The effects of an eight-week customised endurance-training programme on running kinematics and impact associated with fatigue in recreational runners

by

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Thesis presented in partial fulfilment of the requirements for the degree of

PhD of Sport Science in the Faculty of Education

at

Stellenbosch University

(Article-Format PhD Dissetation)

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April 2019

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DECLARATION

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SUMMARY

Background: The unrestrained and easily accessible nature of running has led to an exponential increase in participation in running. However, the incidence rate of injuries is a concern. Loading and fatigability have been linked as underlying injury risk factors. It has been proposed that runners would automatically fine-tune their kinematics after exposure to training to be more efficient for better performance and reduce the occurrence of injuries. However, there is no evidence to support this hypothesis under fatigued conditions.

Aim: The current study investigated the “self-optimisation hypothesis” under fatigued conditions. I again determined the influence of fatigue on novel running parameters that have previously been associated with running injury to provide foundational information on interventions for injury prevention and better performance.

Methods: A pre-post interventional approach was deployed for the current study. Recreational runners (n = 40) were recruited from the Stellenbosch Boland community for the study. The study was carried out in two phases. In the phase I, the participants were subjected to a running fatigue protocol which involved running at incremental speed to volitional exhaustion on a motorised treadmill. Running impact variables at the tibia, lower back and upper back were assessed using tri-axial accelerometers whereas spatio-temporal, and upper extremity kinematic parameters were collected with an Opto-Gait photoelectric system and 2D video analysis respectively before and after the run.

In the phase II, the runners were randomly assigned to either an intervention group or a control group. The intervention group underwent eight-weeks of endurance training while the control group continued with their normal running routine. After the eight-weeks, all the participants were subjected to the same running fatigue protocol and measurements as in the phase I.

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Results: Running induced fatigue resulted in significant increases in contact times, forward trunk lean, and body load ($p < 0.05$). Running impact magnitude at the tibia, external distribution of impact, stride angle, step length, flight times, and arm carriage remained unchanged after fatigue ($p > 0.05$). The eight weeks of endurance training caused reductions in step length, forward trunk lean, and contact times. Step frequency on the other hand increased after the eight weeks of endurance training. There were no significant differences in body load, and running impact variables. The changes in the running kinematics under fatigued conditions after the intervention was accompanied with a significant reduction in the oxygen cost of transport.

Conclusions: Running-induced fatigue resulted in changes in some running kinematic parameters. Such changes are accompanied with increases in the oxygen cost of transport. An exposure to eight weeks of endurance training resulted in significant alterations in the kinematic parameters for better efficiency under fatigued conditions with a corresponding decrease in the oxygen cost of transport.

Keywords: Running kinematics; impact; fatigue; endurance training

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OPSOMMING

Agtergrond: Die onbeperkte en toeganklike aard van draf het aanleiding gegee tot n' eksponensiële toename in deelname daaraan. Die voorkoms van beserings is egter steeds rede tot kommer. Lading en vermoeibaarheid is aangedui as onderliggende faktore vir die risiko van beserings. Daar is voorgestel dat drawwers outomaties hul kinematika fyn aanpas naá oefening om meer doeltreffend te wees vir beter prestasie en die vermindering van beserings. Daar is egter nie bewyse om hierdie hipotese in toestande van vermoeienis te ondersteun nie.

Doel: Die huidige studie het die '"self-optimaliseringshipotese"' onder vermoeide toestande ondersoek. Die invloed van vermoeienis op nuwe drafparameters, wat voorheen met drafbeserings geassosieer is, is ondersoek om inligting te verkry oor intervensies om beserings te verminder en prestasie te verbeter.

Metodes: 'n Voor-naá intervensie-benadering is in die studie toegepas. Ontspanningsdrawwers (n = 40) is uit die Stellenbosch Boland drafgemeenskap gewerf. Die studie is in twee fases uitgevoer. In fase 1 is die deelnemers onderwerp aan 'n draf vermoeienis protokol waar deelnemers op 'n trapmeul teen 'n stapgewyse spoed tot vrywillige uitputting gedraf het. Draf-impakveranderlikes by die tibia, laerug en bo-rug is bepaal met die gebruik van drie-as versnellingsmeters. Data oor tyd-ruimtelike en boonste-ledemaat kinematiese veranderlikes is deur middel van die OptoGait foto-elektriese stelsel en 2D video- ontleding, voor en ná die drafloopsessie ingesamel.

In fase 2 is drawwers lukraak in 'n intervensie- of kontrolegroep. Die intervensiegroep het agt weke van uithourvermoë oefening ondergaan terwyl die kontrolegeroep met hul normale drafoefening aangehou het. Na die agt weke is al die deelnemers aan dieselfde draf vermoeienisprotokol as in fase 1 onderwerp.

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Resultate: Draf geïnduseerde vermoeienis het gelei tot beduidende toenames in kontaktyd, vorentoe rompleun, enaá liggaamslading ($p < 0.05$). Die impakgrootte by die tibia, eksterne verspreiding van impak, tree-hoek, treelengte, vlugtye, en armdra-posisie was onveranderd na vermoeienis ($p > 0.05$). Die agt-week uithouvermoë-oefening het belei tot verkorte treelengte, minder vorentoe rompleun en korter kontaktye. Treefrekwensie het toegeneem na die agt-weke uithouvermoë-oefening. Daar was geen beduidende verskille in liggaamslading en hardloop-impak veranderlikes nie. Die veranderinge in die hardloop-kinematika tydens vermoeienis na die intervensie het saamgeval met ‘n beduidende afname in die koste van suurstofvervoer.

Gevolgtrekkings: Draf-geïnduseerde vermoeienis het gelei tot ‘n verandering in sommige kinematiese parameters. Hierdie veranderinge het gepaardgegaan met ‘n toename in die suurstofkoste van vervoer. Blootstelling aan agt weke se uithouvermoë-oefening het gelei tot beduidende veranderinge in kinematiese parameters met verbeterde doeltreffenheid onder vermoeide toestande, met ‘n gepaardgaande afname in koste van suurstofvervoer.

ACKNOWLEDGEMENTS

As much as this thesis represents three years of dedication, hard work, and sleepless nights, the journey would not have been successful without the physical, spiritual, and emotional support of some individuals and institutions.

I would firstly like to acknowledge the Almighty God for life and strength to come this far. The support and friendship from Rev. Napoleon Essien and the entire First Love fraternity in Stellenbosch were amazing. It was a blessing to know I had a family who were willing to go to any extent to support my spiritual and academic wellbeing.

To my family: Mr. A.A. Sackey, Madam Cecilia Ama Serwah, Eunice, Samuel, Rock, Rainbow, Alpha. Thank you for your encouragement and prayers.

Prof. Otoo Ellis, Prof. Yaw Debra, Dr. Moses Momoniyi and Dr. James Addison Adjei for their contribution in ensuring that the Kwame Nkrumah University of Science and Technology, Ghana provided financial support for my studies.

To Amanda Ntsiki Langa, thank you for being a genuine friend and beloved throughout the years.

A special appreciation to Carl, Anthony, and Loiuse, for assisting with data collection. You did not hesitate to stay beyond your usual working hours. I really appreciate the efforts you made to make this study a success. Lara Grobbelaar, thank you for being a listening ear when I had unending questions and the solid feedback you gave on the study.

Dr. Kurt Hendrich Schutte, I will forever be indebted to you. You took me on and mentored me. This dissertation is a product of the seeds you have sown in me. I will always remember

the early morning runs on the Coetzenburg track, and our Skype meetings. My consultant, co-promoter, and mentor, I am very grateful.

Dr. Philip Graham-Smith (Head of Biomechanics and Innovation, Aspire Academy), thank you for taking time out of your busy schedule to read through the “messy” first draft of this dissertation. The feedback you gave was very helpful.

Prof Dr. Ranel E. Venter, if there is ever a prayer I would like to pray for any PhD candidate, I will ask that they meet a supervisor like you. You were not only interested in the completion of my thesis, but also in my personal well-being and development as an academic and a researcher. You left no stone unturned to push me to the very top. You sacrificed in different ways to get me to present at local and international conferences, and to undergo research visits in Europe, just to mention a few. You believed in me even when I had doubts. This work would not have been possible without you. I will forever be indebted to you. May God richly bless you.

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LIST OF ABBREVIATIONS

PTS	Pre-test maximal speed
VO_2	Oxygen consumption
Vpeak	Peak treadmill speed
INT	Intervention
CONT	Control
2D/3D	Two/three dimension
LED	Light emitting diode
GPS	Global positioning system
HR	Heart rate
Max	Maximum
PSD	Power spectral density
FFT	Fast Fourier transform
MAS	Maximal aerobic speed
PCO_2	Carbon dioxide pressure
PL_cunsum	The cumulative sum of body load
SFreq	Step frequency
Gmax_RV	Root mean square of impact in all three axis of rotation of the accelerometer
Gmax_VT	Vertical impact
EMG	Electromyography
BMI	Body Mass Index
AT	Anaerobic threshold

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PREFACE

This PhD dissertation follows an article-format. Chapter 1 is a general introduction with emphasis on the aims and objectives of the study, the hypothesis, and the motivation for the study. This is followed by a discussion of theoretical context of the key concepts relevant to the study and the problem statement, forming Chapter 2. The status of the current literature with respect to the research topic is discussed, current gags in research literature are highlighted, and the contribution made by the current study are stated in Chapter 2. Chapter 3 provides insight into the methodology deployed in the study. This chapter is included because of restrictions in word count by the various journals to which the articles were submitted for review and publication. As a result of the requirements, methods presented in those articles were condensed and not extensive enough for in-depth capturing of all procedures and systems used. Hereafter, Chapter 4 presents the first research article. The article addresses the first objective of the study. The article was submitted for review and publication in the *International Journal of Applied Exercise Physiology* and hence follows the format and guidelines as stipulated by the journal. The article has been accepted for publication and will be available online in March 2019 as indicated in Appendix A. Research article 2 forms Chapter 5 of the document. The article addresses objectives two and four of the study. The article was submitted to the *Journal of Applied Biomechanics*. The referencing system follows the requirements of the journal (Appendix B). The article is currently under review.

Chapter 6 deals with the third objective of the study. It is an article written in accordance with the guidelines of the *Journal of Strength and Conditioning Research* (Appendix E). An abstract of the article was accepted and presented at the South African Sports Medicine Association Conference, 2017. Proof of acceptance is attached as Appendix D. Chapter 7 consists of the general discussion and the final conclusions of the study. Recommendations for future studies

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and limitations of the current study are also stated in the chapter. The dissertation generally follows the Harvard referencing system.

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CHAPTER 1

INTRODUCTION

A. BACKGROUND

Participation in exercises and sporting activities is no more for elite sports people. The concept "Exercise is medicine" (Chen, Fredericson, Matheson & Philips, 2013) has caught on well throughout the world. A growing interest has been shown in recreational running over the past three decades. Recreational running is suggested as the sports of choice because of the health benefits, easier accessibility, and the relatively low or no cost of participation. According to the National Runner Survey (USA, 2015), the majority of American runners (about 64%) are recreational and could only complete races of between 5km and 10km or a half-marathon. The Australian Bureau of Statistics reported a decline in participation in swimming and diving in 2012, but in contrast, reported that the number of participants in recreational running doubled since 2005. South Africa, boasts more than 40 popular half-marathon races in a year, with the Old Mutual Two Oceans Ultra Marathon in the Western Cape alone reported to receive approximately 16,000 entries each year (Finch, 2014).

The incidence of running-related injuries among recreational runners is however a concern. It has been reported that between 29% and 80% of recreational runners sustain a running related injury within 12 months of running, and about 72% of all stress fractures occur in running (Mizrahi et al., 2000). This is due to the repetitive nature of running. Runners exert a force on the ground with each step, and receives a backward force that is about two to three times the weight of the body (Hamill, Derrick & Holt, 1995). Part of this impact is used to translate the

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body in the forward direction, part of the impact goes through the body vertically, whereas the rest of the impact is deployed medio-laterally (sideways movement).

Fatigue reduces the capacity of the musculoskeletal system of runners to handle the load and the stress placed on the body (Dierks, Davis & Hamil, 2010; Verbitsky, Mizrahi, Voloshin, Treiger & Isakov, 1998), leading to changes in the running impact variables (magnitude, and rate), its attenuation and distribution in order to protect the brain, and also affects changes in the running technique (kinematics) of the runner. This ultimately makes the runners less efficient and more susceptible to injuries.

In distance running, running economy is also a key determinant of running performance. Minimising the cost of running per a given distance is a concern for coaches and athletes. Biomechanical (Moore, 2016) and physiological factors (Lindlein, Zechc, Zochd, Braumanna & Hollander, 2018) have been found to influence the metabolic cost of running.

Researchers have proposed that runners would automatically alter their kinematics after a brief exposure to training to be more efficient, economical, and possibly reduce the occurrence of injuries. Nevertheless, only a hand-full of studies to date (according to the researcher’s knowledge) have investigated this “self-optimisation” theory (González-Mohíno et al., 2016; Lake and Cavanagh, 1996; Moore, Jones & Dixon, 2012). The few studies also reported contradictory findings. While some were in favour of the theory, others refuted it. It is further not certain whether a customised training regime can boost the capacity of fatigued runners to manage effectively the distribution of impact and the changes in running kinematics.

