PREDICTION OF TRANSITION SPEED IN GAITS BASED ON KINETICS AND KINEMATICS VARIABLES

HAFIZAH HARUN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Biomedical Engineering)

Faculty of Biomedical Engineering
Universiti Teknologi Malaysia

JUNE 2016

الْعَالَمِينَ رَبِّ عَلَىٰ إِلَّا أَجْرِيَ إِنْ أَجْرٍ ۖ مِنْ عَلَيْهِ أَسْأَلُكُمْ وَمَا

I seek of you no reward for this: my reward is with none except the Lord of the Universe.

Surah 26 Ash-Shu`arā' (Verse 109):

ACKNOWLEDGEMENTS

بسم الله الرحمن الرحيم

Thank you mak, Kamariah Sa'don, you are and always my inspiration.

ABSTRACT

The kinetic and kinematic aspects of walking and running are very different at their preferred speed. Locomotion at gait transitions is rarely used; hence actual alternation across the transition speed (TS) remains an unexploited area that can potentially merit run/walk in race running. Awareness of the scientific knowledge in gait transition should therefore be valuable. The aim of this thesis was to investigate the gait transition phenomena and predict the transition speed on different gradients based on the oxygen uptake kinetics and lower limb kinematics. The study investigated preferred transition speed (PTS) on different gradient inclinations and was completed in three stages; firstly laboratory experiments TS1 and TS2 determined the actual PTS, subsequent experiments (TS3 and TS4) examined changes of the oxygen kinetics across PTS. The third stage, TS5 used the kinematics data collected to propose mathematical models that examined the PTS. An overall total of seventy-nine participants (48 males and 31 females) were involved at different stages and rigorously undergo the separate experimental protocols. The findings support as well as contradict previous literature results. Firstly, the energy equivalent TS (EETS) based on kinetics of oxygen uptake per unit distance (EETS/km) and per unit stride (EETS/stride) accurately predicted the PTS on the flat but not on other gradients. Secondly, the increased ankle muscular constraint conditions of using weights did not affect the PTS. However, it significantly increased the oxygen uptake kinetics for run/walk on – 8 and 0 % and the Bla on the + 8 %. Based on novelty of the mathematical model, the role of the dorsi and plantar flexors was further evidenced to influence and predict PTS regardless of gradient inclinations. In conclusion, the findings in this thesis indicated that different metabolic energy pathways regulated the run/walk and that ankle muscular constraints determined the PTS. Incorporating the synergistic perspective, cognitive influence plays an important role to overcoming difficulty of walking at running speeds as observed in the occurrence of hysteresis in TS1. Information on the run/walk can be integrated during training and race as recommended from the thesis findings.

ABSTRAK

Aspek kinetik dan kinematik berjalan dan berlari adalah berbeza pada halaju yang tersendiri. Manakala halaju transisi (PTS) di antara berjalan dan berlari jarang digunakan; lari/jalan di dalam zon ini berpotensi meningkatkan prestasi atlet acara larian jarak jauh. Oleh itu, kesedaran pengetahuan saintifik tentang transisi gaya lari/jalan adalah penting. Tujuan tesis ini adalah mengkaji fenomena transisi di antara mod lari dan jalan, dan meramal perubahan PTS pada cerun yang pelbagai berdasarkan kinetik pengambilan oksigen dan kinematik segmen kaki. Kajian terhadap PTS telah dijalankan di atas pelbagai cerun dan dijalankan dalam tiga fasa; iaitu, pertama TS1 dan TS2 untuk mengenalpasti PTS sebenar, fasa kedua (TS3 dan TS4) mengkaji perubahan kinetik pengambilan oksigen dalam zon PTS kedua-dua fasa ini telah dijalankan di dalam makmal. Fasa ketiga (TS5) menganalisa data kinematik yang diperolehi untuk membangunkan beberapa model matematik berkaitan PTS. Seramai tujuh puluh sembilan peserta (48 lelaki dan 31 perempuan) terlibat tetapi jumlah sampel berbeza bagi setiap fasa kajian. Hasil kajian menyokong serta bercanggah dengan dapatan kajian lepas. Pertama, tenaga setara TS (EETS) berdasarkan kinetik pengambilan oksigen per unit jarak (EETS / km) dan per unit langkah (EETS / langkah) dengan tepat meramalkan PTS di cerun mendatar tetapi tidak pada kecerunan lain. Kedua, PTS tidak berubah walaupun kontraksi otot pada pergelangan kaki telah ditingkatkan dengan menambah beban. Namun begitu, kadar kinetik pengambilan oksigen telah meningkat secara signifikan semasa lari/jalan di atas cerun – 8 dan 0 %, disertai peningkatan signifikan pada konsentrasi Bla semasa lari/jalan pada cerun + 8 %. Ketiga, novelti pembangunan model mathematik telah membuktikan pengaruh dan peranan otot *dorsi* dan *plantar flexors* ke atas PTS semasa lari/jalan di semua cerun yang dikaji. Kesimpulannya hasil kajian tesis telah mengenalpasti bahawa dua jenis tenaga metabolik mengawal selia lari/jalan pada cerun yang berlainan, serta kekangan pengecutan otot pada buku lali bertanggungjawab menentukan kadar keupayaan lari/jalan (PTS). Dari perspektif sinergistik, histerisis hasil dapatan kajian TS1 menunjukkan peranan kognitif bagi mengatasi stres apabila terpaksa berjalan pada halaju yang biasa digunakan untuk berlari. Maklumat mengenai lari/jalan boleh disepadukan semasa latihan dan perlumbaan seperti yang disyorkan daripada penemuan tesis ini.

TABLE OF CONTENTS

LIST OF TABLES

TABLE OF FIGURES

LIST OF ABBREVIATIONS

ASIS - Anterior Superior Iliac Spine
Bla - Blood Lactate concentrations
c.o.m - centre of mass
Cr - Cost of Running
Cw - Cost of walking
DNF - Did Not Finish
EETS - Energy Equivalent Transition Speed
Ek - Kinetic Energy
EOTS - Energy Optimal Transition Speed
Ep - Potential Energy
fps - frame per second
IAAF - International Association Athletic Federation
MCU - Motion Capture Unit for Qualisys
PTS - Preferred Transition Speed
RW - run-walk-run
TS - Transition Speed
TSV - tab separated value files
$\bar{V}O_2$ - Volume of Oxygen Consumptions
XLS - Microsoft excel spreadsheet files extension
QTM - Qualisys Track Manager

LIST OF SYMBOLS

δ - A constant value of less than 1.0

ϕ - Treadmill inclinations angle

$\theta \max$ - Maximum ankle angular displacements

$\hat{\theta}$ - Mean ankle angular displacement for one stride durations as calculated using the cosine rule

$\sin \phi$ - Gradient elevations

P - Power

$P \neq \hat{P}$ - Power exerted not equal to power prime (on flat versus gradients)

$\boldsymbol{f}$ - Foot extension

$\hat{f}$ - Foot extension on gradients

$\mathbf{R}$ - The limb length

$\mathbf{L}$ - The step length

$\hat{L}$ - Step length on gradients

$\boldsymbol{R}$ - Mean leg length measured form the anterior superior iliac spine to the floor in shod conditions

V - Velocity of transition (the transition speed)

$\hat{V}$ - Velocity of transition on gradients

E_k - Kinetic energy

Γ - Torque

$\boldsymbol{I}$ - Moment of inertia

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Walking and running are two characteristically different gaits or pattern of locomotion, a term used interchangeably (Zehr and Duysens, 2004), when moving at different range of speeds. Human use each gaits for different task oriented purpose; walking is chosen over running during normal activities of daily life, in theory because walking at preferred speed incurs minimal metabolic energy expenditures to cover a given distance (Long and Srinivasan, 2013). Athletes regulate their pace during competitions such as cycling, swimming, and skating to last the durations and distance, but more importantly as strategy to win (Abbiss and Laursen, 2005; De Koning *et al.* 2011). However, purposeful fast walking and continuous running is preferred during exercise with the intention of increased energy consumptions and caloric expenditures (Harvie, 2011; Noakes, 2003; Williams, 2012).

Massive numbers of individuals from different age categories participate in running and walking as exercise and sport. More than fifty thousand people are reported to register in one running competitions that increases yearly since the 1970s (Bale, 2004; Eden, 2009; Galloway 2013; Malaysia Book of Records, 2014; Wegelin and Hoffman, 2011). These events are so prevalent and appeal to both males and females because of its simplicity not requiring much equipment or involving high levels of motor skills (Harvie, 2011; Noakes, 2003). Rather than for competitive reasons, evidence have shown that humans run for the sake of camaraderie, appreciation of nature, cultivation of positive identity as an active sports person that gave 'life meaning', and importantly to finish (Eden, 2009; Doppelmayr and Molkenthin, 2004; Shipway, 2010).

Various training strategies and pacing tactics easily accessible from popular running literature are available for interested beginners to start racing. However high number of runners DNF (did not finish), 86 % women and 14 % men reported to drop out before the finishing line during a single competition (the 2014 Standard Chartered Kuala Lumpur City Marathon). Fluctuations in velocities and ability to maintain specific pacing ensure finishing and distinguished the different calibre runners (Abbiss and Laursen, 2008; Del Coso *et al.* 2013; Santos *et al.* 2014). In the cross country or ultra distance races athletes constantly alternate between running and walking (run-walk-run), which is a common technique when facing uneven or hilly terrains (March *et al.* 2011). As a method, the run-walk (RW) that consisted of systematic combination of running with short intervals of brisk walking has been adopted for shorter distance races (Galloway, 2010; Galloway, 2013). Anecdotal evidence suggests that systematic use of RW serve to delay fatigue (Galloway, 2013).

