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

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وَمَا أَسْأَلُكُمْ عَلَيْهِ مِنْ أَجْرٍ ۖ إِنْ أَجْرِيَ إِلَّا عَلَىٰ رَبِّ الْعَالَمِينَ

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):

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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.

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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)
f	-	Foot extension
$\hat{f}$	-	Foot extension on gradients
R	-	The limb length
L	-	The step length
$\hat{L}$	-	Step length on gradients
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
I	-	Moment of inertia

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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).

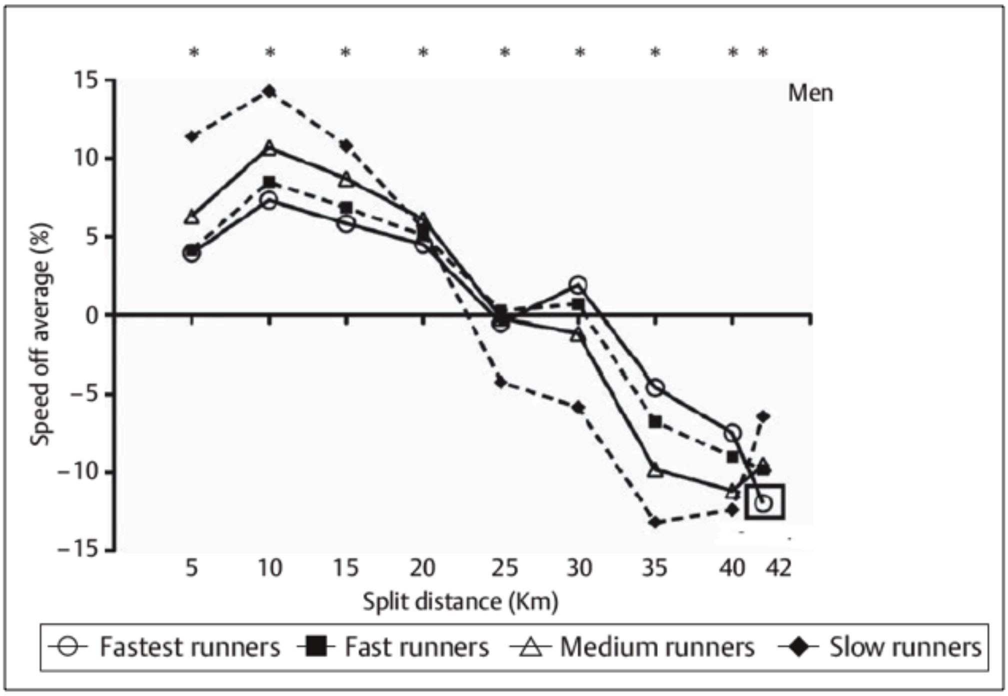


Figure 1.0 : Positive pace (fast to slow) of all calibre runners in a marathon (taken from Santos *et al.* 2014).

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 ($\bar{V}O_2$) 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 ($\bar{\nabla}O_2$ 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.

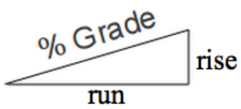
Subjects went through experiments on a motorized treadmill that was inclined to several uphill and downhill gradients in a test laboratory situation.

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 ($\overline{V}O_2$ 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 ($\overline{V}O_2$ **ml.kg.$^{-1}$ stride.$^{-1}$)**.
Metabolic energy expenditure	The amount of oxygen consumed ($\overline{V}O_2$ **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.

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