This study therefore examined how a customised eight-week endurance-training programme would influence running kinematics, and running impact variables under fatigued conditions in recreational runners. The current study again assessed how a running-induced fatigue would influence some running kinematics, impact, and impact distribution. The study also investigated certain parameters namely, body load, external distribution of impact, stride angle, and arm carriage which hitherto had not been investigated with respect to fatigued running. The study deployed inexpensive mobile technology, and at times freely available software to ensure easy application of the findings in a "real-world settings".

B. MOTIVATION

In a recent review on the effects of running-induced fatigue on running kinematics (Winter, Gordon & Watt, 2016), the authors reiterated the limited evidence on the subject and recommended further studies among larger sample groups. The current study therefore investigated the interactions between running induced fatigue and running kinematics among a larger group. The study again added to the body of knowledge by assessing: stride angle, arm carriage, body load, and external distribution of impact in fatigued recreational running which previous studies had not reported on.

Some limitations mentioned in previous studies on running impact and running-induced fatigue related to the fact that the accelerations were not measured at different times during the fatigue protocol, as well as the use of low sampling frequency accelerometers (100Hz). In the current study, wireless tri-axial accelerometers (range ± 16g, sampling at 1024 Hz, 16-bit resolution, and 23.6g weight, Dublin, Ireland) were used to quantify impact at the tibia, and lower and upper back of the body. The tri-axial nature of the accelerometer was to overcome the limitation of unidirectional types of accelerometers which cannot measure in all three axes and cannot overcome axial distortions during running (Norris, Anderson & Kelly, 2014).

The use of training interventions to improve the efficiency of runners has been proposed. However, there is scarce information on this topic and the way in which exposure to training affects the interactions between running-induced fatigue, kinematics and running impact variables is unknown.

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The current study hence provided relevant data that could be relevant for trainers, coaches, and athletes for better performance, and efficiency.

In order to explore the ecological applicability of the findings, accelerometers were chosen over force plates for this study. Other researchers have used force plates to measure the ground reaction force generated at contact, the rate of loading and impact. However, force plates impose constraints on foot placement, which may result in subjects adopting a targeting strategy while running, altering natural gait mechanics (Paolini et al., 2007). Accelerometers are mobile, relatively cheaper and can be attached to the runner both indoors and outdoors to collect data conveniently without altering the runner's gait. The choice of accelerometers also be made it possible to track distribution of impact at different body segments which was not possible with force plates. The study was therefore designed to focus on the issues in the multidisciplinary fields of sport science and sports technology, which could be used to improve runners' performance and possibly reduce the incidence rates of injuries.

C. AIMS OF THE STUDY

The first aim of the study was to determine the influence of metabolic fatigue on running kinematics, running impact, and body load among recreational runners using technology applicable to outdoor settings.

The second aim of the study was to assess the effects of a customised endurance training intervention on running kinematics, impact, body load and external distribution of impact under fatigued conditions in recreational runners.

D. OBJECTIVES

In order to realise the stipulated aims of the study, the following specific objectives were stated:

1. To determine the kinematic changes that occur in recreational runners under fatigued circumstances.
2. To determine the influence of running-induced fatigue on running impact variables in recreational runners.
3. To assess the effects of gender on running kinematics and impact variables under fatigued conditions.
4. To evaluate the effect of a customised endurance training intervention on running impact, and body load in fatigued running.
5. To ascertain the influence of a customised endurance training intervention on running kinematics under fatigued conditions.
6. To determine how running fatigue affects body load and external distribution of impact among recreational runners.

E. HYPOTHESES

The following hypotheses were postulated for this study:

Running-induced fatigue would result in an increase in the magnitude of impact at tibia, and lower back, contact time, step length, arm carriage, forward trunk lean and body load, and cause a reduction in stride angle.

Recreational runners would fine-tune their kinematics to be more efficient under fatigued conditions after eight weeks of endurance training.

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CHAPTER 2

THEORETICAL CONTEXT

A. INTRODUCTION

The number of individuals involved in recreational running is reported to have increased over the past three decades (Buist, Bredeweg, Limmink, Van Mechelen & Diercks, 2010). Recreational running is often preferred to other forms of exercises because of its versatility, cost effectiveness and numerous health benefits. Recreational running is not restricted, it can be done indoors, outdoors and on almost any terrain, and requires little and relatively inexpensive equipment in contrast to other sporting activities.

Running is repetitive in nature. This repetitive nature of running presents injury challenges to the runner. A recreational runner with a weekly average mileage of about 32km is reported to experience about 1.3 million impacts within a year (Derrick, Dereu & Hamil, 2002). A number of studies have reported an incidence rate of between 30% and 70% of running-related injuries (Buist et al., 2010; Taunton, Ryan, Clement, McKenzie, Lloyd-Smith & Zumbo, 2003). Several factors have been speculated as links to running related injuries. Internal factors including body mass index (BMI) (Nielsen et al., 2013; Taunton et al., 2003), running technique (Teng & Powers, 2015), running impact (Derrick et al., 2002; Verbitsky et al., 1998), running kinematics and fatigue (Dierks et al., 2010; Mizrahi et al., 2000) have been cited. Running shoes (Nielsen et al., 2013; Taunton et al., 2003), running surface (García-Pérez, Pérez-Soriano, Llana, Martínez-Nova & Sánchez-Zuriaga, 2013; Johnston, Taunton, Lloyd-Smith & McKenzie, 2003) and weather conditions (Johnston et al., 2003) are some of the external factors suggested as links to running related injuries.

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Running induced fatigue has been hypothesised as a link to running related injuries because it alters the kinematics of running (Strohrmann, Harms & Kappeler-Setz, 2012), and the magnitude of running impact (Verbitsky et al., 1998). About 72% of fatigue related stress fractures in athletes are reported to occur in running (Mizrahi et al., 2000). Two schools of thought on optimising and developing efficient running kinematics and hence running technique in order to improve performance and avoid injuries have been proposed in literature: the "self-optimisation" approach, and coaching or instructing on the "appropriate" running technique. Researches who instructed alterations in running technique, for example the pose method, report negative changes in running efficiency (Dallam, Wilber, Jadelis, Fletcher & Romanov, 2005). On the other hand, Lake and Cavanagh (1996) proposed the self-optimisation hypothesis. They suggest that runners naturally fine-tune or self-optimise towards a more efficient and effective movement pattern over a short period of training, resulting in an improved performance and possible reduction of injuries.

A few studies have investigated this hypothesis, but their findings have been contradictory. Lake and Cavanagh (1996) report no running gait adaptations and no relationship with running economy in recreational male runners who underwent a six-week training programme. In contrast, Moore et al. (2012) show that adaptations in running kinematics (a less extended knee at toe-off, peak dorsiflexion angle occurring later in stance, and slower ankle eversion velocity at touchdown) were able to explain a 94.3 % variance in running economy improvements in novice runners undergoing a ten-week training programme. These inconsistent results could be attributed to gender differences, type of runners used (novice runners versus recreational runners), and length of training programme (six weeks versus ten weeks). It is possible that the ten-week duration allowed longer time for adaptations. Nevertheless, the way in which the self-optimisation theory influences running impact variables, and kinematics under fatigued conditions is yet to be investigated according to my knowledge.

The current study therefore, sought to understand the biomechanical effects of fatigue that may predispose a runner to injuries and how a training intervention could influence such factors. In order

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to do so, the effects of running fatigue on impact variables and running kinematics before and after a customised endurance-training programme were assessed with special interest in recreational running because of the reported increasing number of participants involved.

The theoretical context to this study begins with an overview of running fatigue, an examination of running impact and its relationship with fatigue, and a contextual presentation of training modalities and their relations with kinematics and running impact. The chapter concludes with the characteristics of running kinematics under fatigued conditions, a review of equipment relating to these aspects, and the problem statement.

B. RUNNING FATIGUE

The various definitions of running fatigue, the different methods that have been deployed to induce and measure fatigue in running, and its effects on biomechanical parameters are the focus of this section.

1. DEFINITION OF FATIGUE

Physiological fatigue, has in general been defined as a decline in a person's ability to exert force (Lorist, Kernell, Meijman & Zijdewind, 2002). However, because of the complex nature of the fatigue phenomenon, some authors interested in running related fatigue have adopted specific definitions to reflect general body or metabolic fatigue experienced in running. Running-induced fatigue has hence been determined as a reduction in performance as a result of a decrease in the end-tidal carbon dioxide pressure (Mizrahi et al., 2000; Verbitsky et al., 1998) or the inability to continue a running test because of cardiovascular or peripheral inhibition (Mercer, Vance, Hreljac & Hamill, 2003). The running-related fatigue definitions adopted by such authors in literature mimicked metabolic fatigue and not specific muscle fatigue. The following section therefore looks at how physiological fatigue and running-induced fatigue were measured by various researchers.

2. MEASUREMENT OF FATIGUE

Different ways and criteria to measure physiological fatigue are reported. Researchers in the available literature have deployed three main methods: the direct method, the indirect method, and the use of physiological and psychological indicators. The direct method involves the measurement of the force generating capacity of muscles. This method has been reported as the most reliable way of assessing muscular fatigue (Vøllestad, 1997). The direct method employs the measurement of force generated voluntarily by the muscles. However, the reliability of the direct method has been questioned. For instance, Vøllestad (1997) speculates that muscular force generated voluntarily could be limited by some factors such as lack of motivation. The author suggests that inhibitory effects at various levels in the central nervous system and at the muscle level could affect the force generating capacity of a muscle. In order to overcome the above-mentioned limitation, the indirect method to determine fatigue was introduced. The indirect method is based on the assessment of twitch contractions elicited by either a single or double electrical stimulus delivered to the muscle or nerve during contraction. This method requires the use of relatively expensive equipment (surface electromyography [EMG]) for more accurate and non-invasive detection of the electrical stimuli (Cifrek, Medved, Tonković & Ostojić, 2009).

Running-induced fatigue is seen as more metabolic in nature, making it difficult to either use the direct or indirect methods for its assessment. Therefore, many studies interested in running fatigue have used physiological parameters for the assessment of fatigue (Abt et al., 2011; García-Pérez et al., 2014; García-Pérez et al., 2013; Mercer et al., 2003; Mizrahi et al., 2000; Verbitsky et al.,1998). In some instances, a number of physiological parameters were used in combination with the Borgs

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scale of rate of perceived exertion (RPE Scale) (Dierks et al., 2010; Strohrmann, Seiter & Tröster, 2014) as an easier and more reliable measure of running induced fatigue.

End-tidal carbon dioxide pressure ($PETCO_2$) was used in both the Mizrahi et al. (2000) and the Verbitsky et al. (1998) studies as a measure for running fatigue. The researchers reported that a reduction in the $PETCO_2$ signified the onset of metabolic fatigue. However, the findings of the two studies showed that not all the participants were fatigued according to the $PETCO_2$ criteria. This resulted in the researchers excluding approximately half of the participants during the post-fatigue analysis.

On the other hand, some authors (Abt et al., 2011; Mercer et al., 2003) allowed participants to run to volitional exhaustion. The researchers determined fatigue as the inability to continue the running test. Mercer et al. (2003) speculates that some of the participants might have aborted the test because of reasons other than metabolic fatigue. They suggest that because participants knew they had to run again after the fatigue protocol for post-fatigue analysis, some participants aborted the fatigue protocol prematurely. A combination of measurements could be more appropriate to ascertain fatigue rather than using only a single indicator such as $PETCO_2$ or the termination of a running test as a criterion for the onset of fatigue.

A combination of heart rate, blood lactate, respiratory quotient, rate of perceived exertion (Borgs RPE scale) and volitional exhaustion has been used to determine fatigue in both recreational and novice runners. The fulfilment of a number of criteria such as: maximal heart rate, (i.e. at least 85% [HR max $\geq$ 85%] of the age-predicted maximum, 220 - age); RPE $\geq$ 17 on the 6-20 Borg scale; respiratory quotient (R- value) > 1.15; and volitional exhaustion, have been used a standard for the measurement of running-induced fatigue by a number of researchers (Dierks et al., 2010; Howley, Bassett & Welch, 1995; Koblbauer, Van Schooten, Verhagen & Van Dieën, 2014)). Authors who adopted the combination of factors did not report any limitations with respect to the measurement of fatigue in contrast to those that utilised only one factor.

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Eskofier Hoenig and Kuehner (2008) showed the reliability of another novel way of measuring running fatigue. The authors demonstrated that heart rate variability and a step duration feature are suitable for the classification of running fatigue. The study reported 75.3% accuracy across multiple study participants and 91.8% in the intra-individual case. However, the researchers used Adidas 1 running shoes to measure the step duration feature. The study was limited by the fact that the Adidas 1 running shoe could not provide data for forefoot and mid-foot strikers because of the compression signal that is located at the heel. Hence, only rear foot strikers were used for their study. They reported that the running shoe triggers the runners to automatically adapt to surface situations, runners speed, and fatigue. This feature therefore may adapt the lower extremity kinematics of a runner to meet the demands of fatigue and the running surface and hence alter natural running gait.