Alternation between walking and running gaits or literally known as gait transition, are field of studies investigated in other theoretical areas of research. According to most of the researchers, human switches in both directions of walking to running and vice-versa because the kinetic and kinematic variables involved within each gaits had reached critical limits. By switching from one to the other presents a behaviour that the system is conserving some physiological or biomechanical variables (Beaupied *et al.* 2005; Borghese *et al.* 2006; Diedrich and Warren, 1998; Hanna *et al.* 2000; Hreljac, 1993a, 1995a; Li *et al.* 1999; Long and Srinivasan, 2013; Margaria *et al.* 1963; Minetti *et al.* 1994; Minetti and Ardigo, 2001; Prilutsky and Gregor, 2001; Raynor *et al.* 2002; Segers, 2007). However there remain inconclusive agreements among them regarding mechanisms that triggered gait transition.

The gait transition velocity or preferred transition speed (PTS) also varies and found to be affected by different experimental methodologies used (Hanna *et al.*

2000; Minetti *et al.* 1994; Minetti *et al.* 2003; Segers, 2007a), resulted from activities of daily routines or natural gait change versus more experimentally controlled conditions (Bessot *et al.* 2015; Long and Srinivasan, 2013; Minetti *et al.* 1994; Minetti *et al.* 2003; Segers, 2007a), or influenced by specific strategies that are useful in certain type of sports (Beupied *et al.* 2003; Usherwood and Bertram, 2003). The optimal transition speed (TS) advantageous for different kind of situations has also not been investigated thoroughly (Abdolvahab, 2015; Long and Srinivasan, 2013).

1.2 Background of Problem

Adult human comfortably walk at speeds between 1.2 ± 0.5 m.s.$^{-1}$ and PTS between walking and running occurred around 2.0 ± 0.5 m.s.$^{-1}$ (Alexander, 1989; MacLeod *et al.*, 2014). Walking metabolically cost less at lower speeds and running at higher speeds, hence gait transition is hypothesized to optimize the oxygen uptake kinetics or minimizes the metabolic energy expenditures (Alexander, 1989; Hreljac 1993a, 1993b; Long and Srinivasan, 2013; Margaria *et al.* 1963; Minetti *et al.* 1994). Faster walking is limited by the kinetic / potential energy system of the pendulum mechanism modelled for walking (Cavagna *et al.* 1977; Segers *et al.* 2013; Usherwood, 2005), and kinematics of the ankle joint accelerations decreased considerably as a result of changing gait from walking to running (Hreljac, 1995a; Borghese *et al.* 2006).

Gait transition occurs in both directions of walking to running (walk-run) and from running to walking (run-walk). Theoretically the PTS should be the same regardless of directions, but the PTS of walk-run is usually greater than PTS of run-walk (Diedrich and Warren, 1995; Li, 2000). Factors like methodological differences was cited for discrepancy in the variations observed (Hreljac, 2006). Other factors such as cognitive influence was also suggested (Abdolvahab, 2015; Li, 2000).

When human experimental participants were not told the specific distance and durations they have to travel either on the treadmill (Daniel and Newell, 2002) or overground (Long and Srinivasan, 2013) the gait fluctuated between walking and running up to 3 $m.s.^{-1}$ showing indistinct cut-off or a definite PTS. In experiment where subjects were asked to maintain a single gait for 30 s, human can walk at average speeds of 3.6 $m.s.^{-1}$ and run at 0.4 $m.s.^{-1}$ and when given a chance to change gaits they prefer to switch from run-walk at 1.84 $m.s.^{-1}$ and walk-run at 2.25 $m.s.^{-1}$ (Li, 2000). Humans are capable of running and walking at much lower and higher velocity respectively than their PTS. Furthermore, when race walkers altered aspects of their lower limb kinematics and kinetics to compensate for increased mechanical and muscular power, the unique walking method can reach speeds up to 4 $m.s.^{-1}$ (Borghese *et al.* 1996; Hanley *et al.* 2011). The peak walking speed exhibited by the elite walker is only slightly slower than average running pace of Haile Gebreselasie winning at 2:03:59 in the 2008 Berlin marathon, but matches or even beating the average marathon finishers' pace of 2.2 – 2.7 and 3.8 – 4.0 $m.s.^{-1}$ for the slower and faster group (Del Coso *et al.* 2013).

Humans are however unable to continuously maintain a constant running or fast walking speed for a long durations, distances, and hilly terrains (Hreljac, 2004; Santos *et al.* 2014; Usherwood, 2005:). Velocities fluctuations are displayed as different types of paces; the basic types constitute the positive, negative, even and other variable profiles (Abbiss and Laursen, 2008; De Koning *et al.* 2011). Pacing is the regulation of effort to distribute speed and power output or the energetic reserves to last throughout durations of a sporting event (Abbiss and Laursen, 2008; Del Coso *et al.* 2013; De Koning *et al.* 2011; Dolan *et al.* 2011; Ely *et al.* 2008; Foster *et al.* 2004). An explosive or all-out pace is the least energy conservative and best suited for sprints, as running speed increases the power output would decreased from the start towards the end (Abbiss and Laursen, 2008). Other pace strategies is common in events lasting more than 1 minute (Abbiss and Laursen, 2008). Runners would train their selected pace as tactic to win but end up displaying positive pace profiles (fast to slow) because other factors would affect the eventual pace on actual race day (see Figure 1.0) (Santos *et al.* 2014).

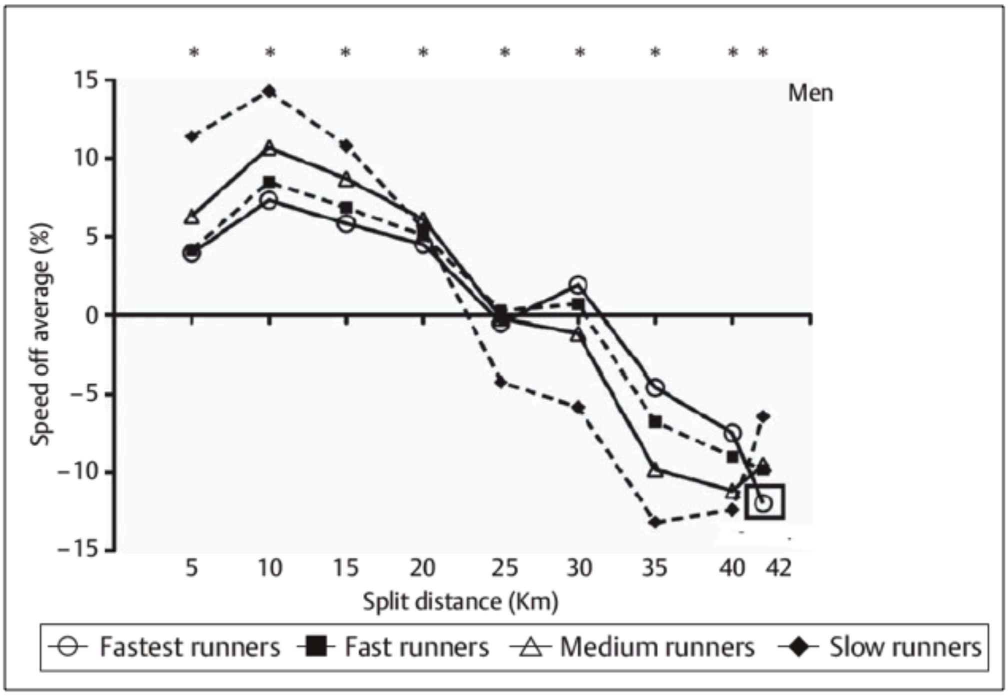


Figure 1.0 : Positive pace (fast to slow) of all calibre runners in a marathon (taken from Santos *et al.* 2014).

Haney and Mercer (2011) stipulated that pace variability increases due to higher fatigue levels as runners get closer towards the finishing line. Del Coso *et al.*, (2013) suggested it could be due to increased muscle temperature and damage causing changes to the footstrike patterns slowing the velocity, while less experienced runners would quit before finishing due to extreme fatigue. Even though the overall paces are positive (Figure 1.0), the faster athletes demonstrated more stable and even pacing pattern compared to the rest (Haney and Mercer, 2011; March *et al.* 2011; Santos *et al.* 2014). These researchers reiterated that fitter and faster men and women run at more consistent speed with only slight reduction in velocities than less competitive runners. However more race participants consist of recreational runners and displaying variable pace or erratic profiles (Gosztyla *et al.* 2006; Haney and Mercer, 2011; Morin *et al.* 2011; Santos *et al.* 2014; Stellingwerff *et al.* 2011).

Galloway (2010) is a runner and coach who used and recommended the regular walk break routine to novices in the 5 k up to marathon distances. This seemingly important skill provide rough guidelines suggesting that if a runner average speed is 1.9 or 3.0 m.s.$^{-1}$ then the self-selected routine of run to walk breaks could be taken at durations 30:30 (seconds) or 4:1 (minutes) respectively (Galloway, 2013). By the way, the average speeds corroborate the transition and maximal walking velocities in human gait transition studies.

