of walking, may allow mechanical work to predict the changes in gait during pregnancy.

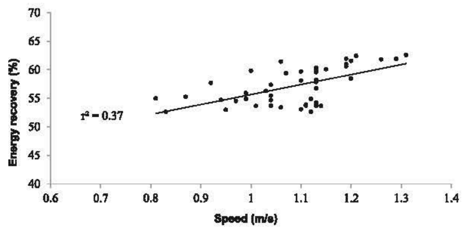

Fig. 3 Relationship between mechanical energy recovery and walking speed throughout pregnancy

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

ZK carried out the walking energy expenditure study, designed the protocol, collected data, and drafted the manuscript. SJM is the principle investigator of the larger conceptual project, the HAPPY-study and participated in critically revising the manuscript, and gave the final approval for the version to be published. All authors read and approved the final manuscript.

Acknowledgements

We would like to acknowledge our co-worker, Abie van Oort, for assisting with the recruitment of the participants. In addition, we would like to extend our gratitude to the participants of the HAPPY-study and the clinic staff for assisting and supporting the recruitment of participants and translation when needed. We also convey our gratitude to The South African Sugar Association and National Research Foundation's Swiss South African Joint Research Programme (UID: 78606) of the HAPPY project. Funding was specific for the collection of physical activity data and resting metabolic rate.

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Prof SJ Moss

ETHICS APPROVAL OF PROJECT

The North-West University Ethics Committee (NWU-EC) hereby approves your project as indicated below. This implies that the NWU-EC grants its permission that, provided the special conditions specified below are met and pending any other authorisation that may be necessary, the project may be initiated, using the ethics number below.

Project title: Longitudinal Patterns of Habitual Physical Activity in Healthy Pregnant South-African Women and Associations with Foetal Growth Parameters and Birth Outcomes	
Ethics number:	N W U - 0 0 4 4 - 1 0 - A 1
Approval date: 2010-07-13	**Expiry date:** 2015-07-12

Special conditions of the approval (if any): None

General conditions:

While this ethics approval is subject to all declarations, undertakings and agreements incorporated and signed in the application form, please note the following:

- *The project leader (principle investigator) must report in the prescribed format to the NWU-EC:*
  - *annually (or as otherwise requested) on the progress of the project,*
  - *without any delay in case of any adverse event (or any matter that interrupts sound ethical principles) during the course of the project.*
- *The approval applies strictly to the protocol as stipulated in the application form. Would any changes to the protocol be deemed necessary during the course of the project, the project leader must apply for approval of these changes at the NWU-EC. Would there be deviated from the project protocol without the necessary approval of such changes, the ethics approval is immediately and automatically forfeited.*
- *The date of approval indicates the first date that the project may be started. Would the project have to continue after the expiry date, a new application must be made to the NWU-EC and new approval received before or on the expiry date.*
- *In the interest of ethical responsibility the NWU-EC retains the right to:*
  - *request access to any information or data at any time during the course or after completion of the project;*
  - *withdraw or postpone approval if:*
    - *any unethical principles or practices of the project are revealed or suspected,*
    - *it becomes apparent that any relevant information was withheld from the NWU-EC or that information has been false or misrepresented,*
    - *the required annual report and reporting of adverse events was not done timely and accurately,*
    - *new institutional rules, national legislation or international conventions deem it necessary.*

The Ethics Committee would like to remain at your service as scientist and researcher, and wishes you well with your project. Please do not hesitate to contact the Ethics Committee for any further enquiries or requests for assistance.

Yours sincerely

Prof MMJ Lowes
(chair NWU Ethics Committee)

APPENDIX C HAPPY STUDY QUESTIONNAIRE

Habitual Activity Patterns during PregnancY

Initials and Surname: ________________________________

Date:____

Trimester: ____________________________________

Measurement:

0 1 2 3 4

1 Demographic Information

Clinic no.______________Contact no______________

ID number	
Birth date	DD / MM / YYYY
Marital status	
Nationality	
Ethnicity	
Home language	
Occupation	
Highest level of education	

Mean household income per annum (encircle the applicable amount)		
< R 50 000	R 50 000 – R 100 000	R 100 000 – R 150 000
R 150 000 – R 200 000	R 200 000 – R 250 000	R 250 000 – R 300 000
R 300 000 – R 400 000	R 400 000 – R 500 000	> R 500 000