3. SUMMARY

The complex nature of fatigue has prompted authors of running studies to define running fatigue to mimic metabolic or general body fatigue instead of specific muscular fatigue. Physiological and psychological parameters instead of the direct and the indirect methods of fatigue measurement have been used to assess running related fatigue. Physiologically induced running related fatigue has hence been linked to changes in running form and other biomechanical parameters. The next section reviews the reported effects of running-induced fatigue on some biomechanical parameters.

C. EFFECTS OF FATIGUE ON BIOMECHANICAL PARAMETERS IN RECREATIONAL RUNNING

Running fatigue has been reported by some authors to impair efficiency of movement and reduce the shock absorption capacity of the lower extremity (Verbitsky et al., 1998). Running fatigue is reported to cause a change in running kinematics (Derrick et al., 2002), and an increase the risk of stress fractures (Mizrahi et al. 2000). Verbitsky et al., (1998) speculate that both male and female

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recreational runners lose their capacity to absorb impact shock when they are fatigued. This is because the musculoskeletal system becomes weaker and less capable of handling the shock it receives. Fatigued runners as a result spend longer time making contact with the foot on the ground resulting in an increase in the sudden deceleration of the foot after contact.

Physiological fatigue has been suggested as a significant factor that affects biomechanical aspects of recreational running. In a study involving 11 female recreational runners, Christina, White and Gilchrist (2001) report a change in running kinematics with fatigue. Before and after fatigued exercises to either the invertors or dorsi-flexors of the right foot, participants of the study ran at 2.9m/s on a treadmill. Running kinematics were affected significantly by fatigue. For instance, a decrease in the angle the foot makes with the running surface at initial contact was reported after the fatigue exercises.

Stride length and step frequency have been reported to be affected by running fatigue (García-Pérez et al., 2013). Twenty-seven male and female recreational runners underwent a fatigue protocol consisting of a 30-minute run at 85% maximal aerobic speed (MAS). The participants ran on both a treadmill and over ground before and after the running fatiguing protocol. Stride frequency significantly reduced whereas stride length significantly increased on both surfaces as a result of fatigue (García-Pérez et al., 2013).

Running impact and impact attenuation (Derrick et al., 2002; Mizrahi et al., 2000) have also been found to be modified by fatigue. Ten recreational runners ran to volitional exhaustion on the treadmill in the study by Derrick and colleagues (Derrick et al., 2002) to ascertain how fatigue influences running impact. Running impact from the head and the legs was analysed before and after the fatigue protocol. It was reported that peak impact at the leg and impact attenuation increased with running fatigue. Mizrahi et al. (2000) also demonstrated that impact at the shank increases with running fatigue in a study among 14 recreational runners during a 30-minute ran on the treadmill at a speed 5% higher than their anaerobic threshold (AT).

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However, literature on the effects of running fatigue on biomechanical variables is still inconclusive. Literature on running impact and kinematics is limited (Winter et al., 2016) and the available findings are contradictory. The following section therefore elaborate on the effects of running induced fatigue on running impact, and highlight the different reasons that might have contributed to the inconsistent findings.

D. RUNNING IMPACT

Running impact is defined as “the strong shock waves transmitted throughout the body as a result of the sudden deceleration of the foot at heel strike during running” (Killian, 2007: 2). The impact received during running is transmitted throughout the body. The body naturally distributes and dissipates the impact through the bones and the muscles before reaching the head. This is to protect the brain and maintain consistent environmental perception for the vestibular and visual systems (Hamill et al., 1995). Running impact is measured as factors of gravitational acceleration (g; $9.81m/s^2$). Normal impact shock values during running is said to range between 5 and 14 g’s (Flynn, Holmes & Andrews, 2004). Increases in impact shock magnitude, frequency and attenuation through the body in running have been linked to an increased likelihood of degenerative diseases, stress fractures and other overuse injuries (Hamill et al., 1995; Mercer et al., 2003; Mizrahi et al., 2000).

1. EFFECTS OF RUNNING FATIGUE ON IMPACT

The magnitude, and dissipation of impact in running have been reported by some authors to increase with fatigue (Derrick et al., 2002; Mizrahi et al., 2000; Verbitsky et al., 1998). In contrast, other authors report a reduction or no significant changes in the magnitude of impact after fatigue (García-Pérez et al., 2014; Abt et al., 2011; Mercer et al., 2003). Some researchers speculate that the increased

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impact with developing fatigue is as a result of a diminished protection capacity of the fatigued muscles (Mizrahi et al., 2000; Verbitsky et al., 1998). On the other hand, the authors who report no significant increases in impact suggest that fatigued runners adopt a running technique to compensate for the reduced protection capacity of the fatigued muscles. For instance, it is speculated that runners adopts a more flexed knee which results in decreases in contact times, leading to leg stiffness and therefore a reduction in the magnitude of the vertical impact generated during contact in running (Derrick, 2004). The direction of change in impact as a result of running related fatigue remains unresolved and further studies is required to ascertain it (Mercer et al., 2003).

The debate on the direction of change in impact with respect to running fatigue has not been put to bed in the available literature. Verbitsky et al. (1998) report an increase in tibia impact and impact attenuation as a result of running fatigue. This is also supported by other researchers (Derrick et al., 2002; Mizrahi et al., 2000). However, other authors argued otherwise. Researchers such as Christina et al. (2001) report a reduction in impact and impact attenuation after a fatigue protocol. Christiana et al. (2001) speculate that their results are contrary because of the fatigue protocol they adopted; they induced fatigue at the dorsiflexors and invertors which was different from metabolic fatigue induced by Mizrahi et al. (2000); and Verbitsky et al. (1998) in their studies.

Verbitsky et al. (1998) used 22 male subjects (Age 30.8 ± 5.1 years; height 173 ± 7.3 cm) for the study. The researchers speculated that the human musculoskeletal system becomes less capable of handling heel strike-induced shock waves when the muscles are significantly fatigued, resulting in increases in impact and impact attenuation. The researchers induced fatigue in the participants by ascertaining their AT through incremental load on a treadmill. They were then made to run at the speed corresponding to individual AT for 30 minutes whiles breathe by breath gaseous exchange was sampled. Minute by minute ventilation, carbon dioxide production, PETCO$_2$ ventilator equivalent for oxygen, and ventilator equivalent of carbon dioxide were calculated 30 seconds before the test and monitored throughout the 30-minute run to ascertain metabolic fatigue.

In contrast, Abt et al. (2011) report no significant changes in impact after a running (metabolic) fatigue protocol. Although, the protocol adopted induced metabolic fatigue, as was the case in the Mizrahi et al. (2000) and Verbitsky et al. (1998) studies, the intensities of the protocols were different. Abt et al. (2011) used a physiologically high intensity exhaustive run to induce metabolic fatigue in their 12 male and female subjects (age: 24.5 +/- 4.1 years, height: 174 +/- 9 cm). The researchers used a Modified Astrand protocol for the study. The protocol consisted of an initial three-minute workload at 0% gradient at a speed selected by the subjects. The speed was then increased to an approximated speed from the subject’s daily training time. At that constant speed, the treadmill incline was increased by 2.5% every two minutes until volitional exhaustion. The authors report no significant changes in tibia impact and impact attenuation. They suggest that it is likely the running fatigue experienced by the runners in their study, that caused the subjects to terminate the test was not the same type of fatigue that was experienced in a prolonged, lower-intensity running protocol used by Mizrahi et al. (2000) and Verbitsky et al. (1998).

In another study involving ten recreational runners (Derrick et al., 2002), the researchers used a high intensity exhaustive run to induce running (metabolic) fatigue. The metabolic fatigue protocol deployed resembled the intensity of that of the study of Abt et al. (2011), but the researchers made their subjects run at a constant speed predetermined by a previous running test (average 3200-m running velocity at maximal effort), mimicking the approach of Mizrahi et al. (2000) and Verbitsky et al. (1998). Derrick et al. (2002) used runners whose characteristics were similar to that of Abt et al. (2011): (age: 25.8 ± 7.0, and 24.5 ± 4.1 years, respectively) and a similar number of participants (10 and12 respectively). The researchers report increases in tibia impact and impact attenuation. The finding was contrary to that of Abt et al. (2011), although a similar protocol intensity, number of participants and characteristics were used.

Mercer et al. (2003) deployed a different protocol to induce running (metabolic) fatigue in a study that involved 10 male runners (age: 24 ± 6 years, height 184 ± 10 cm). The authors made the participants undergo an incremental graded test to exhaustion as a running fatigue protocol. The graded test involved increasing both the speed and the inclination of the treadmill from 3% to 7.5% until volitional exhaustion. The authors report no significant differences in impact at the pre and post fatigue state in contrast to earlier reports (Derrick et al., 2002; Mizrahi et al., 2000; Verbitsky et al., 1998). Their findings nevertheless were in agreement with that of Abt et al. 2011. Mercer et al. (2003) speculate that the time of data collection might have affected the outcome of their results. They collected data at the first minute of the post fatigue run, when the participants were unlikely to have been fatigued. This alone may not have accounted for the differences in results, because the entire graded test to induce the running fatigue was terminated by the subjects at volitional exhaustion, when they could not continue the run because of fatigue. Hence, it could be possible that the participants were fatigued at the time of data collection making the claim speculative. However, the contradicting findings reported and the different fatiguing protocols support speculations of the complexity of the nature of fatigue (Enoka, & Duchateau, 2008). Conversely, the studies that incorporated a graded test (changes in treadmill incline) consistently reported no significant changes in running impact. The complex nature of fatigue, the different fatigue protocols, and the time of data collection are speculated as possible reasons for the contradictory reports on the effects of running fatigue on impact and impact attenuation.

Recent studies have used the incremental speeds to exhaustion protocol successfully to induce running (metabolic) fatigue. In novice runners (gender: 10 females, 7 males; age: 26.4 ± 3.1 years; height: 172 ± 10.2 cm), Koblbauer et al. (2014) made their participants start walking on the treadmill at a speed of 6 km/h. Speed was increased with 1kmh^{-1} every two minutes until an intensity of 13 on the Borg scale of RPE was reached. The participants then continued to run at that speed until an RPE of 17 or 90% maximum heart rate was recorded.

In recreational runners, a similar protocol, incremental speeds to AT, also resulted in higher effect sizes in the studies by Mizrahi et al. (2000) and Verbitsky et al. (1998). The incremental speeds to

AT involved gradually increasing the speed from time to time till the blood lactate levels rose to at least 4mmols/ltr. Nevertheless, more research is needed to really ascertain the effect of running (metabolic) fatigue on impact and impact distribution characteristics and the type of fatigue protocol that could successfully induce running related fatigue.

Data-collection procedures also differ in literature. While some researchers collected data at different periods during the fatigue protocol (Abt et al., 2011), some collected theirs at the first minute after the fatigue protocol (Mercer et al., 2003), where-as others collected data at the last minute. The results reported by Mercer et al. (2003) suggest that collecting data at the first minute after the post-fatigue run may not be appropriate as there is a higher possibility that runners might not have been fatigued at that time. Derrick et al. (2002) collected data at the beginning, middle and end of the protocol and report that the participants were most fatigued at the end of the protocol. Therefore, based on the Mercer et al. (2003) and Derrick et al. (2002) reports, data collection at the last minutes before and after the fatigue protocol for pre and post fatigue analysis could present more accurate results. Table 2.1 shows studies with different fatigue protocols and the different effect sizes reported by the authors.

Table 2.1: Running fatigue protocols used by some studies and the effect sizes in tibia impact change.

Study	Fatigue protocol	Duration	Effect size
Mizrahi et al. (2000)	Incremental speed to AT, 5% AT to exhaustion	30mins	1.28
Derrick et al. (2002)	Avg. 3200m speed	16mins	1.26

Mercer et al. (2003)	Maximal effort graded running	13mins	0.20
Abt et al. (2011)	Brief high intensity exhaustive run	17. 8mins	0.16

Table 2.2. illustrates the differing data-collection procedures deployed by different authors in the English literature.

Table 1.2: Summary of some data collection procedures used in different studies

Study	**Data collection**
Mercer et al. (2003)	Before and after the fatigue protocol
Derrick et al. (2002)	Beginning, middle and at the end of the protocol
Abt et al. (2011)	Beginning, middle and at the end of the an exhaustive run
Kyrolainen et al. (2000)	Separated trials before, during and after a marathon run.

Authors have also speculated that the running surface (treadmill, track, grass etc.) may affect the results and the interpretation of findings. In a recent study among 20 recreational runners (gender: 11 men, 9 women; Age: 34 +/- 8 years; height: 172 +/- 8 cm; mass: 63.6 +/- 8.0 kg), García-Pérez et al. (2014) looked at the interaction between running fatigue, running impact and running surfaces. The participants performed three separate running test on different days. Maximal speed was first determined through a five – minute maximal effort run on a 400-meter track. The participants then performed two additional test involving randomised runs (400 m at 4 m/s) over ground and on the treadmill before and after the metabolic fatiguing protocol. The metabolic fatigue protocol consisted of a 30-minute run at 85% of the pre-determined MAS.