The technique is somehow unclear, especially to participants that consist mostly of recreational and female runners who train alone without proper coaches. These runners usually walk when they reached extreme tiredness or sometimes take longer breaks than planned (Shipway, 2010). They also find it difficult to run back after the walk breaks (Barrios, 2003; Chase and Hobbs, 2010). Subjective cues like walk up the hills and climbs, run the flats and downhill also do not help have. This demonstrates the internal demand to decide and cognitive influence to match pacing during a race. Implications of interspersing walking into running from the perspective of kinematics and kinetics have also not been discussed. Moreover academic literatures regarding the techniques of RW are scarce or non-existent (De Koning *et al.* 2011; Haney and Mercer, 2011).

1.3 Problem Statement

Humans can choose to walk, run or rest and switch from walking to running close to 2.0 $m.s.^{-1}$ because it is metabolically more economical during activity of daily lives (Alexander, 1989; Minetti *et al.* 1994). With motivations to win increase caloric expenditures are disregarded, adult humans are capable to maintain a single very fast walking at 3.0 to 4.0 $m.s.^{-1}$ or continuously run above 2.5 $m.s.^{-1}$ during time constraints or short bursts of exercise and fitness activities (Long and Srinivasan, 2013). However there is conflict between conserving metabolic energy expenditure, delaying blood lactate accumulation and fatigue to last a race distance versus fulfilment of participations during competitions since the goal is to finish (Shipway, 2010).

Not considering injury, the faster athletes always finished. Slower runners either finished very late or DNF. The difference between the two groups is the more even against variable pacing profiles (Abbiss and Laursen, 2008; De Koning *et al.*

2011; Haney and Mercer, 2011; March *et al.* 2011; Santos *et al.* 2014). Fatigue, elevation or changes in terrain can influence pace of runner, walking was more efficient and faster than running when facing these challenges (Barrios, 2003; Chase and Hobbs, 2010). The RW strategy allowed non-elite runners to achieve similar finish time with running only group with reduced muscle discomfort (Hottenrott *et al.* 2014). The RW has been a successful strategy for cross-country and ultra distance runners because energy expenditure is regulated (Lambert *et al.* 2004). Despite research like this, information pertaining to the amount of regular walk and run intervals and why runners complaint of difficulty to return to running after walk breaks is also inadequate.

1.4 Purpose of Study

Aim of the present thesis was to investigate the gait transition phenomena and predict the transition speed on different gradients based on the oxygen uptake kinetics and lower limb kinematics. Several mechanisms that have been previously proposed as the influencing factor that trigger gait transition were also investigated. The findings will contribute as valuable insight into the RW as skills for runners and trainers.

1.4.1 Research Objective

The following are objectives of this thesis:

1. To identify the preferred transition speed (PTS) between running and walking on different gradient inclinations and factors that affect them.
2. To examine the oxygen uptake kinetics ($\overline{V}O_2$) during extended walking and running across the range of transition velocities and identify the theoretically optimal transition speed, which may have implications on types of pacing.

3. To examine the kinematics data at stance and swing of the final walking phase and proposed mathematical models to assess influence of gradients on the PTS.

1.4.2 Research Questions

To achieve the above research objectives the following research questions were asked:

RQ1. What is the PTS between walk-run and run-walk on different gradient inclinations?

RQ2. How do the stage interval durations affect the PTS?

RQ3. 3.1 What is the kinetics of oxygen consumptions ($\bar{V}O_2$ in ml. kg.$^{-1}$.min.$^{-1}$) of both continuous walking (Cw) and continuous run (Cr) on three gradient conditions?

3.2 If the two metabolic cost curves intersects, what are the optimal or theoretical transition speed based on energy equivalent costs (EETS/km) per unit distance and (EETS/stride) per frequency of stride walking and running at overlapping speeds on each gradient condition compared to the PTS?

RQ4. What is the affect of increasing muscular effort on the PTS, oxygen uptake kinetics and blood lactate concentrations?

RQ5. Kinematically, how does the rigid stiff-limbed configuration of the thigh, leg and foot determine gait transition from walk-to-run on different gradient inclinations?

1.5 Significance of Study

Athletes of different sports and standings have trained and used different pacing strategies to regulate rate of work output and optimize overall performance. However, the optimal concept of the RW pacing remains unclear (Abbiss and Laursen, 2008). The RW technique claimed to relieves the perception of pain and fatigue experienced during a race was based more on anecdotal reports (Haney and Mercer, 2011; Morgan and Pollock, 1977). Furthermore races are run on undulating terrains, gait alternations between running and walking on various gradient inclinations and the metabolic energy expenditure during extended walking and running may provide further information on the different pacing techniques.

Both walking and running at velocities of gait transition is considered unnatural, but are potentially informative as shown by Gutmann *et al.* (2006). In their experiment subjects were forced to walk and run at a controlled speed for several weeks. By adjusting their stride length and frequency, the subjects were able to adapt to the situations fairly quickly with significantly efficient metabolic and mechanical costs.

Experiments evaluating the alteration of leg mass distribution as in adding weights to the ankle or changing the position of the body's centre of mass (with gradients) would also predictively result in changes to maximum walk or run speed. The results analysed would be informative for athletes, example those undergoing rehabilitation so they can exercise with high exertion but without the impacts of running. Alternatively, make walking harder as on gradients and controlling the speeds to avoid triggering the walk-run transition. Therefore information on the process of regulating the physiological and biomechanical processes at the borders between running and walking becomes very important.

1.6 Scope and Limitations of the Study

A mixed of recreational and trained athletes from both gender and various types of sports participated in the study. Four data gathering experiments to investigate the gait transition phenomena were undertaken and most of the participants were repeats during different sessions of the experiments.

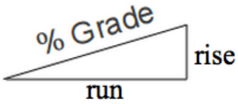
Subjects went through experiments on a motorized treadmill that was inclined to several uphill and downhill gradients in a test laboratory situation.

1.7 Operational Definition

Definitions below listed several terminologies and specific terms frequently used in the thesis:

Efficiency	Skilful performance that was completed with the least amount of energy expended and musculoskeletal stress.
Footrace	Races on foot that cover various distances, either a walk or run gait is used. Be it a race walking or running events that are distance such as the marathons or triathlons.
Gait transitions	A phenomenon or occurrence when the walk and run gaits switches back and forth or alternates.
Gradients	0 % gradient - Flat or the treadmill is at neutral, level or horizontal position, both uphill (positive: +ve) and downhill (negative: -ve) incline. Gradual gradients are between ± 8 % and steep

	between ± 16 % (as registered on the treadmill control).
Mechanical cost	The cost related to the intensity of motion. During the swing and stance phase of walk and run the lower limbs moves and its displacements, velocities/torque, and accelerations require muscular power to produce work. The work redirects the trajectory of the body's centre of mass upward and forward at each transition steps. The mechanical cost is optimal at different speeds for each walk or run gait (least costly at low speed for walking - quantified by the sum of its potential and kinetic energies, and at higher speed for running - involving exchanges between both kinetic and potential energies with elastic energy).
Metabolic cost	The cost related to physiological functions involving intensity of the cardiorespiratory system experienced during walking or running at different speeds. The intensity can be perceived to occur at different levels - the overall body (global) when amount of oxygen uptake ($\bar{V}O_2$ in **ml.kg.$^{-1}$ km.$^{-1}$)** are measured as the metabolic energy costs relative to the distance travelled or it can be more localised at the lower limbs (peripheral) when measured relative to the stride frequency ($\bar{V}O_2$ **ml.kg.$^{-1}$ stride.$^{-1}$)**.
Metabolic energy expenditure	The amount of oxygen consumed ($\bar{V}O_2$ **ml.kg.$^{-1}$ min.$^{-1}$)** collected via indirect calorimetry (open

	circuit respirometry) during walking or running on the treadmill.
Optimal	With respect to the physiological and mechanical costs; shown as costing the least in terms of energy expenditure and/or the least musculoskeletal strain. It can be seen as motion that has a balance posture and most stable either during static standing or dynamic during walking and running.
Pace	Is similar to speed since both describe how fast someone is moving. Pace considers the amount of time an athlete can cover a given distance (example: 10 min per km pace).
Pacing	The actual distribution of speed, power output or energetic reserves during a given sporting event.
Pacing strategy	Self-selected tactic that athlete adopt from beginning of event.
Percent gradients	Rise and run of slopes; 100 % slope is 45• (degree) in angle; 0 % is flat; ± 8 % is graded uphill or downhill at 4.57•; and ± 16 % is either uphill or downhill at 9.09• . 
Preferred speed	While tested on the treadmill and given a choice, participants would verbally claimed that a particular speed is more preferable for a certain gait (either a walk or a run).

Predicted transition speed	Is the EETS; in theory the speed at which Cw = Cr whereby humans chose to switch from one gait to the other depending on the directions of accelerations (slow to fast: walk-to-run or fast to slow: run-to-walk)
Preferred transition speed	Is the PTS; due to accelerations (or decelerations) of the treadmill, the participants would alternate between walk and run gait but prefer or choose to use one comfortable gait that was different from the earlier gaits. The alternative gait chosen could be maintained throughout a specified time interval as designed in each experimental protocol.
Transition region	A region where the participants consistently alternate between both walking and running. They were unsure about which gait to use, stating that both gaits was uncomfortable. But when the treadmill was decelerated or accelerated, there will be a speed when they could use a specific or preferred gait for the durations given.