2 Pregnancy Demographic Information

<table>
<tr><td colspan="2">Pre-pregnancy weight (kg)</td><td colspan="2"></td></tr>
<tr><td colspan="2">Weeks of pregnancy (weeks)</td><td colspan="2"></td></tr>
<tr><td colspan="2">Type of pregnancy (single, twin or triplets)</td><td colspan="2"></td></tr>
<tr><td colspan="2">Expected date of birth</td><td colspan="2"></td></tr>
<tr><td colspan="2">Number of children at home</td><td colspan="2"></td></tr>
<tr><td colspan="2">Number of previous miscarriages</td><td colspan="2"></td></tr>
<tr><td>Medicinal use</td><td>Yes</td><td colspan="2">No</td></tr>
<tr><td rowspan="5">Type of medication</td><td>Name of medication</td><td>Type of medication</td><td>Dosage</td></tr>
<tr><td>1.</td><td></td><td></td></tr>
<tr><td>2.</td><td></td><td></td></tr>
<tr><td>3.</td><td></td><td></td></tr>
<tr><td>4.</td><td></td><td></td></tr>
<tr><td rowspan="2">Smoking status</td><td>Current smoker</td><td>Ex smoker</td><td rowspan="2">Non-smoker</td></tr>
<tr><td>Number of cigarettes per day
____________</td><td>Date which you stopped smoking
____
DD / MM / JJJJ</td></tr>
<tr><td rowspan="2">Alcohol use in the last 3 months</td><td rowspan="2">Non drinker</td><td colspan="2">Drinker</td></tr>
<tr><td colspan="2">Number of drinks per day
___________/ wine/beer/spirits</td></tr>
<tr><td>Drug use in the last 3 months</td><td>Yes</td><td colspan="2">No</td></tr>
</table>

3 Contra-Indications & Risk factors

Do you have one of the following conditions	Yes	No
Anemia		
Cardiac dysrhythmia		
Chronic bronchitis		
Poorly controlled type 1 diabetes		
Extreme morbid obesity		
Extreme underweight (BMI < 12)		
Extremely sedentary lifestyle		
Intrauterine growth restriction in current pregnancy		
Poorly controlled hypertension		
Orthopaedic limitations		
Poorly controlled hyperthyroidism		
Heavy smoker		
Hemodynamically significant heart disease		
Restrictive lung disease		
Incompetent cervix / cerclage		
Multiple gestation at risk for premature labour		
Persistent second- or third trimester bleeding		
Placenta previa after 26 weeks of gestation		
Premature labour during the current pregnancy		
Ruptured membranes		
Preeclampsia / pregnancy-induced hypertension		

4 Anthropometric information

Body mass index					
Length		Weight		BMI	
Waist / Hip ratio					
Waist circumference		Hip circumference		Waist / Hip circumference	
Skinfolds					
Triceps		Supra-iliac		Mid-thigh	
Fat percentage					
Bod-Pod Body composition					
Fat percentage		Lean body mass			
Fat mass		Lung volume			
Bio-electrical Impedance					
Total Body Water		Fat percentage			

5 Blood pressure, Resting Metabolic Rate and Nutritional information

Heart rate (beats/min)	
Resting heart rate (beats/min)	
Blood pressure (mm Hg)	/
Resting Metabolic Rate (ml O_2 / kg)	
ActiHeart	
AEE (ckal/day)	
DEE	
TEE	
Nutritional calculations	
Total Dietary Intake	

6 Foetal growth parameters

Expected birth weight (grams)	
Head circumference (cm)	
Abdominal circumference (cm)	
Femur length (cm)	
Bi-parietal diameter (cm)	
Ponderal Index	
Simfus Fundus Heigth (cm)	

Medical practitioner: ______________________________

APPENDIX D INFORMED CONSENT

Habitual

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Physical activity, Sport and Recreation
Tel: (018) 018 299 1821

E-Mail: Hanlie.moss@nwu.ac.za@nwu.ac.za

<u>Informed consent</u>

PART 1

You are invited to participate in the above study conducted by the North West University with the purpose to understand the changes in gait, posture and energy expenditure during walking, throughout the pregnancy and post-partum.

Measurements will be conducted during four stages/measurement points of your pregnancy. These stages are: 1st trimester (9 - 12 weeks), 2nd trimester (20 - 22 weeks), 3rd trimester (28 - 32 weeks) and 3 months after the birth of the baby. The duration of the test will be approximately one hour and 30 minutes. The test protocol will be explained during the evaluation. You will be requested to remove your upper clothes for accurate anthropometric- and body composition measurements. Your habitual physical activity will be measured by Actiheart® heart rate monitor with integrated accelerometer (CamNtech Ltd., UK), which will require you to wear this instrument for 7 consecutive days and return it in its original state. After this, an eight minute step test with a ramp protocol on a step box (21.5 cm in height) will be performed. As with any exercise test, certain risks and discomforts may apply. The risks involved in this exercise test may include abnormal blood pressure, fainting, disorder of heartbeat, and in the most extreme instances, heart attack, stroke or death. Every effort will be made to minimize these risks by continuously monitoring participants throughout exercise testing. It is the participant's responsibility to inform the study investigator if you feel dizzy, ill-feeling or any other symptoms. If any discomfort is experienced, you may stop at any time during the step test. A resting metabolic rate measurement will also be performed. You will be requested to breathe through an anti-bacterial filter for 15 minutes after a 10 minute resting period. For gait analysis, you will be required to change into appropriate clothing, cycling shorts and a tank top which would allow marker placement on the skin and minimize any artefacts from clothing motion. The reflective markers will be applied on the several anatomical landmarks on your body. You will be asked to walk along a specified 15 meter walkway at a self-selected speed, until measurements are successfully recorded. This procedure will be between 15 and 30 minutes. While there are no physical risks with this test, as you will be walking at self-elected speed, you may need some time to get accustomed to wearing reflective sensors on your body while walking. Although these trials are video recorded, the motion analysis cameras are programmed to only track reflective markers on your skin, and will not be capturing any facial or recognizable features that can identify you. A walking energy expenditure will also be measured. You will be requested to wear a portable K4b2 telemetry system (Cosmed, Italy) which will be attached to a harness you will be wearing. You will be breathing via Rudolph type mask which will be attached to a portable telemetry system. This measurement will take between 5 -10 minutes. During this test, there are no known physical risks, however, you might feel some discomfort if this is your time wearing a mask over your nose and mouth. You will be given as much time necessary to get accustomed to the equipment.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. If you decide to participate, you are free to withdraw your consent and to discontinue participation at any time without penalty. Ethical approval has been obtained from the North-West University (NWU-00044-10-A1).