The study reports that, tibia impact was lower on treadmill than track but reports no significant post-fatigue changes on tibia impact on both running surfaces (track and treadmill). The researchers suggest that running over ground when fatigued decreased impact acceleration severity but it had no such effect when running on the treadmill. They report a lower forehead impact on the treadmill than over ground, but this was only realised in the pre-fatigue condition. The Garcia-Perez et al. (2014) study only assessed impact at the tibia and forehead. Therefore, the study does not provide information on the influence of running surface on the distribution of impact at different body segments such as the trunk, which forms the bulk of the human body. However, it is worthy to note that the different surfaces influenced the severity of impact acceleration and magnitude.

Garcia-Perez et al. (2014) speculated that the altered environment of treadmill running may force the runner to make adjustments in gait to maintain performance or to reduce the risk of injury and thereby reduce the magnitude of the tibia impact. Contrary, other researchers (Derrick et al., 2002; Mizrahi et al., 2000; Verbitsky et al., 1998) conducted their studies on treadmill and reported increases in tibia impact after fatigue. Garcia-Perez et al. (2014) also speculate that, the lower peak tibia impact observed in the treadmill case may in part be a consequence of greater effective mass at foot-strike. It has however been demonstrated that a greater effective mass could mean an increase in knee flexion angles. Increases in knee flexion angles have been linked to increases in ground reaction forces (Derrick, 2004) and tibia impact (Derrick et al., 2002).

The findings of the Garcia-Perez et al. (2014) study were not consistent with that of others (Derrick et al., 2002; Mizrahi et al., 2000). The later report increased impact as a result of fatigue in studies conducted on treadmills. However, they support the findings of Abt et al. (2011) and Mercer et al. (2003) who report no significant changes in impact and impact attenuation as a result of running fatigue. Again, the Garcia-Perez et al. (2014) study suggests that the type of running surface could

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affect the impact received at the tibia. Previous studies did not consider the fact that the running surface may influence their results. Almost all the studies on the effect of running fatigue on running impact were conducted on the treadmill, which results, according to Garcia-Perez and colleagues (2014), the results may not be applicable to other surfaces and more specially to track. However, as no significant differences on impact were realised between the track and the treadmill after fatigue in the Garcia-Perez et al. (2014) study, the influence of running surfaces on impact after fatigue remains speculative and requires further studies.

The study of (Garcia-Perez et al., 2014) was not without limitations. The accelerometers used in study sampled at a very low rate (100Hz) which could have affected the outcome of the study. The total mass of the accelerometers was 55g, which is much higher than the recommended total mass of 3g (Norris et al., 2014). The over-ground run was also done on a rubberised track, which is not the “‘“normal”’”-running surface for recreational running.

An earlier study by Jones and Doust (1996) reports that a treadmill inclination of 1% depicts the energetics of outdoor running. The study compared running at different treadmill gradients (0%, 1%, 2%, and 3%) to outdoor running. The researchers demonstrated that running outdoors differs in oxygen cost from running indoors. They report that running on a treadmill at an incline of 1% gradient depicts outdoor energetics. However, this inclination has not been adhered to in literature with respect to running related fatigue studies. The fatigue protocols adopted by most researchers to determine the influence of running related fatigue on impact did not take into consideration the fact that recreational running is mostly an outdoor event and therefore, studies on it should as much as possible depict outdoor demands. According to the knowledge of the researcher, only three studies adhered to this inclination (González-Mohíno et al., 2016; Nummela, Stray-Gundersen & Rusko, 1996; Santos-Concejero et al., 2014). Nevertheless, both González-Mohíno et al. (2016) and Santos-Conjero et al. (2014) were not interested in how running fatigue influences running kinematics. Although Nummela et al. (1996) considered the influence of running fatigue on running kinematics, few parameters (step length and flight times) were considered. The study was not among recreational runners. The researchers also did not include running impact or impact distribution. Further studies with adherence to the 1% inclination could provide some basis for the interpretation of findings from running-related fatigue studies on treadmills and its applicability to outdoor settings.

2. IMPACT ATTENUATION

The reduction of the severity of the impact generated at contact as it travels along the body, referred to as impact attenuation has been a major concern in a number of studies (Abt et al., 2011; Derrick et al., 2002; Mercer et al., 2003; Mizrahi et al., 2000; Verbitsky et al., 1998). The human body naturally reduces and attenuates running impact to maintain a consistent environment for brain functioning (Hamill et al., 1995). Impact attenuation has been determined from tibia and head impacts. Running fatigue has been shown to significantly increase impact attenuation in recreational runners (Derrick et al., 2002). Authors have reported that the increase in shock attenuation during fatigued running was due to increases in peak leg impacts (Mercer et al., 2003). However, because of the conflicting reports on the effect of running fatigue on tibia impact, findings on impact attenuation have also been contradictory.

Some studies, (Abt et al., 2011; Garcia-Perez et l., 2014) reported no significant increases in impact attenuation after fatigued running. Interestingly, Mercer et al. (2003) report a reduction in impact attenuation as a result of running related fatigue (about 12% lower) even though tibia impact did not change significantly in their study, in contrast to that of Derrick et al. (2002). Both Mercer et al. (2003) and Derrick et al. (2002) used the same number of recreational runners (n = 10). However, Mercer et al. (2003) used only male runners in their study. It is not clear whether the difference in gender of the participants contributed to the differences in outcomes of the two studies with respect to impact attenuation. Impact attenuation has been used to predict injury in runners (Mercer et al., 2003).

Researchers have speculated that a reduction in impact attenuation means that impact received at the tibia was not optimally reduced as it travelled vertically along the body. In contrast, in the Derrick et al. (2002) study, increases in impact attenuation accompanied an increase in tibia impact. Such scenario has been reported to lead to injuries at the lower extremity (Verbitsky et al., 1998). This is because increases in impact are suggested to lead to an increase in vertical ground reaction force. However, because of the effective mass theory (the portion of the mass of a body segment required to adequately model the impact received) (Derrick, 2004; Derrick et al., 2002), increases in impact attenuation because of an increase in tibia impact may not necessarily imply an increase in injury potential.

Derrick et al. (2002) speculated that if the impacts are increased because of a reduced effective mass, then there is no increased injury potential due to the impact. The authors suggest that this is because impact forces would actually decrease during the exhaustive run and that the impact forces rather than impact accelerations are linked to injury potential. Therefore, it is important that increases in impact magnitude and attenuation are not accessed exclusively, but in addition to changes in running kinematics. There is also the need to consider other options such as impact distribution in the prediction of potential injury in running which could also give an indication of potential injury sites.

3. IMPACT DISTRIBUTION

Running exposes, the musculoskeletal system to repeated high impact loads at the initial stage of the support phase of a stride. The impact which is reported to be about 2.32 body weights is attenuated throughout the skeletal system and affects all body segments (Hamill et al., 1995). However, though there is literature on the effect of running fatigue on kinematics and impact, none of the studies

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considered the distribution of the impact at different body segments (Fig. 2.1) and how the impact distribution responds to running fatigue. Researchers have often quantified impact attenuation by measuring peak impact at the tibia and the head in the time domain (Abt et al., 2011; Derrick et al., 2002; García-Pérez et al, 2014) or by measuring the power spectral density (PSD) at frequencies related to tibia and head impacts (10 – 20Hz) (Mizrahi et al., 2000; Verbitsky et al., 1998). PSD is calculated from the Fast Fourier Transform of unfiltered vertical stance phase accelerations from zero to the Nyquist frequency (Shorten & Wanslow. 1992).

Nevertheless, knowledge on impact distribution is important for the understanding of underlying biomechanical principles responsible for running related injuries at specific injury sites, as increases in impact are suggested to cause injuries in specific body segments. For instance, increased impact at the tibia has been reported to cause an imbalance in contractions of the muscles acting on the shank, resulting in loading imbalance on the tibia and exposing the bone to higher bending stresses and higher risk of stress injury (Mizrahi et al., 2000). Therefore, it is of utmost importance to study the effects of fatigue on impact distribution at different body segments in recreational runners. This will give information on the necessary adjustments in running form relevant to injury prevention.

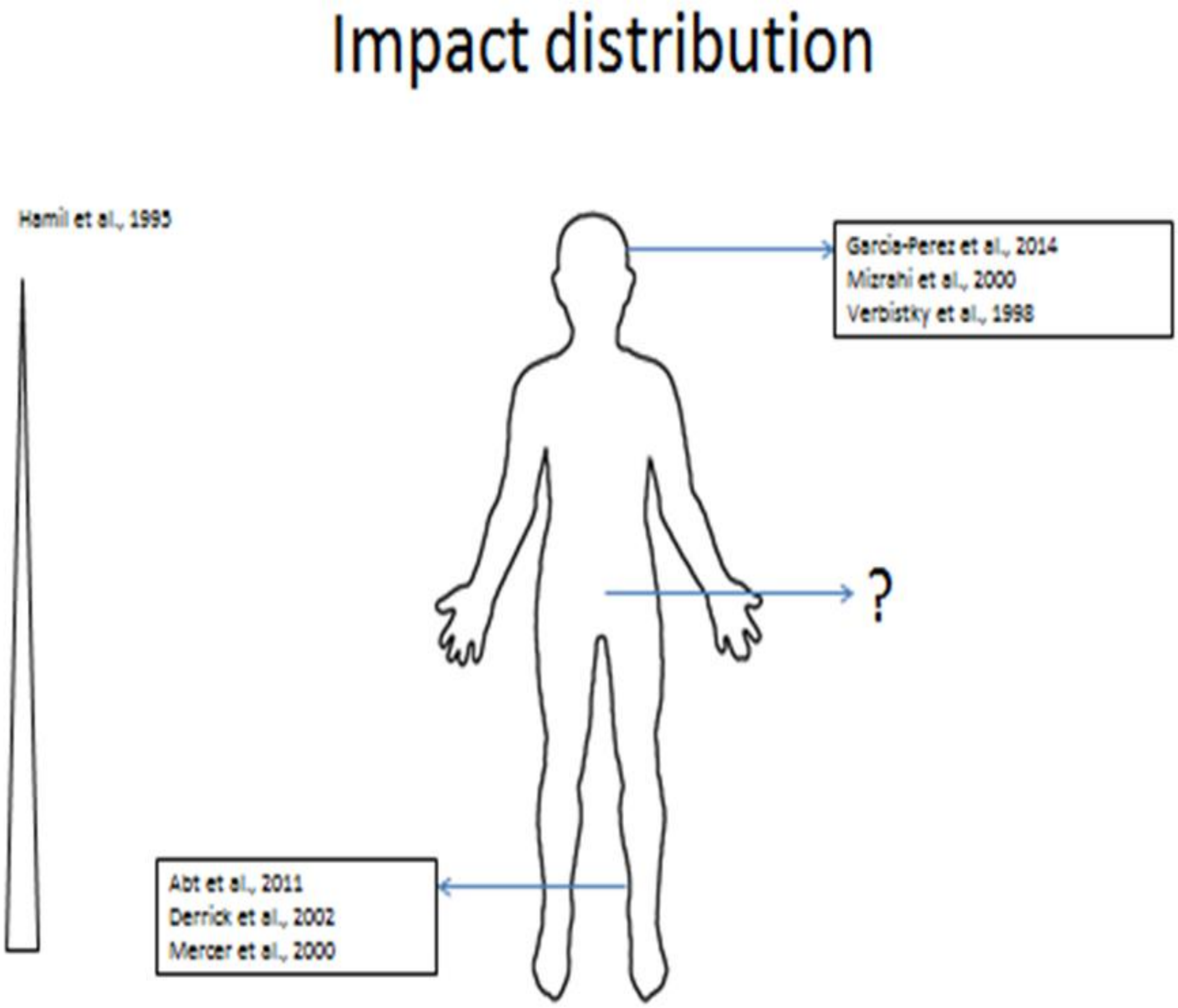

Figure 2.1: Schematic representation of some studies measuring impact (head and tibia) and impact attenuation after a fatigue protocol.

4. SUMMARY

The debate on the way in which running impact changes with respect to running induced fatigue has not been put to bed. The findings from studies relating to running fatigue and impact are contradictory. The different fatigue protocols, the characteristics of the subjects, the equipment used for data collection and the period within which data are collected have been cited as some of the reasons for the differences in results.

E. BODY LOAD

In an attempt to determine the physical and physiological demands of team players and ascertain their levels of efficiency (Dalen, Ingebrigtsen, Ettema, Hjelde, & Wisløff, 2016; Roe Halkier, Beggs, Till & Jones, 2016), and the efficacy of a training programme (Scott, Lockie, Knight, Clark, & Janse de Jonge, 2013) and possibly prevent injuries (Gabbett, 2016; Gabbett & Jenkins, 2011), the concept of player load has been deployed.

The quantification of player load has been carried out with video analysis. However, sideways movements, decelerations, tackles and other complex movements were found to be ignored by the video analysis system. The use of tri-axial accelerometers at the lower and upper back for the estimation of player load has recently been reliably validated (Hollville, Coutirier, Guilhem, & Rabita, 2005). Pearson correlation were reported to range between 0.82 and 0.87 at low speeds and 0.74 and 0.90 at high intensities. The standard error of estimate was small (<0.6) when compared to force platforms.