1.8 Organization of thesis

The thesis was organized into six chapters. In Chapter 1 the introduction, background, objectives, significance and scope of study was presented. Chapter 2 described the Literature Review and explained details on the basic differences and similarities between the walk and run gait and theoretical perspectives of gait transitions studies related to humans. Information on footraces and sport competitions, types of pacing and factors that affect pacing were also included.

Chapter 3 is the Research Methodology that described the research design, participants, details of equipment and measurements, and the general experimental protocols that were used during the three experimental stages (stage 1 - TS1, stage 2 - TS2, TS3, and TS4, and stage 3 - TS5). This chapter also discussed the operational framework undertaken in the thesis.

Chapter 4 is the Results and Analysis that included summaries of findings from the three experimental stages (five separate sections for TS1, TS2, TS3, TS4 and TS5). Each subchapter contains an introduction to the study, results and analysis, and their respective summaries of findings. Stage 1 is section 4.2 (TS1) reporting findings for determination of the PTS on five gradients and two acceleration directions. Stage 2 consisted of section 4.3 (TS2) determination of factors affecting the PTS at various stage interval durations, section 4.4 (TS3) findings on the oxygen uptake kinetics data ($\bar{V}O_2$ ml.kg.$^{-1}$ min.$^{-1}$), metabolic cost of walking and running (Cw and Cr) on overlapping speeds across gait transitions. The Cw and Cr were calculated using two methods relative to the distance travelled (ml.kg^{-1}m^{-1}) and secondly relative to the frequency of stride (ml.kg^{-1}stride^{-1}). And section 4.5 (TS4) the metabolic efficiency was further examined with ankle loading and locomotion across individual subjects gait transition speed. Finally stage 4 is section 4.6 (TS5) that formulated the three mathematical equations novel to this thesis, and examined the stance and swing phase as pendulum mechanics at the final walk speed. A kinematic model was produced to predict and describe human gait transition speed on different gradients.

Chapter 5 is Discussion; this chapter discusses findings from all the three stages of studies in chapter 4 and attempts to tie the overall findings. Included in this chapter are summaries in response to the Operational Framework (Figure 3.1) shown in Chapter 3.

Chapter 6 is the Conclusion. It concludes the overall purpose of this thesis, contribution to knowledge and state the recommendations for future work in the area of gait transition studies.

1.9 Summary

This chapter serves as a guideline of the thesis where the introduction, background, problem and purpose statements, research objectives and questions, significance, scope and definitions of terms are presented.

It was the aim of the thesis to describe the human gait transition on the perspective of movement efficiency (kinematic and oxygen uptake kinetics). Findings from the study would probably contribute to further understanding on the strategy of alternating between gaits and on different gradient inclinations, whether it is better to alternate or merely use a single gait but varies the speed for the purpose of completing a distance foot race.

REFERENCES

Abbiss, C. R., & Laursen, P. B. (2005). Models to explain fatigue during prolonged endurance cycling. *Sports Medicine*, *35*(10), 865-898.

Abbiss, C. R., & Laursen, P. B. (2008). Describing and understanding pacing strategies during athletic competition. *Sports Medicine*, *38*(3), 239-252.

Abernethy, B., Burgess-Limerick, R., Engstrom, C., Hanna, A., & Neal, R. J. (1995). Temporal coordination of human gait. *Advances in Psychology*, *111*, 171-196.

Abernethy, B., Hanna, A., & Plooy, A. (2002). The attentional demands of preferred and non-preferred gait patterns. *Gait & Posture*, *15*(3), 256-265.

Abdolvahab, M. (2014). Positive hysteresis and negative hysteresis in human gait transition. Doctoral Dissertation, University of Connecticut.

Abdolvahab, M. (2015). A synergetic model for human gait transitions. *Physica A: Statistical Mechanics and its Applications*, *433*, 74-83.

Aerts, P., Van Damme, R., Van Elsacker, L., & Duchene, V. (2000). Spatio-temporal gait characteristics of the hind-limb cycles during voluntary bipedal and quadrupedal walking in bonobos (Pan paniscus). *American Journal of Physical Anthropology, 111*(4), 503.

Ahn, A. N., Furrow, E., & Biewener, A. A. (2004). Walking and running in the red-legged running frog, Kassina maculata. *Journal of Experimental Biology, 207*(3), 399-410.

Alexander, R. (1980). Optimum walking techniques for quadrupeds and bipeds. *Journal of Zoology*, *192*(1), 97-117.

Alexander, R. (1989). Optimization and gaits in the locomotion of vertebrates. *Physiology Review, 69*(1199-1227), 29-64.

Alexander, R. M. (1991). Energy-saving mechanisms in walking and running. *Journal of Experimental Biology*, *160*(1), 55-69.

Alexander, R. M. (2003). Modelling approaches in biomechanics. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 358*(1437), 1429-1435.

Alexander, R. (2004). Bipedal animals, and their differences from humans. *Journal of Anatomy, 204*(5), 321-330.

Alexander, R., & Jayes, A. (1983). A dynamic similarity hypothesis for the gaits of quadrupedal mammals. *Journal of Zoology, 201*(1), 135-152.

Anderson, F. C., & Pandy, M. G. (2001). Dynamic optimization of human walking. *Journal of Biomechanical Engineering, 123*(5), 381-390.

Anderson, T. (1996). Biomechanics and running economy. *Sports Medicine, 22*(2), 76-89.

Ardigo, L., Saibene, F., & Minetti, A. (2003). The optimal locomotion on gradients: walking, running or cycling? *European Journal of Applied Physiology, 90*(3-4), 365-371.

Bale, J. (2004). *Running cultures: Racing in time and space*. London: Routledge.

Bale, P., Rowell, S., & Colley, E. (1985). Anthropometric and training characteristics of female marathon runners as determinants of distance running performance. *Journal of Sports Sciences, 3*(2), 115-126.

Barrios, D. S. (2003). *Runner's World Complete Guide to Trail Running*. Rodale Books.

Bartlett, J. L., & Kram, R. (2008). Changing the demand on specific muscle groups affects the walk–run transition speed. *Journal of Experimental Biology, 211*(8), 1281-1288.

Beuter, A., and Lefebvre, R. (1988). Un modele theorique de transition de phase dans le locomotion humaine. *Canadian Journal of Applied Sport Science,* 13, 247-53.

Beaupied, H., Multon, F., & Delamarche, P. (2003). Does training have consequences for the walk–run transition speed? *Human Movement Science, 22*(1), 1-12.

Bentley, D. J., Cox, G. R., Green, D., & Laursen, P. B. (2008). Maximising performance in triathlon: Applied physiological and nutritional aspects of elite and non-elite competitions. *Journal of Science and Medicine in Sport, 11*(4), 407-416.

Bessot, N., Lericollais, R., Gauthier, A., Sesboüé, B., Bulla, J., & Moussay, S. (2015). Diurnal variation in gait characteristics and transition speed. *Chronobiology International*, *32*(1), 136-142.

Biewener, A. A., Farley, C. T., Roberts, T. J., & Temaner, M. (2004). Muscle mechanical advantage of human walking and running: implications for energy cost. *Journal of Applied Physiology, 97*(6), 2266-2274.

Billat, V. L., Slawinski, J., Danel, M., & Koralsztein, J. P. (2001). Effect of free versus constant pace on performance and oxygen kinetics in running. *Medicine and Science in Sports and Exercise, 33*(12), 2082-2088.

Borghese, N., Bianchi, L., & Lacquaniti, F. (1996). Kinematic Determinants of Human Locomotion. *Journal of Physiology, 494*(3), 863-879.

Bramble, D. M., & Lieberman, D. E. (2004). Endurance running and the evolution of Homo. *Nature, 432*(7015), 345-352.

Bredeweg, S. W., Zijlstra, S., & Buist, I. (2010). The GRONORUN 2 study: effectiveness of a preconditioning program on preventing running related injuries in novice runners. The design of a randomized controlled trial. *BMC Musculoskeletal Disorders, 11*(1), 196.

Bundle, M. W., & Weyand, P. G. (2012). Sprint exercise performance: does metabolic power matter? *Exercise and Sport Sciences Reviews, 40*(3), 174-182.

Cade, R., Packer, D., Zauner, C., Kaufmann, D., Peterson, J., Mars, D., Rogers, J. (1992). Marathon running: physiological and chemical changes accompanying late-race functional deterioration. *European Journal of Applied Physiology and Occupational Physiology, 65*(6), 485-491.

Cannon, W. B. (1929). Vob. IX July, 1929 No. 3 Organization for physiological homeostasis. *Physiological Reviews, 9*(3).

Cappozzo, A. (1984). Gait analysis methodology. *Human Movement Science, 3*(1), 27-50.

Cappozzo, A., Figura, F., Marchetti, M., & Pedotti, A. (1976). The interplay of muscular and external forces in human ambulation. *Journal of Biomechanics, 9*(1), 35-43.

Carrier, D. R. (1984). The Energetic Paradox of Human Running and Hominid Evolution. *Current Anthropology, 25*(4), 483-495.

Cavagna, G. A. (1977). Storage and utilization of elastic energy in skeletal muscle. *Exercise and Sport Sciences Reviews, 5*(1), 89-130.

Cavagna, G. A., Heglund, N. C., & Taylor, C. R. (1977). Mechanical work in terrestrial locomotion: two basic mechanisms for minimizing energy expenditure. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *233*(5), R243-R261.