1. Department performing the research: **Physical activity, Sport and Recreation (PhASRec)**
2. Title of the project: **The relationship between gait mechanics and walking economy throughout pregnancy**
3. Full names, surname and qualifications of the researcher/project leader: **Sarah Johanna Moss (PhD., MBA. Registered Biokineticist)**
4. Job title of the project leader/researcher: **Associate Professor, Niche area research leader: PhASRec**
5. Full names, surname and qualifications of the persons performing the tests: **Zarko Krkeljas, MSc, C.S.C.S.**
6. Name of supervising doctor: **Dr's Strydom, Thomas & Van Rensburg**
7. Precautions taken to protect the participants: **All measurements will be performed by a trained biomechanist who is trained to identify risk factors in pregnant women during exercise testing. The supervising gynaecologists are informed of the time of testing and will be contacted in case of an emergency.**

....

Signature: Project leader Date:

PART 2

To the under signed of part 3 of this document:

It is important that you read and understand the following general principles that are applicable to all participants in research projects:

1. Participation in this project is completely voluntarily and no pressure however subtle may be placed on you to participate.
2. It is possible that you my personally not obtain any personal advantage from participating. The knowledge that is however generate by your participation my be to the advantage of others
3. By consenting to participation in this project, you also consent to the data obtained by the researchers to be used as they see fit for scientific purposes with the prerequisite that the identity of the participant will be kept confidential and the participant will not be connected to the data without consent
4. You are free to withdraw from the project at any time without any explanation and without receiving any penalty as a consequence. You are however requested to consider that your withdrawal can influence the statistical reliability of the project negatively.
5. A summary of the project, the risks associated and any discomfort that might be experiences during the project, as well as the advantages of the project is explained in Part 1 on this document.
6. You are encouraged to direct any questions with regards to the project and the measurements to be taken to the project leader and staff involved. They will be happy to answer you and discuss the research with you.
7. If you are under the age of 18 years, you are not permitted to participate in this study
8. You are informed that it is requested of you to state that you will not hold the University accountable for any damages, injuries or death unless there were neglect from the University or any of its employees or staff.
9. If you are married, your spouse is requested to distance himself from any claims against the University in the event of damages of death with regards to the project as explained in part 1 unless it is due to negligence from the University, the employees or the students.

PART 3

Consent

Title of the project: **The relationship between gait mechanics and walking economy throughout pregnancy**

I, the undersigned..(full names) have read the information with regards to the project as explained in Part 1 and Part 2. I have also heard the oral version thereof and declare that I understand. I was given the chance to discuss relevant aspects of the project with the leader and here with declare that I voluntarily participate in the project. I here with give consent to participate in the project.

I will not hold the University or any of its employees or students accountable for any damages incurred by me during participation in the project except in the case of negligence from the University. I further agree not to process any legal action against the university due to damages of good of personally as a result of participation in the project, unless it was due to the negligence of the University, its employees or students.

....
(Signature of the participant)

Signed at POTCHEFSTROOM on the   ………………………….

WITNESSES

1. ....

2. …...

Signed at POTCHEFSTROOM on the   …………………………

Research on married participants the following consent is requested:

I,..(full names), the spouse of the participant in this project, here with declare that I will not place any legal complaints against the University for any treatment of injuries, damages or death of the person participating in this project unless it was as the result of negligence from the university, its staff or students

Signature: .... Date: ……………………

APPENDIX E LANGUAGE REVIEW

23 March 2015

I, **Ms Cecilia van der Walt,** hereby confirm that I took care of the **editing** of the **thesis** of **Mr Zarko Krkeljas** titled ***The relationship between gait mechanics and walking economy throughout pregnancy.***

C. Van der Walt

MS CECILIA VAN DER WALT

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