The concept of physical and physiological loading has not been explored in running. Some studies have reported the loss of control of the musculosketal system by runners when fatigued (Mizrahi et al., 2000; Verbitsky et al., 1998) which may result in side movements and inefficiencies. VO_2 max, heart rate, and blood lactate have been the major criteria that have been used by researchers to determine the physiological demands of running. However, these methods are sometimes intrusive and may not be successfully done outside laboratory settings. Again, those parameters give an indication of internal load and do not consider external load that results from bodily movements (Scott et al., 2013). In addition, the RPE of athletes has been used as an indicator of physiological load. Nevertheless, the RPE is subjective and is based on the athlete's perception of the effort and intensity (Gabbett, 2016) which sometimes could be psychological and may not be accurate. The use of tri-axial accelerometers for the measurement of physiological loading have also been deployed in team players. Tri-axial accelerometers have been used in running studies, however, their use have been restricted to the measurement of impact and the extraction of spatio-temporal kinematics.

Recreational and endurance running unlike team sports such as soccer is a continuous event that may not involve sharp turns and sudden breaks. However, the use of systems such as the global positioning system (GPS) in estimation of loading could be flawed in the fact it is not able to ascertain mediolateral and anteroposterior movements of the body. The GPS cannot be used in indoor running. Information on the physical and physiological demands could be helpful in the prediction of fatigue and the effectiveness of training interventions for athletes and coaches. It could also help coaches assess the response and adaptation of athletes to a training regime.

F. RUNNING ANALYSIS

Although there is some literature on running fatigue and its relationship with impact and impact attenuation, there has been a call for further research because of the contradictory findings (García-Pérez et al, 2014; Mercer et al., 2003). The different fatigue protocols used by researchers have been speculated as the major reason for the inconsistent findings. Again, how impact is distributed in running and how fatigue affects it, is yet to be studied. However, it is speculated that impact distribution data could serve as a yardstick for the prediction of potential injury and injury sites. However, potential injury prevention and prediction are best assessed when running impact

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characteristics are combined with kinematics (Derrick et al., 2002). Therefore, the following section considers the literature available on running analysis with special interest in kinematics and how they are affected under fatigued conditions.

Human motion analysis has been used to simplify human movement to ascertain both normal and pathological function of the musculoskeletal system of the body. Research on running analysis is vital for better performance and injury prevention. Two categories of parameters are of interest in running; kinematics and kinetics (refer to Fig. 2.2). Kinetics involves the study of the forces responsible for the movement of the body segments and the whole body at large, whereas the study of the positions, angles, velocities and accelerations of body segments and joints during running is termed ‘running kinematics’.

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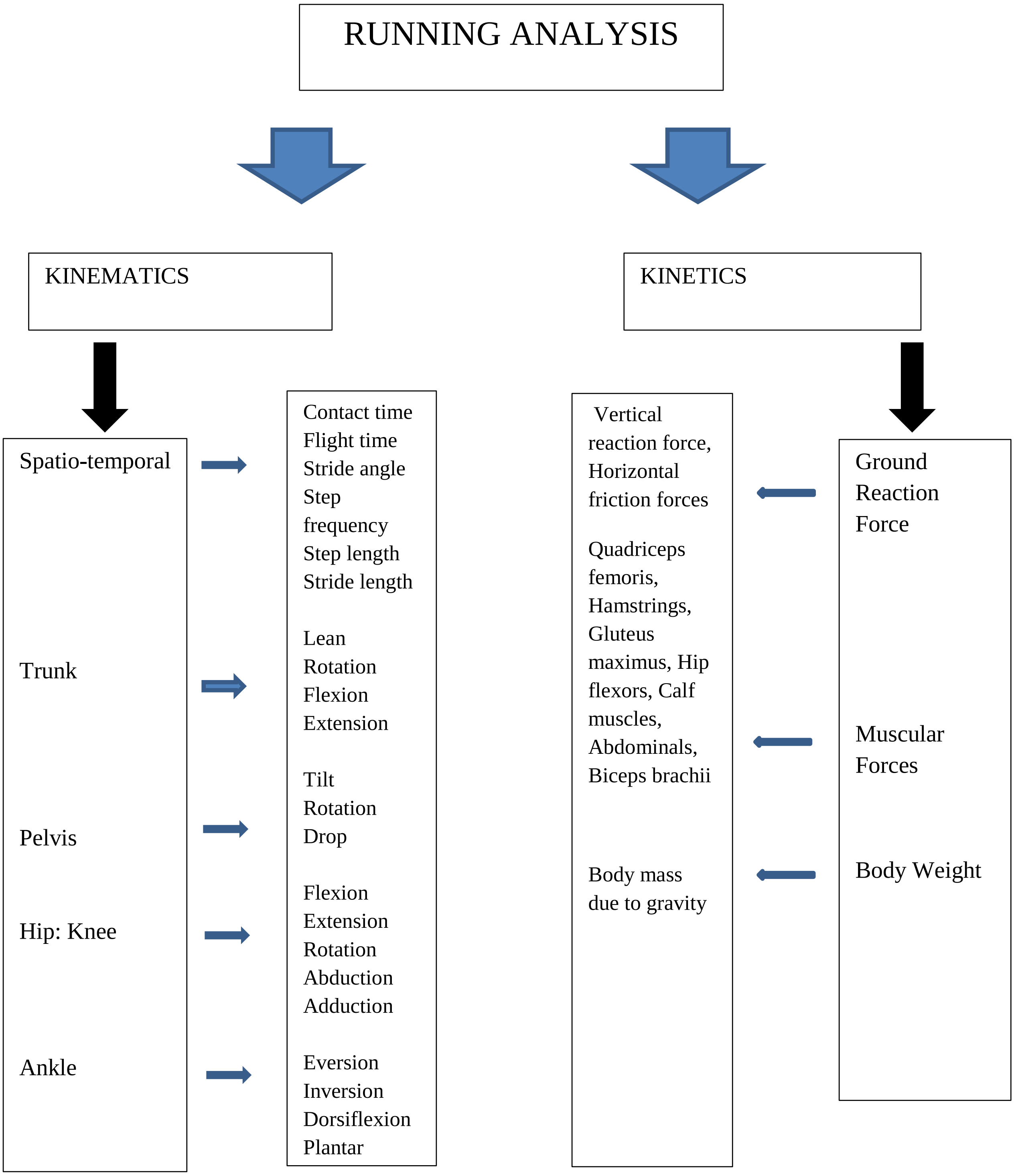

Figure 1.2: Kinematic and kinetic parameters of running

Changes in kinematics and kinetics have closely been linked to performance, injury prevention and energy expenditure/ running economy. Running analysis is complex because of the number of

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parameters involved. For the purposes of this study, the next sections of this chapter focus on the running kinematics that were relevant for the determination of the aims and specific objectives of the study.

G. RUNNING KINEMATICS AND FATIGUE

Some kinematic parameters have been studied with respect to running related-fatigue. However, literature has not exhaustively reported on all the kinematic parameters. The influence of running related fatigue on some of the studied kinematic parameters has also been contradictory. There is limited evidence of how running-induced fatigue affects running kinematics. Therefore, there is a need for more evidence of the influence of running related fatigue on kinematics because of their close reported relationships with injuries.

1. FORWARD TRUNK LEAN

Forward trunk lean, as shown in Figure 2.3, is defined as the angle between the upper body and the vertical (Strohrmann et al., 2012). Forward trunk lean has been linked to running related injuries. For instance, patellofemoral pain syndrome, the most common running related injury (Taunton et al., 2003), accounting for about 40% of running related injuries, has been linked to forward trunk lean (Teng & Powers, 2015).

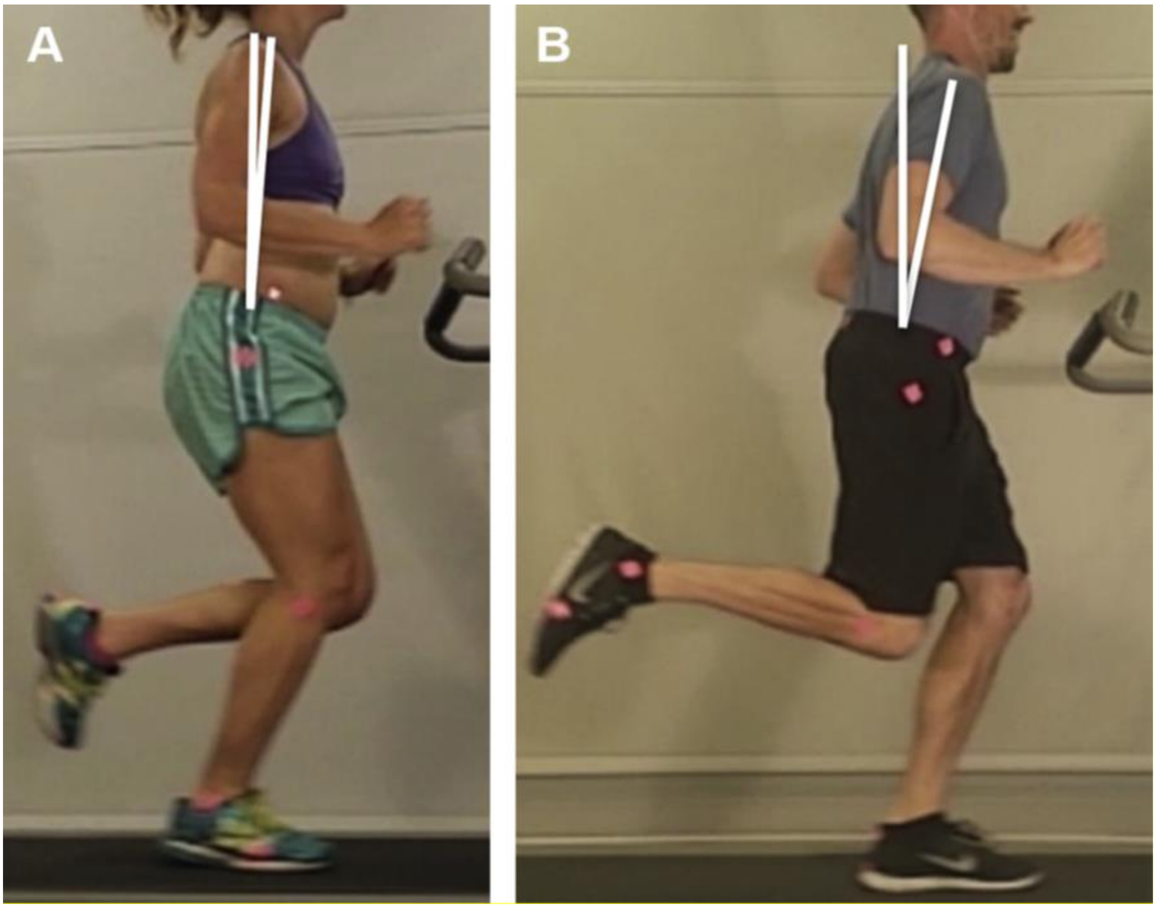

Figure 2.2: Trunk lean. (A) A relatively upright trunk posture and (B) a forward trunk lean, (adapted with permission from Elsevier publications; see Appendix E)

Teng and Powers (2015) suggested that a more upright position is associated with greater knee loads. They demonstrated that a small increase in forward trunk lean (~7 degrees) resulted in lowering the stress across the patellofemoral joint without a significant increase in ankle demand. Increases beyond the 7 degrees could also mean that the posterior chain muscles are not strong enough, resulting in increasing the strain on the hamstrings and the back during running. How trunk forward changes under-fatigued conditions and its implications on performance are assessed in the following sections.

Forward trunk lean and running fatigue

The relationship between running related fatigue and forward trunk lean remains unanswered in the current literature. To the researcher's knowledge, only three studies have analysed the effects of fatigue on forward trunk lean. Hart, Kerrigan, Fritz and Ingersoll. (2009) determined the effect of

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fatigue in the lumbar spinal muscles on a lumbar hyperextension chair in 50 recreational runners (women = 24; men = 26; age 22.3 +/- 2.7 years; height = 169.2 +/- 6.5 cm). The participants were runners with, and without a history of lower-back pain. After running for six minutes at a self-selected comfortable pace on a treadmill, the runners were exposed to a fatiguing isometric lumbar extension exercise, before repeating the six-minute running protocol. For the group with a history of recurrent low back pain (n = 25), a reduced lumber spine extension angle, reflecting loss of lordosis and an increase in forward trunk lean were reported after the fatiguing exercises. On the other hand, the group with a history of recurrent lower-back pain (n = 25) exhibited a slight increase in spine extension, indicating a slightly more lordotic position of the lumbar spine, and a decrease in trunk flexion angles after fatiguing exercise. This difference emphasises the possibility that forward trunk lean could be associated with injuries. It should be noted that the fatigue protocol of Hart et al. (2009) did not induce metabolic or general body fatigue, which is the case in running.

Strohrmann et al. (2012) on the other hand induced running related (metabolic) fatigue in different levels of runners: beginners (n = 6), intermediate (n = 6), advanced (n = 6) and experts (n = 3). The researchers subjected their participants to running at 85% of a predetermined maximum speed until volitional exhaustion. The maximum speed was determined through incremental speeds, starting from 5.8 km/hr with increments of 1.2 km/hr after every three minutes. They reported that the beginners' forward trunk lean increased significantly with fatigue compared to the more experienced runners. However, the average sample size in each group was six, which might not be strong enough for the findings to be generalised.