Cavanagh, P., & Williams, K. (1982). The effect of stride length variation on oxygen uptake during distance running. *Medicine and Science in Sports and Exercise,, 14*(1), 30.

Cavanagh, P. R., & Kram, R. (1989). Stride length in distance running: velocity, body dimensions, and added mass effects. *Medicine and Science in Sports and Exercise, 21*(4), 467-479.

Chase, A., & Hobbs, N. (2010). *Ultimate Guide to Trail Running: Everything You Need to Know About Equipment* Finding Trails* Nutrition* Hill Strategy* Racing* Avoiding Injury* Training* Weather* Safety*. Rowman & Littlefield.

Chorley, J. N., Cianca, J. C., Divine, J. G., & Hew, T. D. (2002). Baseline injury risk factors for runners starting a marathon training program. *Clinical Journal of Sport Medicine, 12*(1), 18-23.

Conoboy, P., & Dyson, R. (2006). Effect of aging on the stride pattern of veteran marathon runners. *British Journal of Sports Medicine, 40*(7), 601-604.

Coyle, E. F, Coggan, A. R.(1984) Effectiveness of carbohydrate feeding in delaying fatigue during prolonged exercise. *Sports Medicine,* 1 (6), 446-58

Daniels, G., & Newell, K. (2002). Perceived task expectations and the walk–run gait transition. In *Proceedings of the 23rd Army Science Conference, Orlando*.

Daniels, G. L., & Newell, K. M. (2003). Attentional focus influences the walk–run transition in human locomotion. *Biological psychology, 63*(2), 163-178.

Davis, R. B. (1997). Reflections on clinical gait analysis. *Journal of Electromyography and Kinesiology, 7*(4), 251-257.

De Koning, J. J., Bobbert, M. F., Foster, C. (1999). Determination of optimal pacing strategy in track cycling with an energy flow model. *Journal of Science and Medicine in Sport*, *2*(3), 266-277.

De Koning, J. J., Foster, C., Bakkum, A., Kloppenburg, S., Thiel, C., Joseph, T., & Porcari, J. P. (2011). Regulation of pacing strategy during athletic competition. *PloS one*, *6*(1), e15863.

Del Coso, J., Fernández, D., Abián-Vicen, J., Salinero, J. J., González-Millán, C., Areces, F., Pérez-González, B. (2013). Running pace decrease during a marathon is positively related to blood markers of muscle damage. *PloS one, 8*(2), e57602.

Derrick, T. R., Hamill, J., & Caldwell, G. E. (1998). Energy absorption of impacts during running at various stride lengths. *Medicine and Science in Sports and Exercise, 30*(1), 128-135.

Diedrich, F. J., & Warren Jr, W. H. (1995). Why change gaits? Dynamics of the walk-run transition. *Journal of Experimental Psychology: Human Perception and Performance, 21*(1), 183.

Diedrich, F. J., & Warren Jr, W. H. (1998). The dynamics of gait transitions: Effects of grade and load. *Journal of Motor Behavior, 30*(1), 60-78.

Dolan, S. H., Houston, M., & Martin, S. B. (2011). Survey results of the training, nutrition, and mental preparation of triathletes: practical implications of findings. *Journal of Sports Sciences, 29*(10), 1019-1028.

Doppelmayr, M., & Molkenthin, A. (2004). Motivation of participants in adventure ultramarathons compared to other foot races. *Biology of Sport*, *21*(4), 319-323.

Donelan, J. M., & Kram, R. (1997). The effect of reduced gravity on the kinematics of human walking: a test of the dynamic similarity hypothesis for locomotion. *Journal of Experimental Biology, 200*(24), 3193-3201.

Donelan, J. M., & Kram, R. (2000). Exploring dynamic similarity in human running using simulated reduced gravity. *Journal of Experimental Biology, 203*(16), 2405-2415.

Donelan, J. M., Kram, R., & Kuo, A. D. (2001). Mechanical and metabolic cost as a function of step length in human walking. *American Society of Biomechanics.* San Diego, California.

Drucker, E. G. (1996). The use of gait transition speed in comparative studies of fish locomotion. *American Zoologist*, *36*(6), 555-566.

Eden, B. L. (2009). Encyclopedia of Sports in America: A History from Foot Races to Extreme Sports. *Reference Reviews, 23*(7), 46-47.

Elliott, B., & Blanksby, B. (1979). Optimal stride length considerations for male and female recreational runners. *British Journal of Sports Medicine, 13*(1), 15.

Elliott, J. B. (2012). Marathon pacing and elevation change. *arXiv preprint arXiv:1205.0057*.

Ely, M. R., Martin, D. E., Cheuvront, S. N., & Montain, S. J. (2008). Effect of ambient temperature on marathon pacing is dependent on runner ability. *Medicine and Science in Sports and Exercise, 40*(9), 1675-1680.

Enomoto Y, Kadono H, Suzuki Y, Chiba T, Koyama K. (2008). Biomechanical analysis of the medalists in the 10,000 metres at the 2007 World Championships in Athletics. *New Studies in athletics*, *3*, 61-66.

Esteve-Lanao, J., San Juan, A. F., Earnest, C. P., Foster, C., & Lucia, A. (2005). How do endurance runners actually train? Relationship with competition performance. *Medicine and Science in Sports and Exercise*, *37*(3), 496-504.

Esteve-Lanao, J., Rhea, M. R., Fleck, S. J., & Lucia, A. (2008). Running-specific, periodized strength training attenuates loss of stride length during intense endurance running. *The Journal of Strength & Conditioning Research*, *22*(4), 1176-1183.

Farley, C. T., & Ferris, D. P. (1998). 10 Biomechanics of Walking and Running: Center of Mass Movements to Muscle Action. *Exercise and Sport Sciences Reviews, 26*(1), 253-286.

Farley, C. T., & Taylor, C. R. (1991). A mechanical trigger for the trot-gallop transition in horses. *Science*, *253*(5017), 306-308.

Ferber, R., McClay Davis, I., & Williams Iii, D. S. (2003). Gender differences in lower extremity mechanics during running. *Clinical Biomechanics, 18*(4), 350-357.

Ferris, D. P., Louie, M., & Farley, C. T. (1998). Running in the real world: adjusting leg stiffness for different surfaces. *Proceedings of the Royal Society of London. Series B: Biological Sciences, 265*(1400), 989-994.

Foster, C., de Koning, J. J, Hettinga, F. (2004). Effect of competitive distance on energy expenditure during simulated competition, *International Journal of Sports Medicine,* 25 (3): 198-204

Fukuba, Y., Whipp, B. J. (1999). A metabolic limit on the ability to make up for lost time in endurance events. *Journal Applied Physiology,* 87(2), 853-61

Fredericson, M., & Misra, A. K. (2007). Epidemiology and aetiology of marathon running injuries. *Sports Medicine, 37*(4-5), 437-439.

Galloway, J. (2010). *Marathon: You Can Do It!* : Shelter Publications, Inc.

Galloway, J. (2013). *The Run-Walk-Run Method*: Maidenhead: Meyer & Meyer Sport (UK) Verlag.

Gatesy, S. M. (1999a). Guineafowl hind limb function. I: Cineradiographic analysis and speed effects. *Journal of Morphology, 240*(2), 115-125.

Gatesy, S. M. (1999b). Guineafowl hind limb function. II: Electromyographic analysis and motor pattern evolution. *Journal of Morphology, 240*(2), 127-142.

Getchell, N., & Whitall, J. (1997). Transitions in gait as a function of physical parameters. *Journal of Sport & Exercise Psychology* , 19, S55-S55.

Getchell, N., & Whitall, J. (2004). Transitions to and from asymmetrical gait patterns. *Journal of Motor Behavior*, *36*(1), 13-27.

Geyer, H., Seyfarth, A., & Blickhan, R. (2006). Compliant leg behaviour explains basic dynamics of walking and running. *Proceedings of the Royal Society B: Biological Sciences, 273*(1603), 2861-2867.

Gibson, A. S. C., De Koning, J. J., Thompson, K. G., Roberts, W. O., Micklewright, D., Raglin, J., & Foster, C. (2013). Crawling to the Finish Line: Why do Endurance Runners Collapse? *Sports Medicine, 43*(6), 413-424.

Gosztyla, A. E., Edwards, D. G., Quinn, T. J., & Kenefick, R. W. (2006). The impact of different pacing strategies on five-kilometer running time trial performance. *The Journal of Strength & Conditioning Research, 20*(4), 882-886.

Grieve, D., & Gear, R. J. (1966). The relationships between length of stride, step frequency, time of swing and speed of walking for children and adults. *Ergonomics, 9*(5), 379-399.

Grillner, S., Halbertsma, J., Nilsson, J., & Thorstensson, A. (1979). The adaptation to speed in human locomotion. *Brain research*, *165*(1), 177-182.

Gutmann, A. K., Jacobi, B., Butcher, M. T., & Bertram, J. E. (2006). Constrained optimization in human running. *Journal of Experimental Biology, 209*(4), 622-632.

Hagio, S., Fukuda, M., & Kouzaki, M. (2015). Identification of muscle synergies associated with gait transition in humans. *Frontiers in Human Neuroscience*, 9, 48

Haney Jr, T. & Mercer, J. A. (2011). A Description of Variability of Pacing in Marathon Distance Running. *International Journal of Exercise Science, 4*(2), 6.