The other study (Koblbauer et al., 2014), also induced running related (metabolic) fatigue in runners (n = 17; 10 women, 7 men; age: 26.4 ±3.1 years; height 172 ± 10.2 cm). The participants went through a steady-state running-induced fatigue protocol. They starting running on a treadmill at a speed of 6 km/hr. The speed was consistently increased after two minutes by 1 km/hr until an intensity of 13 on the Borg's RPE scale. The participants then continued running at that speed until an RPE of 17 or

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90% of heart rate maximum, after which the participants continued running for two more minutes. The researchers reported significant increases in trunk flexion, and decreases in trunk extension. They speculated that trunk kinematics appear to be significantly affected during fatigued running and should not be overlooked. Nevertheless, the Koblbauer et al. (2014) study was conducted with novice runners. The characteristics of the runners might have affected the outcome of the study. The results may differ in a relatively experienced group such as recreational runners or in an elite group as was shown by Strohrmann et al. (2014). The study used cameras that sampled at lower rate (100 samples/s). It is unclear whether a higher sampling rate may have affected the results. Therefore, there is a need for further studies to ascertain the effect of running fatigue on forward trunk lean as forward trunk lean has been linked to the most common running related injury (Patellofemoral pain syndrome) and lower-back pain, as previously mentioned.

Forward trunk lean and running Impact

It has been speculated that changes in running kinematics affects the amount of vertical impact experienced by runners. The relationship between forward trunk lean and running impact has not been assessed. The focus of available literature on forward trunk lean has largely been on its connection to stress on the patello-femoral joint and posterior chain muscles of the thigh. However, increases in running impact could result in running related injuries depending on how kinematics change in response (Derrick, 2004). It would be interesting to determine how changes in running impact could influence the direction of change in forward trunk lean and vice-versa. This could help in better understanding the mechanism of injury at the patellofemoral joint for instance.

2. CONTACT TIME

Ground contact time is the amount of time the foot spends making contact with the ground. Three ways of making contact have been identified; rear foot, mid-foot, and fore-foot (Di Michele & Merni,

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2014). This classification is based on which part of the foot makes the initial contact with the ground during running. Mid-foot and fore-foot strikers are reported to have shorter contact times compared to their rear-foot counterparts (Di Michele & Merni, 2014).

Contact time has been linked to running efficiency and lower extremity stiffness in running. Variances in leg stiffness (between 90 and 96%) can be explained by examining ground contact time (Morin, Samozino, Zameziati & Belli, 2007). There is a reported relationship between contact times and leg stiffness. It has been shown that an increase of 10% in contact time could lead to about 25% decrease in leg stiffness (Morin et al., 2007). Leg stiffness has been reported as a predictor of running related injuries. It has been suggested that too little stiffness cause soft tissue injuries, while too much stiffness is linked to hard tissue injuries. Dutto and Smith (2002) report a correlation between leg stiffness and fatigue. The study recruited 15 runners (four females, 11 males). The participants run at a speed corresponding to about 80% of peak oxygen consumption pre-determined a week before the fatigue run. The fatigue run involved runners running at the pre-determined speed until volitional exhaustion. The researchers report that fatigue results in a decrease in leg stiffness and running economy. Because leg stiffness and running economy are much more difficult to quantify compared to contact times (Dutto & Smith, 2002 ; Farley, Claire & González, 1996), contact times can be used to predict the potential of injury because of its close relationship with leg stiffness. Recent studies (Santos-Concejero et al., 2014) have established a relationship between running efficiency and contact times.

Contact times and running fatigue

Few studies (García-Pérez et al., 2013; Nagel, Fernholz, Kibele & Rosenbaum, 2008; Nummela et al., 1996; Weist, Eils & Rosenbaum, 2004) have studied the influence of fatigue on contact times. In a study (Nummela et al., 1996) involving 14 male runners (8 sprinters, 6 endurance runners). The researchers made their participants ran at a velocity equal to individual maximum velocity of a maximum anaerobic running power during a 400-meter run until exhaustion. Nummela et al. (1996)

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report increase of about 20.5% in contact times as a result of running fatigue but all the other recent studies (García-Pérez et al., 2013; Nagel et al., 2008; Weist et al., 2004) report no significant changes in contact times during post fatigue. Nagel et al. (2006) report significant increases in contact times before and after a marathon run. The researchers took measurements before and after a marathon run among 200 participants. Nummela et al. (1996) included sprinters while Nagel et al. (2006) used only marathon runners but both studies report significant increases in contact times.

However, a recent study (García-Pérez et al., 2013) among recreational runners (17 men, 10 women; age = 34.0 ± 7.8; height = 173.0 ± 8.0 cm; mass = 66.2 ± 9.4 kg) contradicted the results of the two previously mentioned studies. Participants were subjected to three testing procedures in the study. The first one was a five-minute run on a 400-meter track to determine MAS. Before and after a metabolic fatiguing protocol of 30 minutes running at 85% of MAS, the participants then randomly ran 400m on a track or on a treadmill after a 15 minutes warm up. García-Pérez et al. (2013) report no significant changes in contact times among recreational runners on both the treadmill and the track, which is in agreement with Weist et al. (2004). They speculated that their results might have been affected by the low sampling accelerometers used for the extraction of data. Therefore, further study is required to ascertain the influence of running related fatigue on contact times in recreational runners.

Weist et al. (2004) conducted a prospective cohort study involving 30 runners (22 men, 8 women; age = 34.5 ± 8.8; height = 177.9 ± 8.2 cm; weight = 69.6 ± 8.9 kg). After eight-minutes of warm-up at a comfortable pace, the participants ran continuously at a speed selected by the individuals until volitional exhaustion. It was then followed with six minutes of cool-down. One sensor insoles were synchronised with EMG for measurements in the study. The researchers found that contact area and contact times were only slightly affected. The weekly running mileage of the participants used in the study was 60.8 ± 28.2 km/hr. This mileage is quiet high and might not fit classification as recreational runners.

Contact time and running impact

Running speed and joint orientation are some of the factors that have been speculated to result in an increase in running impact peak magnitudes. Contact times and running speed have been reported to be indirectly correlated i.e. an increase in contact times reduces running speed (de Ruiter et al., 2013). This relationship infers that an increase in contact time results in an increase in running impact. However, evidence of the relationship between contact time and running impact is scarce and remains speculative.

3. STRIDE AND STEP LENGTH

The horizontal distance between two successive contact points of the same foot during running or walking is termed the stride length. Step length on the other hand is the distance between two consecutive foot contacts. The length and rapidity of the strides or steps, affect running performance, economy, and efficiency. Changes in stride length have been linked to the magnitude of running impact at the fatigued state.

Stride length, step length and running fatigue

Literature on the relationship between stride length and running-related fatigue is scarce. Running fatigue resulted in an increase in stride length in a study among recreational runners (Derrick et al., 2002). However, only 10 subjects participated in the study. A high-intensity exhaustive run as described previously was used to induce running fatigue in the participants. It would be interesting to know whether a different running fatigue protocol would elicit a similar response among a larger population of recreational runners.

In an earlier study, Williams, Snow and Agruss (1991) report a significant increase in step length after fatigue. High-speed cinematographic measurements were recorded under three different

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conditions (competitive over-ground, non-competitive: over-ground, and treadmill) amongst 11 collegiate runners. They speculated that the increase in step length was as a result of an increase in the non-support time when running under fatigued conditions.

However, in a more recent study, Kadono, and Michiyoshi. (2015) report a reduction in step length after fatigue and also a reduction in the non-support time. The six runners (height = 177.0 ± 7.0 cm; mass = 64.2 ± 7.1 kg) performed two running trails. The first was an all-out 600-meter with a positive pacing strategy in which peak running speed was reached at the initial stage of the run and decreased gradually toward the end of the run. The researchers captured data with a high-speed camera and a force plate at the 550m mark of the run. An 80-meter run with no fatigue was used as the second trial. The trial was at a constant velocity as recorded at the 550m mark of the previous run. Nevertheless, the subjects for both studies were not recreational runners. Kadono, and Michiyoshi. (2015) used elite middle distance runners whereas Williams et al. (1991) used collegiate distance runners. The influence of running fatigue on step length and flight time in recreational runners may vary. Differences in mileage and fitness levels might cause different responses to fatigue. Further studies among recreational runners could explain the direction of change and the relationship between step length and flight times.

Stride length, step length and running impact

It is unclear how step length and stride length affect running impact and impact distribution. The relationship between the parameters have not been exploited in current literature. Derrick et al. (2002) found that an increase in step length accompanied an increase in tibia impact. However, it is not clear whether the increase in one caused the other. It is speculated that the step/stride length of runners would be altered in response to fatigue due to the suggested loss of control of the musculoskeletal system in the fatigued state (Verbitsky et al., 1998) in recreational running. One could suggest that an increase in step length would lead to increases in impact at the tibia, as increases in step length are speculated to lead to increases in contact times. However, without any empirical evidence to support the claim, it remains speculative.

4. STRIDE ANGLE

The effects of running related fatigue on kinematics remains inconclusive. Researchers have not been able to assess how running induced fatigue affects all the running kinematics. Two of such parameters that have not been considered in running related fatigue studies are arm swing/carriage and stride angle.

Stride angle is defined as the angle between the theoretical arc traced by the centre of gravity during the step and the line of the ground (see Figure 2.4). Stride angle has been reported to affect contact time in running (Santos-Concejero et al., 2014). A recent study identified stride angle as a novel indicator of running economy and potential injury (Santos-Concejero et al., 2014). Thirty male runners were recruited for the study (age = 31.6 ± 8.0 years, height = 176.9 ± 6.0, mass = 65.6 ± 5.4). The participants were subjected to a maximal incremental test to exhaustion. The test involved runners running at 9km/hr with increments of 1.5km/hr after every 4 minutes until volitional exhaustion. The researchers demonstrated that increases in stride angles resulted in a reduction in contact times and better efficiency. They speculated that stride angle might be a marker of a runner's ability to effectively maximize swing time and minimize contact time with effective energy transfer during ground contact. Although stride angle has been reported as, an easier parameter to measure (Santos-Concejero et al., 2014) compared to leg stiffness, only two studies have looked at this important parameter in literature. The influence of stride angle on running impact and impact distribution in the fatigued state is yet to be studied. Literature on stride angle and its relationship with injury prediction factors such as fatigue and running impact would be important. This is because of the fact that it can be obtained easily with the OPTOGait photoelectric cell system even outside laboratory settings without interfering with the athletes running form, and as a single parameter could provide vital information on running efficiency and possible injury.

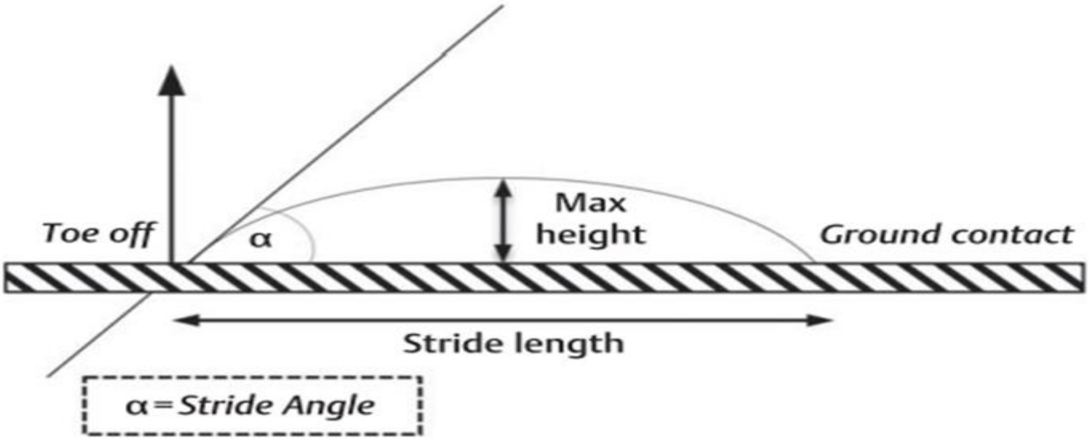

Figure 2.5: Stride angle: adapted with permission from Jordan Santos; see Appendix E

5. ARM SWING/CARRIAGE

Arm swing has been found as a potential link to running economy and running related injuries. In a study to investigate the effects of arms swing on the energy cost of running and lateral balance, the researchers (Arrellano & Kram, 2011) analysed 10 participants (5 men, 5 women; age = 24.4 +/- 4.2 years; mass = 65.4 +/- 11.7 kg) in two conditions (with and without arm swing whiles running on an instrumented treadmill). They report that when running without arm swing, the net metabolic cost increased significantly by 8% compared to running with arm swing. They suggested that actively swinging the arms provides both metabolic and biomechanical benefits during human running. The findings of the study conflicted earlier reports by Pontzer, Holloway, Raichlen and Lieberman (2009), who tested the passive arm swing and active arm swing hypothesis among 10 recreational runners (6 males, 4 females; mass = 61.9 ± 14.1 kg). The researchers divided their participants into control, weight bearing, and no arms. The control group were made to walk normally at three speeds (1.0, 1.5, and 2.0 m/s), and run normally at three speeds (2.0, 2.5, and 3.0 m/s). The weight-bearing group also walked and ran at the same speeds with a 1.2kg weight on each arm just proximal to the elbow.

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The no arms group also repeated the speeds for the two groups with their arms tightly folded on their chest. They found a decrease in moment of inertia of the upper body and an increase in angular acceleration of the shoulders in the no arms condition, while there was an increase in moment of inertia and angular acceleration of the arms in the weight bearing condition. However, they report no effect on locomotor cost in restricting (not swinging) the arms. In a follow up study, Arellano and Kram. (2014) supported their earlier findings (Arrellano & Kram, 2011). They report in this follow-up study, that step variability and net metabolic cost increased when running without arm swing. However, it is not clear whether the participants deployed in their study were runners.

Strohrman et al. (2014), on the other hand drew a virtual line of symmetry in the midline of their runners and investigated the movement of the hands during arm swing in three different classifications (see Figure 2.5). The movement of the arms during swing was referred to as arm carriage. The researchers reported that the arms function to stabilise and balance the core by counterbalancing the opposite leg. The study involved runners completing two running trials at 8km/hr and 10km/hr in the three conditions (arms parallel, arms targeting the midline of the body, and arms crossing the symmetry line of the body). They suggested that arms should be parallel to the midline of the body and driving forwards to reduce the stress on the pelvis (Strohrman et al., 2014).

However, the researchers could not provide any evidence of how driving the arms forward and parallel to the body as suggested would influence efficiency. Therefore, how fatigue influences arm carriage and its relationship with impact and impact distribution is yet to be investigated. It would be interesting to know whether carrying the arms in the “appropriate way” could affect spatio-temporal kinematics and running impact. The relationship between arm carriage and forward lean could be biomechanically relevant with regards to injury prevention. This is because; arm swinging has been linked to movement of the torso (Arellano & Kram, 2014). Establishing the relationship could help in understanding the mechanisms of patellofemoral pain syndrome for instance, which has been linked to trunk movement.

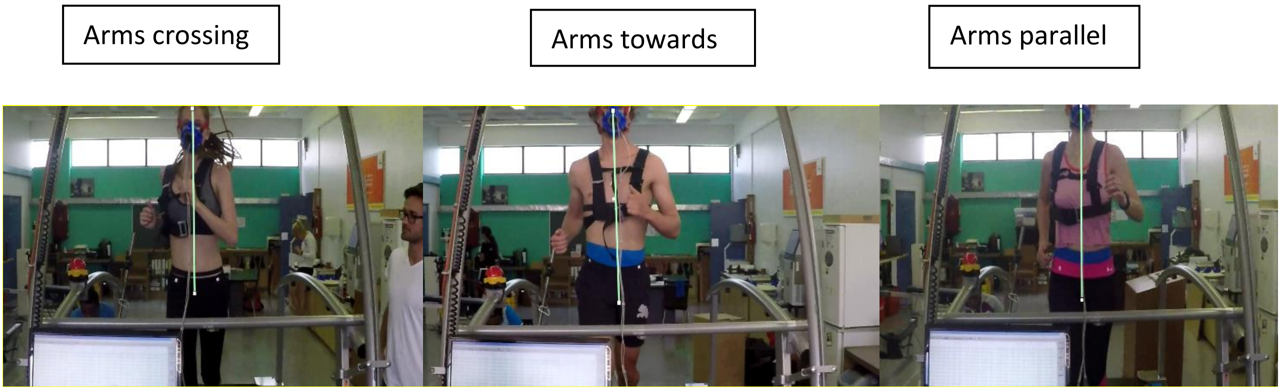

Figure 2.3: Classifications of arm carriage (adopted from Strohrmann et al., 2014)

6. SUMMARY: RUNNING KINEMATICS

The influence of running fatigue on kinematics and the relationship between running kinematics and impact are still debatable. The direction of change of running kinematics under fatigued conditions is still unresolved. Some noble kinematics are also yet to be assessed under running fatigued conditions. A recent review (Winter et al., 2016) concluded that there is limited evidence on the effect of running fatigue on running kinematics, reiterating the need for further studies on the subject.

H. GENDER, RUNNING FATIGUE AND RUNNING KINEMATICS

Men and women runners have been reported to have different incidence profiles to running related injuries (Buist et al., 2010; Nielsen et al., 2013; Sinclair, Shore, Taylor & Atkins, 2015). Some researchers (Sinclair, Greenhalgh, Edmundson, Brooks & Hobbs, 2012) speculated that women may be at a higher risk of chronic injuries compared to men due to differences in running kinematics. The biomechanical factors underlying this gender biased risk and injury profiles are still unclear.

A recent study (Sean et al., 2016) reports significant differences in both recreational and elite competitive athletes in terms of the influence of gender and gait kinematic variables. The study involved 481, who were divided into competitive (Gender: 59 men, 47 women; age: 38.88 ± 11.61 years), and recreational (Gender: 160 men, 215 women; age: 42.21 ± 18.99) based on self-reported mileage (2.61 ± 0.25, and 2.50 ± 0.26 m/s competitive and recreational respectively). The protocol consisted of runners running at a self- selected pace they deemed comfortable for 20 seconds. The authors reported significant differences as a result of gender in frontal plane knee angles in the recreational runners, and sagittal plane knee angles in the competitive group. The study did not include fatigue interactions with the kinematic parameters. It is further unclear whether a younger population of recreational runners would elicit different results. Other researchers have also reported on gender differences in running kinematics. Limb and joint stiffness (Sinclair et al., 2015); tibiocalcaneal kinematics (Sinclair, Chockalingam & Vincent, 2014); and knee abduction, knee internal rotation and ankle eversion (Sinclair et al., 2012). The kinematics considered in the previous studies were measured with VICONS which are more expensive and are most often laboratory-confined.

Another study (Wilson, Loss, Willey & Meardon, 2015), determined whether there would be differences in running mechanics and joint kinetics in women under fatigued running. The researchers speculate that the changes in women’s running due to fatigue do not contribute to the gender-biased nature of patellofemoral pain syndrome. However, the Wilson et al. (2015) study was limited to running mechanics and joint kinematics. There is paucity of knowledge on gender differences in terms of load distribution, running impact magnitude, and spatio-temporal kinematics. The underlying mechanisms behind the different injury profiles between male and female runners are therefore inconclusive. Whether changes in running kinematics due to fatigue is gender sensitive are also unclear.

The current study therefore examined gender differences in running kinematics, body load, and external distribution of impact in an attempt to provide foundational information on some of the biomechanical principles behind the reported differences in injury profiles in male and female runners.

I. SYSTEMS AND INSTRUMENTATIONS

Research on biomechanical analysis has become much easier and reliable because of advancement in systems and instrumentation. Researchers interested in running fatigue, impact and kinematics have used different instruments and equipment over the years to acquire relevant data. The subsequent sections shift the attention to literature on instrumentation to identify the instruments that have been used, and their merits and demerits on the effect of running fatigue relating to kinematics and impact

Five basic measuring systems have been identified for human movement analysis. Three of the five focus on the specific act of the movement. Dynamic EMG and force plate serve as one facet of diagnostic technique. They are responsible for the period and relative intensity of muscle function, and the functional demands experienced during the weight-bearing period. A motion analysis system (e.g. VICONS) defines the magnitude and timing of individual joint action. The other two analysis systems are: - measurement of stride characteristics (e,g. accelerometer, OptoGait), and energy cost measurements for efficiency (e.g. accelerometer, VO_2).

Biomechanical analysis has been done using expensive and complex systems such as three-dimensional (3-D) motion captures (Shache, Blanch, Rath, Wrigley & Bennel, 2002), EMG (Karamanidis, Arampatzis & Brugemann, 2004), and force plates (Wearing et al., 2000). In contrast, less expensive and easy-to-set-up options such as OptoGait photoelectric system (Leinhard, Urry & Smeathers, 2013), wearable sensors (García-Pérez et al., 2014), two dimensional (2-D) motion captures (Maykut & Ford, 2015) and GAITrite electronic walkway (Lee et al., 2014), have also been deployed by researchers and clinicians to analyse human movement under different conditions for different reasons. The choice of method and instrumentation is dependent on several factors. A systematic review on gait analysis methods (Baker, 2009) recommends that methods and instruments

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for gait analysis should be “reproducible, stable (independent of mood, motivation and pain), accurate, appropriately validated, capable of distinguishing between normal and abnormal, must not alter the function it is measuring, and cost effective”.

Recreational running is mostly done outdoors and not in the laboratory. It is therefore essential that instruments are used that could easily be used outdoors for reproducibility of studies involving recreational runners. Again, the accessibility, cost and data extraction procedures of the instruments should be considered, to enable coaches, athletes and especially recreational runners to easily acquire them to monitor and improve performance, and prevent injuries.

An option that has been provided in literature for ground reaction force, impact measurement and running kinematics is force plates. The next sections look at options of specific systems available for the objectives of the current study.

1. FORCE PLATES

The traditional ways of biomechanical analysis have been through force plates, EMG and 3-D motion captures. However, the use of these systems is accompanied by several challenges and constraints. Cost and complexity in their usage have been reported in literature (Higginson, 2009). Force platforms have been used to measure ground reaction force, loading rates, centre of pressure, joint moment, and power (Higginson, 2009). Nevertheless, they impose constraints on foot placement, which may result in subjects adopting a targeting strategy while running, altering natural gait mechanics (Wearing et al., 2000).

Moreover, this targeting strategy has been linked to inaccuracy of results. For instance, Wearing et al. (2000) report an increase in step length variability as a result of the targeting strategy. This led to, the introduction of instrumented treadmills (Divert et al., 2005: Derrick, 2004) to avert the targeting strategy. However, a major drawback in instrumented treadmills is the fact that it cannot be used

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outside laboratory settings, hence the need for a system that could work outside laboratory settings with considerable accuracy and reliability such as accelerometers (Norris et al., 2014).

In contrast, Verniba, Vergara and Gage (2015), in a study to investigate the effect of visual targeting on spatiotemporal, kinematic, and kinetic measures of gait and their variability, report no significant differences between targeting and natural trials on the magnitude or variability of any gait measures. Nevertheless, they tested these parameters in a walking trial with a self-selected speed by subjects. Running obviously involves higher and increasing speeds than walking, it also has flight periods that are absent in walking. Therefore, it is possible that the results of the study would have been different if Verniba et al. (2015) had adopted a running trail or the data were collected with increasing speeds. The kinematic measures of interest considered in the study were: ankle, knee, and hip sagittal angles, hence their results cannot be generalised to all kinematic parameters. Wearing et al. (2000) earlier reported an increase in step length variability as a result of the targeting strategy, which has not been refuted in literature. Again, force plates are expensive, not easily accessible, and complex in operation as compared to OptoGait photoelectric cell system and wearable sensors such as accelerometers (Baker, 2009; Norris et al., 2014). The alternative equipment that has been proposed to address the challenges associated with the force plate is the accelerometer.

2. ACCELEROMETERS

Wearable inertial motion sensors consisting of accelerometers, gyroscopes and magnetic sensors present an easy and affordable platform for the collection of biomechanical data for gait analysis (Norris et al., 2014). Wearable sensors are non-intrusive, and require no receivers and cameras for data collection, and can therefore be used outside laboratory conditions. Inertial motion sensors are again preferred for human biomechanics studies because they are highly transportable, cost effective, and consume low power during operation (Fong & Chan, 2010).

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Accelerometers have been used to measure running impact at body segments and shock attenuation throughout the body (Abt et al., 2011; Derrick et al., 2002; García-Pérez et al., 2014; Mizrahi et al., 2000; Verbistky et al., 1998). They are lightweight, wearable and can be used both indoors and outdoors without interfering with runners' gait patterns. Accelerometers exploit the property of inertia, that is, resistance to change in motion to sense changes in linear motion and the hooks law (F = kx) (Lobo & Dias, 2007). They are made of a crystal that produces a voltage charge when compressed or distorted. These measurements are represented as electronic voltage signals. The signals can be filtered to reduce the effect of noise and transformed to reveal information, specific to running gait (Killian, 2007).

However, the place of attachment could negatively affect the accuracy of the results. It has been reported in literature that bone-mounted accelerometers present the most accurate way of recording accelerometry data (Lafortune, 1991; Lafortune, Henningt & Vallant, 1995; Norris et al., 2014). This method nevertheless involves, surgically attaching the accelerometer directly to the bone, which is unethical and not feasible outside laboratory settings (Lafortune et al., 1995). The use of bone-mounted accelerometers is also time consuming. For instance, Lafortune (1991) spent five hours on only one subject in his study. Bone attachment therefore may not be appropriate when dealing with a larger sample size.

On the other hand, skin-mounted accelerometers have been found to be accurate when attachment is at the right place and firmly secured to the area of interest. A recent systematic review by Norris et al. (2014) on method analysis of accelerometers and gyroscopes in running gait made some recommendations for extraction of accurate data with skin mounted accelerometers. For example, they recommend placement at the anterior/distal aspect of the tibia if tibia impact is of interest. The general rule has been placing and securing the accelerometers with adhesive tapes on bony landmarks to reduce skin movements as much as possible. However, bone-mounted accelerometers are not considered a method of choice when data obtained would be normalised for each subject with respect

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to his/her initial measurements. Therefore, any error due to loss of amplitude or high-frequency components of acceleration signal is not significant (Verbitsky et al., 1998).