Hanley, B., Bissas, A., & Drake, A. (2011). Kinematic characteristics of elite men's and women's 20 km race walking and their variation during the race. *Sports Biomechanics, 10*(02), 110-124.

Hanna, A. J., Abernethy, B., Neal, R. J., & Plooy, A. M. (1996). Anthropometric predictors of human gait transitions. In L. M. Gilleard, W. Sinclair, P. Smith, & R. Swain (Eds.), *Proceedings of the first Australasian Biomechanics Conference. Sydney* (pp. 22-23).

Hanna, A., Abernethy, A., Neal, R. J., & Burgess-Limerick, R. (2000). Triggers for the transition between human walking and running. *Energetics of Human Activity*, 124-164.

Harun, H. H., & Lakany, H. (2003). Kinematics variations of gait from two 5 km cross-country races, *Proceedings of the IASTED International Conference on Biomechanics,* 215-219.

Harvie, R. (2011). *Why We Run*: Hachette UK.

Hay, J. G. (2002). Cycle rate, length, and speed of progression in human locomotion. *Journal of Applied Biomechanics, 18*(3), 257-270.

Haynes, G. C., & Rizzi, A. A. (2006). Gaits and gait transitions for legged robots. In *Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006.* (pp. 1117-1122). IEEE.

Herbst, L., Knechtle, B., Lopez, C. L., Andonie, J. L., Fraire, O. S., Kohler, G., Rüst C.A., Rosemann, T. (2011). Pacing strategy and change in body composition during a Deca Iron triathlon. *Chinese Journal of Physiology,* 54(4), 255-263.

Heglund, N. C., and Taylor, C.R. (1988). Speed, stride frequency and energy cost per stride: how do they change with body size and gait? *Journal of Experimental Biology,* 138(1), 301-318.

Hildebrand, M. (1985). Functional Vertebrate Morphology: Chapter 3 - Walking and Running. *Cambridge: Belknap Press.*

Hoffman, M. D., Ong, J. C., & Wang, G. (2010). Historical analysis of participation in 161 km ultramarathons in North America. *The International Journal of The History of Sport, 27*(11), 1877-1891.

Hottenrott, K., Ludyga, S., Schulze, S., Gronwald, T., & Jäger, F. S. (2014). Does a run/walk strategy decrease cardiac stress during a marathon in non-elite runners?. *Journal of Science and Medicine in Sport*, 19(1), 64-68.

Hoyt, D. F., and Taylor, (1981). Gait and energetics of locomotion in horses. *Nature* 292, 239–240,

Hreljac, A. (1993a). Determinants of the gait transition speed during human locomotion: kinetic factors. *Gait & Posture,* 1(4), 217-223.

Hreljac, A. (1993b). Preferred and energetically optimal gait transition speeds in human locomotion. *Medicine and Science in Sports and Exercise,* 25(10), 1158-1162.

Hreljac, A. (1995a). Determinants of the gait transition speed during human locomotion: kinematic factors. *Journal of Biomechanics, 28*(6), 669-677.

Hreljac, A. (1995b). Effects of physical characteristics on the gait transition speed during human locomotion. *Human Movement Science, 14*(2), 205-216.

Hreljac, A. (2000). Stride smoothness evaluation of runners and other athletes. *Gait & Posture, 11*(3), 199-206.

Hreljac, A., & Ferber, R. (2000). The relationship between gait transition speed and dorsiflexor force production. *Archives of Physiology and Biochemistry, 108*(1-2), 90-90.

Hreljac, A., & Marshall, R. N. (2000). Algorithms to determine event timing during normal walking using kinematic data. *Journal of Biomechanics, 33*(6), 783-786.

Hreljac, A., Marshall, R. N., & Hume, P. A. (2000). Evaluation of lower extremity overuse injury potential in runners. *Medicine and Science in Sports and Exercise, 32*(9), 1635-1641.

Hreljac, A., Arata, A., Ferber, R., Mercer, J. A., & Row, B. S. (2001). An electromyographical analysis of the role of dorsiflexors on the gait transition during human locomotion. *Journal of Applied Biomechanics, 17*(4), 287-296.

Hreljac, A., Parker, D., Quintana, R., Abdala, E., Patterson, K., & Sison, M. (2002). Energetics and perceived exertion of low speed running and high speed walking. *Facta universitatis-series: Physical Education and Sport, 1*(9), 27-35.

Hreljac, A. (2004). Impact and overuse injuries in runners. *Medicine and Science in Sports and Exercise, 36*(5), 845-849.

Hreljac, A., Imamura, R. T., Escamilla, R. F., & Edwards, W. B. (2007a). When does a gait transition occur during human locomotion? *Journal of Sports Science & Medicine, 6*(1), 36.

Hreljac, A., Imamura, R., Escamilla, R. F., & Edwards, W. B. (2007b). Effects of changing protocol, grade, and direction on the preferred gait transition speed during human locomotion. *Gait & posture, 25*(3), 419-424.

Hubel, T. Y., & Usherwood, J. R. (2013). Vaulting mechanics successfully predict decrease in walk–run transition speed with incline. *Biology letters, 9*(2), 20121121.

Hunter, I., & Smith, G. A. (2007). Preferred and optimal stride frequency, stiffness and economy: changes with fatigue during a 1-h high-intensity run. *European Journal of Applied Physiology, 100*(6), 653-661.

Hutchinson, J. R., Famini, D., Lair, R., & Kram, R. (2003). Biomechanics: Are fast-moving elephants really running? *Nature, 422*(6931), 493-494.

Ivanenko, Y. P., Labini, F. S., Cappellini, G., Macellari, V., McIntyre, J., & Lacquaniti, F. (2011). Gait transitions in simulated reduced gravity. *Journal of Applied Physiology,* 110(3), 781-788.

Jordan, K., Challis, J. H., & Newell, K. M. (2006). Long range correlations in the stride interval of running. *Gait & posture, 24*(1), 120-125.

Joyner, M. J., & Coyle, E. F. (2008). Endurance exercise performance: the physiology of champions. *The Journal of Physiology, 586*(1), 35-44.

Kadaba, M. P., Ramakrishnan, H. K., Wootten, M. E. (1990). Measurement of lowerextremity kinematics during level walking. *Journal of Orthopaedic Research,* 8(3), 383-392.

Kram, R., & Taylor, C. R. (1990). Energetics of running: a new perspective. *Nature*, *346*(6281), 265-267.

Kram, R., Domingo, A., & Ferris, D. P. (1997). Effect of reduced gravity on the preferred walk-run transition speed. *The Journal of Experimental Biology*, *200*(4), 821-826.

Kuo, A. D. (2007). The six determinants of gait and the inverted pendulum analogy: A dynamic walking perspective. *Human movement science*, *26*(4), 617-656.

Lambert, M. I., Dugas, J. P., Kirkman, M. C., Mokone, G. G., & Waldeck, M. R. (2004). Changes in running speeds in a 100 km ultra-marathon race. *Journal of Sports Science & Medicine, 3*(3), 167.

Lee, C. R., & Farley, C. T. (1998). Determinants of the center of mass trajectory in human walking and running. *Journal of Experimental Biology*, *201*(21), 2935-2944.

Li, L., Van den Bogert, E. C., Caldwell, G. E., van Emmerik, R. E., & Hamill, J. (1999). Coordination patterns of walking and running at similar speed and stride frequency. *Human Movement Science, 18*(1), 67-85.

Li, L. (2000). Stability landscapes of walking and running near gait transition speed. *Journal of Applied Biomechanics*, *16*(4), 428-435.

Lieberman, D. E., & Bramble, D. M. (2007). The Evolution of Marathon Running. *Sports medicine, 37*(4-5), 288-290.

Long, L. L., & Srinivasan, M. (2013). Walking, running, and resting under time, distance, and average speed constraints: optimality of walk–run–rest mixtures. *Journal of The Royal Society Interface, 10*(81), 20120980.

Luhtanen, P., and Komi, P. V. (1978). Mechanical factors influencing running speed. In: E Asmussen and K Jorgensen (eds.), Biomechanics VI-B (pp. 23-29). Baltimore: University Park Press.

Lysholm, J., & Wiklander, J. (1987). Injuries in runners. *The American Journal of Sports Medicine, 15*(2), 168-171.

Macera, C. A., Pate, R. R., Woods, J., Davis, D., & Jackson, K. (1991). Postrace morbidity among runners. *American Journal of Preventive Medicine, 7*(4), 194-198.

MacLeod, T. D., Hreljac, A., Imamura, R., Collins, A., Blackburn, T., Olcott, C., & Wang, S. J. (2014). Changes in the preferred transition speed with added mass to the foot. *Journal of Applied Biomechanics*, *30*(1).

Malcolm, P., Segers, V., Van Caekenberghe, I., De Clercq, D. (2009). Experimental study of the influence of the m. tibialis anterior on the walk-to-run transition by means of a powered ankle-foot exoskeleton. *Gait & Posture*. 29(1):6-10

Malisoux, L., Francaux, M., Nielens, H., & Theisen, D. (2006). Stretch-shortening cycle exercises: an effective training paradigm to enhance power output of human single muscle fibers. *Journal of Applied Physiology*, *100*(3), 771-779.

March, D. S., Vanderburgh, P. M., Titlebaum, P. J., & Hoops, M. L. (2011). Age, sex, and finish time as determinants of pacing in the marathon. *The Journal of Strength & Conditioning Research*, *25*(2), 386-391.

Margaria, R., Cerretelli, P., Aghemo, P., & Sassi, G. (1963). Energy cost of running. *Journal of Applied Physiology, 18*, 367.

Mattern, C. O., Kenefick, R. W., Kertzer, R. (2001). Impact of starting strategy on cycling performance. *International Journal of Sports Medicine*, 22 (5), 350-355

McMahon, T. A., Valiant, G., & Frederick, E. C. (1987). Groucho running. *Journal of Applied Physiology, 62*(6), 2326-2337.

Mercer, J. A., Devita, P., Derrick, T. R., & Bates, B. T. (2003). Individual effects of stride length and frequency on shock attenuation during running. *Medicine and Science in Sports and Exercise, 35*(2), 307-313.

Mercier, J., Le Gallais, D., Durand, M., Goudal, C., Micallef, J. P., & Préfaut, C. (1994). Energy expenditure and cardiorespiratory responses at the transition between walking and running. *European Journal of Applied Physiology and Occupational Physiology*, *69*(6), 525-529.

Miller, R. H., Umberger, B. R. and Caldwell, G. E. (2011). Limitations to maximum sprinting speed imposed by muscle mechanical properties. *Journal of Biomechanics,* 45, 1092-1097.

Millet, G. Y., Morin, J.-B., Degache, F., Edouard, P., Feasson, L., Verney, J., & Oullion, R. (2009). Running from Paris to Beijing: biomechanical and physiological consequences. *European Journal of Applied Physiology, 107*(6), 731-738.

Minetti, A., & Alexander, R. (1997). A theory of metabolic costs for bipedal gaits. *Journal of Theoretical Biology, 186*(4), 467-476.

Minetti, A., Ardigo, L., & Saibene, F. (1994). The transition between walking and running in humans: metabolic and mechanical aspects at different gradients. *Acta Physiologica Scandinavica, 150*(3), 315-323.

Minetti, A. E. (1998a). The biomechanics of skipping gaits: a third locomotion paradigm? *Proceedings of the Royal Society of London. Series B: Biological Sciences, 265*(1402), 1227-1233.

Minetti, A. E. (1998b). A model equation for the prediction of mechanical internal work of terrestrial locomotion. *Journal of Biomechanics, 31*(5), 463-468.

Minetti, A. E. (2001). Biomechanics: Walking on other planets. *Nature*, *409*(6819), 467-469.

Minetti, A., & Ardigo, L. (2001). The transmission efficiency of backward walking at different gradients. *Pflügers Archiv - European Journal of Physiology*, *4*(442), 542-546.

Minetti, A. E., Moia, C., Roi, G. S., Susta, D., & Ferretti, G. (2002). Energy cost of walking and running at extreme uphill and downhill slopes. *Journal of Applied Physiology, 93*(3), 1039-1046.

Minetti, A. E., Boldrini, L., Brusamolin, L., Zamparo, P., & McKee, T. (2003). A feedback-controlled treadmill (treadmill-on-demand) and the spontaneous speed of walking and running in humans. *Journal of Applied Physiology, 95*(2), 838-843.

Mochon, S., & McMahon, T. A. (1980). Ballistic walking: An improved model. *Mathematical Biosciences, 52*(3), 241-260.

Moldenhauer, C., & Sturtevant, N. R. (2009). Evaluating Strategies for Running from the Cops. In *Proceedings of the 21st International Joint Conference on Artificial Intelligence (IJCAI'09)*, 584–589.

Morgan, W. P., Pollock, M. L. (1977). Psychologic characterization of the elite distance runner. *Annals of the New York Academy of Sciences*, *301*(1), 382-403.

Morin, J., Tomazin, K., Edouard, P., & Millet, G. (2011). Changes in running mechanics and spring–mass behavior induced by a mountain ultra-marathon race. *Journal of Biomechanics, 44*(6), 1104-1107.

Neptune, R. R., Kautz, S., & Zajac, F. (2001). Contributions of the individual ankle plantar flexors to support, forward progression and swing initiation during walking. *Journal of Biomechanics, 34*(11), 1387-1398.

Neptune, R., & Sasaki, K. (2004). Insight from ground reaction forces into the preferred gait transition speed. In *9th Annual Meeting of the Gait and Clinical Movement Analysis Society,* Lexington, Kentucky.

Neptune, R. R., & Sasaki, K. (2005). Ankle plantar flexor force production is an important determinant of the preferred walk-to-run transition speed.*Journal of Experimental Biology*, *208*(5), 799-808.

Niemuth, P. E., Johnson, R. J., Myers, M. J., & Thieman, T. J. (2005). Hip muscle weakness and overuse injuries in recreational runners. *Clinical Journal of Sport Medicine, 15*(1), 14-21.

Nilsson, J., & Thorstensson, A. (1987). Adaptability in frequency and amplitude of leg movements during human locomotion at different speeds. *Acta physiologica Scandinavica, 129*(1), 107-114.

Nilsson, J., Thorstensson, A., & Halbertsma, J. (1985). Changes in leg movements and muscle activity with speed of locomotion and mode of progression in humans. *Acta Physiologica Scandinavica, 123*(4), 457-475.

Noakes, T. D. (1992). The hyponatremia of exercise. *International Journal of Sport Nutrition*, *2*(3), 205-228.

Noakes, T. D. (2003). *Lore of running*. (4th edition). Champaign, Illinois: Human Kinetics Publishers.

Novacheck, T. F. (1998). The biomechanics of running. *Gait & Posture, 7*(1), 77-95.

Oakes, J. (1997). Walking the walk. *Marathon and Beyond* 1: 27-41.

Padilla, S., Mujika, I., Angulo, F. (2000). Scientific approach to the 1-h cycling world record: a case study. *Journal Applied Physiology,* 89, 1522-1527.

Padulo, J., Powell, D., Milia, R., & Ardigò, L. P. (2013). A paradigm of uphill running. *PloS one, 8*(7), e69006.

Patla, A. E., & Sparrow, W. A. (2000). Factors that have shaped human locomotor structure and behavior: the "joules" in the crown. *Energetics of Human Activity*, 43-65.

Peeling, P., Dawson, B., Goodman, C., Landers, G., Wiegerinck, E. T., Swinkels, D. W., & Trinder, D. (2009). Cumulative effects of consecutive running sessions on hemolysis, inflammation and hepcidin activity. *European Journal of Applied Physiology, 106*(1), 51-59.

Prilutsky, B. I., & Gregor, R. J. (2001). Swing-and support-related muscle actions differentially trigger human walk–run and run–walk transitions. *Journal of Experimental Biology, 204*(13), 2277-2287.

Rauch, H. G. L., St. Clair Gibson, A., Lambert, E. V. (2005). A signalling role for muscle glycogen in the regulation of pace during prolonged exercise. *British journal of sports medicine*, *39*(1), 34-38.

Raynor, A. J., Yi, C. J., Abernethy, B., & Jong, Q. J. (2002). Are transitions in human gait determined by mechanical, kinetic or energetic factors? *Human Movement Science, 21*(5), 785-805.

Reilly, T., Secher, N., Snell, P., & Williams, C. (1992). Physiology of Sports. *Medicine & Science in Sports & Exercise, 24*(2), 278.

Roberts, T. J., Kram, R., Weyand, P. G., & Taylor, C. R. (1998). Energetics of bipedal running. I. Metabolic cost of generating force. *Journal of Experimental Biology, 201*(19), 2745-2751.

Rotstein, A., Inbar, O., Berginsky, T., & Meckel, Y. (2005). Preferred transition speed between walking and running: effects of training status. *Medicine and Science in Sports and Exercise*, *37*(11), 1864.

Rubenson, J., Heliams, D. B., Lloyd, D. G., & Fournier, P. A. (2004). Gait selection in the ostrich: mechanical and metabolic characteristics of walking and running with and without an aerial phase. *Proceedings of the Royal Society of London-B, 271*(1543), 1091.

Saibene, F., & Minetti, A. E. (2003). Biomechanical and physiological aspects of legged locomotion in humans. *European Journal of Applied Physiology, 88*(4-5), 297-316.

Salo, A., Bezodis, I.N., Batterham, A.M. & Kerwin, D.G. (2011). Elite sprinting: are athletes individually step frequency or step length reliant? *Medicine and Science in Sports and Exercise*, *43*(6), 1055-1062.

Sandals, L. E., Wood, D. M., Draper, S. B. (2006). Influence of pacing strategy on oxygen uptake during treadmill middle-distance running. *International Journal of Sports Medicine*, 27 (1), 37-42

Santamaria, V., & Furst, D. (1994). Distance runners' causal attributions for most successful and least successful races. *Journal of Sport Behavior, 17*(1), 43-51.

Santos-Lozano, A., Collado, P. S., Foster, C., Lucia, A., & Garatachea, N. (2014). Influence of sex and level on marathon pacing strategy: insights from the New York City race. *International Journal of Sports Medicine*, *35*, 933-938.

Satterthwaite, P., Larmer, P., Gardiner, J., & Norton, R. (1996). Incidence of injuries and other health problems in the Auckland Citibank marathon, 1993. *British Journal of Sports Medicine, 30*(4), 324-326.

Sawyer, B. J., Blessinger, J. R., Irving, B. A., Weltman, A., Patrie, J. T., & Gaesser, G. A. (2010). Walking and running economy: inverse association with peak oxygen uptake. *Medicine and Science in Sports and Exercise, 42*(11), 2122.

Sears, F. W., Zemansky, M. W., & Young, H. (1982). University Physics–6th Edition: Addison. *Westley Publishing Company*.

Segers, V., Aerts, P., Lenoir, M., & De Clercq, D. (2006). Spatiotemporal characteristics of the walk-to-run and run-to-walk transition when gradually changing speed. *Gait & Posture, 24*(2), 247-254.

Segers, V. (2007). *A Biomechanical analysis of the realization of actual human gait transition.* (Doctoral dissertation - Ghent University).

Segers, V., Lenoir, M., Aerts, P., & De Clercq, D. (2007a). Kinematics of the transition between walking and running when gradually changing speed. *Gait & Posture*, *26*(3), 349-361.

Segers, V., Aerts, P., Lenoir, M., & De Clerq, D. (2007b). Dynamics of the body centre of mass during actual acceleration across transition speed. *Journal of Experimental Biology, 210*(4), 578-585.

Segers, V., Lenoir, M., Aerts, P., & De Clercq, D. (2007c). Kinematics of the transition between walking and running when gradually changing speed. *Gait & Posture, 26*(3), 349-361.

Segers, V., De Smet, K., Van Caekenberghe, I., Aerts, P., & De Clercq, D. (2013). Biomechanics of spontaneous overground walk-to-run transition.*Journal of Experimental Biology*, *216*(16), 3047-3054.

Sellers, W. I., Cain, G. M., Wang, W., & Crompton, R. H. (2005). Stride lengths, speed and energy costs in walking of Australopithecus afarensis: using evolutionary robotics to predict locomotion of early human ancestors. *Journal of The Royal Society Interface, 2*(5), 431-441.

Sentija, D., & Markovic, G. (2009). The relationship between gait transition speed and the aerobic thresholds for walking and running. *International Journal of Sports Medicine, 30*(11), 795.

Shipway, R (2010). *On the run: Perspectives on long distance running.* (Doctoral dissertation - Bournemouth University).

Sparrow, W., & Newell, K. (1998). Metabolic energy expenditure and the regulation of movement economy. *Psychonomic Bulletin & Review, 5*(2), 173-196.

Sparrow, W. A. (2000). *Energetics of human activity*. Champaign, Illinois: Human Kinetics Publishers.

Srinivasan, M., & Ruina, A. (2006). Minimal model of a locomoting bipedal animal. *Journal of Biomechanics, 39*, S119.

St Clair Gibson, A., Lambert, M. I, Noakes, T. D. (2001). Neural control of force output during maximal and submaximal exercise. *Sports Medicine*, *31*(9), 637-650.

St Clair Gibson, A., Noakes, T. D. (2004). Evidence for complex system integration and dynamic neural regulation of skeletal muscle recruitment during exercise in humans. *British Journal of Sports Medicine*, *38*(6), 797-806

Stellingwerff, T., & Jeukendrup, A. E. (2011). Don't forget the gut - it is an important athletic organ! *Journal of Applied Physiology, 110*(1).

Steudel-Numbers, K. L., & Wall-Scheffler, C. M. (2009). Optimal running speed and the evolution of hominin hunting strategies. *Journal of Human Evolution, 56*(4), 355-360.

Stock, J. T., O'neill, M. C., Ruff, C. B., Zabecki, M., Shackelford, L., & Rose, J. C. (2011). Body Size, Skeletal Biomechanics, Mobility and Habitual Activity from the Late Palaeolithic to the Mid-Dynastic Nile Valley. *Human Bioarchaeology of the Transition to Agriculture*, 347-367.

Sutherland, D. H. (2001). The evolution of clinical gait analysis part l: kinesiological EMG. *Gait & posture, 14*(1), 61-70.

Sutherland, D. H. (2002). The evolution of clinical gait analysis: Part II Kinematics. *Gait & posture, 16*(2), 159-179.

Sutherland, D. H. (2005). The evolution of clinical gait analysis part III–kinetics and energy assessment. *Gait & posture, 21*(4), 447-461.

Swain, D. P. (1997). A model for optimizing cycling performance by varying power on hills and in wind. *Medicine and Science in Sports and Exercise*, *29*(8), 1104-1108.

Tanawongsuwan, R., & Bobick, A. (2003). Performance analysis of time-distance gait parameters under different speeds. In *International Conference on Audio- and Video-Based Biometric Person Authentication* (pp. 715-724). Springer Berlin Heidelberg.

Thompson, K., MacLaren, D., Lees, A., & Atkinson, G. (2003). The effect of even, positive and negative pacing on metabolic, kinematic and temporal variables during breaststroke swimming. *European Journal of Applied Physiology, 88*(4-5), 438-443.

Thorstensson, A., and Roberthson, H. (1987). Adaptations to changing speed in human locomotion , speed of transition between walking and running. *Acta physiologica Scandinavica*, *131*(2), 211-214.

Townshend, A. D., Worringham, C. J., & Stewart, I. (2010). Spontaneous pacing during overground hill running. *Medicine and Science in Sports and Exercise, 42*(1), 160-169.

Tseh, W., Bennett, J., Caputo, J. L., & Morgan, D. W. (2002). Comparison between preferred and energetically optimal transition speeds in adolescents. *European Journal of Applied Physiology, 88*(1-2), 117-121.

Tucker, R., Rauch, L., Harley, Y. X., & Noakes, T. D. (2004). Impaired exercise performance in the heat is associated with an anticipatory reduction in skeletal muscle recruitment. *Pflügers Archiv European Journal of Physiology*, *448*(4), 422-430.

Tucker, R., & Noakes, T. D. (2009). The physiological regulation of pacing strategy during exercise: a critical review. *British Journal of Sports Medicine*,*43*(6), e1-e1.

Turvey, M. T., Holt, K. G., LaFiandra, M. E., & Fonseca, S. T. (1999). Can the transitions to and from running and the metabolic cost of running be determined from the kinetic energy of running? *Journal of Motor Behavior, 31*(3), 265-278.

Usherwood, J. R. (2005). Why not walk faster? *Biology letters, 1*(3), 338-341.

Usherwood, J. R. (2010). Inverted pendular running: a novel gait predicted by computer optimization is found between walk and run in birds. *Biology Letters, 6*(6), 765-768.

Usherwood, J. R., & Bertram, J. E. (2003). Gait transition cost in humans. *European Journal of Applied Physiology,* 90(5-6), 647-650.

Usherwood, J. R., Szymanek, K. L., & Daley, M. A. (2008). Compass gait mechanics account for top walking speeds in ducks and humans. *Journal of Experimental Biology, 211*(23), 3744-3749.

Van Coppenolle, I., & Aerts, P. (2004). Terrestrial locomotion in the white stork (Ciconia ciconia): spatio-temporal gait characteristics. *Animal Biology-Leiden, 54*(3), 281-292.

Van Gent, R., Siem, D., van Middelkoop, M., van Os, A., Bierma-Zeinstra, S., & Koes, B. (2007). Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. *British Journal of Sports Medicine, 41*, 469-480.

Watier, B., Villeger, D., Costes, A., & Moretto, P. (2015). A preliminary study suggests that walk-to-run transition is consistent with mechanical optimization. *Computer Methods in Biomechanics and Biomedical Engineering*, *18*(sup1), 2080-2081.

Wegelin, J. A., & Hoffman, M. D. (2011). Variables associated with odds of finishing and finish time in a 161-km ultramarathon. *European Journal of Applied Physiology, 111*(1), 145-153.

Weir, J. d. V. (1949). New methods for calculating metabolic rate with special reference to protein metabolism. *The Journal of physiology, 109*(1-2), 1.

Weyand, P. G., Sternlight, D. B., Bellizzi, M. J., & Wright, S. (2000). Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *Journal of Applied Physiology*, *89*(5), 1991-1999.

Weyand, P. G., Smith, B. R., Puyau, M. R., & Butte, N. F. (2010). The mass-specific energy cost of human walking is set by stature. *The Journal of Experimental Biology, 213*(23), 3972-3979.

Whittle, M. W. (1996). Clinical gait analysis: A review. *Human Movement Science, 15*(3), 369-387.

Whittle, M. W. (2003). *Gait Analysis: an introduction (third edition)* Oxford: Butterworth -Heinemann.

Willems, P., Cavagna, G., & Heglund, N. (1995). External, internal and total work in human locomotion. *The Journal of Experimental Biology, 198*(2), 379-393.

Williams, K., Cavanagh, P., & Ziff, J. (1987). Biomechanical studies of elite female distance runners. *International Journal of Sports Medicine, 8*, 107-118.

Williams, P. T. (1997). Relationship of distance run per week to coronary heart disease risk factors in 8283 male runners: the National Runners' Health Study. *Archives of internal medicine, 157*(2), 191-198.

Williams, P. T. (2012). Non-exchangeability of running vs. other exercise in their association with adiposity, and its implications for public health recommendations. *PLoS One*, *7*(7), e36360.

Yamamoto, M., & Kanehisa, H. (1995). Dynamics of anaerobic and aerobic energy supplies during sustained high intensity exercise on cycle ergometer. *European Journal of Applied Physiology and Occupation Physiology,* 71(4):

320-5.

Zatsiorsky, V. (1994). Advanced Sport Biomechanics. *Pensilvania, Estados Unidos: The Pennsylvania State University, Boimechanics Laboratory*.

Zehr, E. P., & Duysens, J. (2004). Regulation of arm and leg movement during human locomotion. *The Neuroscientist, 10*(4), 347-361.