The use of skin-mounted accelerometers has been a common method for measuring impact shock (Abt et al., 2011; García-Pérez et al., 2013; García-Pérez et al., 2014; Mizrahi et al., 2000; Vertbisky et al., 1998). The ease of use and portability of such devices are very valuable to the study of impact biomechanics.

Three types of skin-mounted accelerometers have been used in literature: uniaxial, bi-axial and tri-axial accelerometers. The systematic review by Norris et al. (2014) recommends the use of bi-axial or tri-axial accelerometers in research because of distortions reported in axial alignments during testing which cannot be overcome with uniaxial accelerometers.

3. SUMMARY OF ADVANTAGES OF ACCELEROMETERS OVER FORCE PLATES

Accelerometers are relatively cheaper than force plates. The targeting strategy often deployed by participants using force plates could result in less accurate results than that with accelerometers. The mobile nature of accelerometers makes it possible for continuous capturing of impact data unlike the force platforms. Accelerometers also save time. Fewer trials are required for data collection compared to force plates.

Runners adopt considerable kinematics to keep up with speed (Derrick, 2004), improve performance and prevent injuries (Teng & Powers, 2015). In other to assess and analyse them all, researchers have used other systems such as 3-D and 2-D analysis, and the OptoGait. The advantages and disadvantages of these systems for running analysis are examined in the next section.

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4. 3-D AND 2-D MOTION CAPTURE

The gold standard for running gait analysis for both clinical and research purposes are reported to be the 3-D motion capture (McLean et al., 2005). However, the use of 3-D analysis imposes significant financial, spatial, and temporal costs (Maykut & Ford, 2015). There is therefore a need for a cheaper option in biomechanical running gait analysis. Especially in recreational running as recreational runners may be interested in feedback on their performance and running technique for injury prevention. This option is presented by the 2-D motion-capture.

The concurrent reliability and validity of 2-D motion capture has been tested in treadmill running (Maykut & Ford, 2015). The 2-D analysis demonstrated excellent intra-rater reliability (ICCs: 0.951-0.963) for the measurement of frontal plane kinematic variables of running performance (Maykut & Ford, 2015). The researchers conclude that data capture using 2-D software provide support for the utility of 2-D video analysis in the evaluation of frontal plane variables.

A review of 2-D analysis of biomechanical parameters (Souza, 2016) demonstrated that 2-D motion could reliably be used to analyse both lower and upper extremity kinematics such as forward trunk lean. A recent study (Pipkin, Kotecki, Hetzel & Heiderscheit, 2016) supported the findings of Souza (2016). Pipkin et al. (2016) demonstrated that the qualitative assessment of specific kinematic measures during running can be reliably performed with the use of a high-speed video camera. The running kinematic parameters of interest considered in the Pipkin et al. (2016) study also included forward trunk lean.

5. OPTOGAIT SYSTEM

The OptoGait system (Microgate, Italy, 2010) is made up of photoelectric cells situated along transmitting and receiving bars of 1 m in length. The bars can be extended to 100 m with a maximum distance of 6 m between them. The two bars contain infrared light emitting diodes, which enable communication between them. The system automatically calculates spatio-temporal parameters by sensing interruptions in communication between the transmitting and receiving bars (Lee et al., 2014; Leinhard et al., 2013). The OptoGait system is the upgraded version of the OptoJump® system (Microgate, Bolzano, Italy). The OptoJump works similarly to the OptoGait and has been used to measure functional parameters in sporting activities (Glatthorn et al., 2011).

A recent study to test the concurrent validity and reliability of the OptoGait photoelectric system for the measurement of spatio-temporal parameters in healthy individuals report that the system is a valid instrument for the assessment of spatiotemporal gait parameters of healthy young adults (Lee et al., 2014). However, Leinhard et al. (2013) report two major drawbacks with the use of the system. They state that the floor-based OptoGait system has an excessive diode height with respect to the floor. The system again records in one dimensional. The researchers speculate that the height of the diodes makes the system only suitable for individuals who are able to raise their feet sufficiently during walking in order to achieve a step length exceeding their foot length. This limitation could however be overcome in running and in healthy individuals, because, running involves step lengths that are higher than foot length as a result of the increasing speed. The system has been used for the measurement of running kinematics in recreational (Santos-Concejerro et al., 2014) and competitive running (Santos-Concejero et al., 2015) populations.

Moreover, the OptoGait system has the benefit of being quick to setup, simple to use, and inexpensive (Lee et al., 2014). The system requires no maintenance and sensor calibration, is resistant to wear and tear, and offers the possibility to modulate the length and the width of the system (Leinhard et al., 2013). The OptoGait also perform functional assessments other than quantitative gait analysis. The system also presents the measurement of a novel parameter, namely stride angle, which has been linked to running economy and injury in literature (Santos-Concejerro et al., 2014). Stride angle cannot be extracted from other systems such as the force plate or wearable sensors.

6. SUMMARY

Although, force plate, EMG and 3-D analysis have been touted as the instrument of choice for biomechanical analysis, the challenges associated with their use, are a concern to researchers. Accelerometers are preferred to force plates in the measurement of running impacts, and 2-D is preferred to 3-D analysis because of cost-effectiveness of data on running kinematics. The OptoGait photoelectric system provides an additional important variable (stride angle) which neither the force plate nor EMG can provide, aside from being cheaper and easier to set up.

J. RUNNING ECONOMY AND RUNNING BIOMECHANICS

Running economy is a key parameter for running performance, especially in distance and middle distance running (Lazzer, Taboga, Salvadego, Rejc, Simunic, Narici, Buglione, Giovanelli, Antonutto, Grassi, Pisot, di Prampero, 2015). Running economy has been defined as the the rate of oxygen consumed at a given submaximal running velocity (Moore, 2016). Over the years, there have been variations in the definition of running economy to overcome the challenge of speed sensitivity and substrate utilisation. The cost of oxygen over a given distance (Santos-Concejero et al., 2014), or caloric unit cost deduced from respiratory exchange ratio (Lindlein et al., 2018) has been used in an attempt to overcome a limitation in the use of VO_2 (Fletcher, Esau & MacIntosh, 2010), is speed sensitivity. It appears that the respiratory exchange ratio method of running economy measurement has been reported to be most appropriate when running economy is ascertained at varying speeds due to its sensitivity to speed. At a constant speed on the other hand, several authors (Barnes et al., 2015;

Mooses et al., 2015; Santos Concejero et al., 2014) have successfully used either VO_2 or oxygen cost of transport (O_2COT) as an indicator of running economy.

The relationship between biomechanical factors and running economy has been addressed by several authors. Ground reaction forces (Farley &McMahon, 1992), ground contact times and stride angle (Santos-Concejero et al., 2014), forward trunk lean (Anderson, 1996), and arm swing (Arellano & Kram, 2014), are some of the biomechanical parameters linked to running economy.

The reports on the interactions between RE and a brief exposure to training is nevertheless still uncertain due to the contradictory findings (Moore, 2016). It is further unclear whether the self-optimisation hypothesis is applicable under fatigued conditions. The next section examines the available literature on RE, training interventions, and fatigued running.

K. TRAINING INTERVENTION

Another factor that has been suggested to contribute to the differences in findings in studies reporting on the effect of running fatigue on kinematics and impact distribution is the fitness levels of the study participants, i.e. whether they are trained or untrained. The description authors have given to their participants depicts some level of differences in terms of how trained they are. For instance, Verbitsky et al. (1998) describe their participants as physically active recreational runners. Mercer at al. (2003), on the other hand, describe their runners as slightly trained and experienced with treadmill running. The two studies report contradictory results on tibia impact and kinematics as a result of running fatigue. Abt et al. (2011) used competitive well-trained runners and report no significant changes in running impact and kinematics contrary to the findings of Derrick et al. (2002) and Verbitsky et al. (1998) who used untrained recreational runners. Although both studies (Abt et al., 2011; Derrick et al., 2002) deployed a similar protocol to induce running-related fatigue, they report contradictory reports with respect to the effect running fatigue may have on kinematics and running impact.

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Three studies (Abt et al., 2011; Derrick et al., 2002; Mercer et al., 2003) used a similar number of participants, 10, :10, and :12 respectively. The major difference that is apparent in the three studies is the level of training of the participants. Therefore, the contradictory findings reported by the studies could possibly be as a result of the fitness levels of the participants.

Hitherto, it has been theorised that runners subconsciously alter their running technique after being exposed to some level of training to be more efficient and effective. However, only three studies (González-Mohíno et al., 2016; Lake and Cavanagh, 1996; Moore et al., 2012), according to the knowledge of the researcher, have investigated this theory. However, the three studies that have tested this hypothesis reported contradictory findings. The most recent study among the three (González-Mohíno et al., 2016) reported that continuous and interval training significantly affects running kinematics in recreational running. The study was conducted with 11 recreational runners randomly assigned to either a continuous training group (n = 5) or an interval-training group (n = 6). A maximal incremental test on a treadmill was used to determine runners' MAS. The participants started at an initial speed of 2.2m/s for five minutes as a warm up session. The speed was increased every minute by 0.28 m/s until volitional exhaustion. The training stimulus for the six weeks (interval or continuous) was based on the MAS of each participant. They report an increase in step length, whereas contact time decreased after the training programme. However, six participants each were used in both training (interval and continuous) programmes in the González-Mohíno et al. (2016) study. A sample size of six may not be strong enough to generalise findings to the larger population of runners.

In contrast, Lake and Cavanagh (1996) report no significant changes in kinematic variables between pre- and post-training. The researchers grouped their participants into a control group and an intervention group. After an incremental speed to exhaustion protocol to determine maximal aerobic capacity. The intervention group went through six weeks of training, while the control group continued with their usual running. Nevertheless, the kinematic parameters of interest of the two

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studies were different. Lake and Cavanagh (1996) considered vertical oscillation, shank angle at foot strike, trunk angle, trunk lean, maximal ankle plantarflexion and maximal knee flexion, whereas step length, step frequency, flight time, and contact time were the kinematic parameters of choice for González-Mohíno et al. (2016).

Moore et al. (2012) agree with the findings of González-Mohíno et al. (2016). Moore et al. (2012) used 14 female beginner runners (age = 34.1 ± 8.8 years, height = 1.64 ± 0.009 m, mass = 69.1 ± 10.8 kg). The “Balke-Ware” walking GXT to volitional exhaustion was the protocol deployed by the researchers to ascertain the maximal aerobic capacity of the runners. The protocol involved a familiarisation trail consisting of walking on a treadmill at a constant speed of 5.4 km/hr at a 0% gradient while increasing the gradient by 1% after every minute until exhaustion. Running economy and VO_2 were then determined with participants running on a level treadmill at three speeds (2.08, 2.31, and 2.53 m/s) with nine-minute rest between consecutive runs. A ten-week training session involving walking and running was then given to the participants. Both kinematic and kinetic variables (knee extension, plantarflexion, peak eversion, and peak propulsion force) significantly changed from before to after the training intervention. However, the authors (Moore et al., 2012) used female novice runners. Their participants also underwent 10 weeks of training, whereas Lake and Cavanagh (1996) trained their participants for six weeks. The extra weeks of training and the characteristics of the runners (i.e. novice or recreational) may have accounted for the differences in results between the two studies. Further research involving male and female recreational runners is therefore necessary to ascertain the effect of training on running kinematics.

The influence of a training intervention on running impact variables is inconclusive, whereas that of body load and external distribution of impact is yet to be assessed. The way in which training also affects fatigue outcomes in running has not been considered by previous research. Identification and quantification of the effect of training on running impact and kinematics under fatigued conditions are necessary for appropriate interventions for injury prevention and optimal performance.

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L. SUMMARY

There is a paucity of literature on the influence of running fatigue on some kinematic parameters and impact. Stride length was found not to change after fatigue in the Mercer et al. (2003) study. Angular kinematics such as hip extension angle at toe-off, knee flexion angle and ankle planter flexion were also studied by Kellis and Liassou (2009). Derrick et al. (2002) report increases in knee flexion, and rear-foot angle with increase in tibia impact. However, not all kinematic parameters have been studied and the findings in literature with respect to running fatigue and kinematics are also conflicting. The direction of change of impact and impact attenuation under fatigued conditions is still debatable. The applicability of findings in current literature to outdoor running has been cautioned. The different running protocols adopted to induce running related fatigue have mainly been cited as responsible for the different results. In addition, some novel running kinematic parameters that are linked to injuries and running economy are yet to be considered in running related fatigue studies. Further studies are hence needed to clarify and provide data on all the kinematics and the direction of change in impact because of their speculated close links to injury and performance.

Training has also been an issue of concern in literature. The effects of training on biomechanical parameters are yet to be clarified. Whiles some studies report changes in biomechanical parameters, other researchers found no significant changes. The scarcity of literature on training intervention on running kinematics and impact reiterates the need for further studies in order to ascertain how training influences running kinematics and impact. This information would provide guidelines to trainers and coaches to tailor appropriate training programmes to avert the factors that may predispose runners to injuries.

Finally, yet importantly, distribution of impact as it travels along the body during running is yet to be studied. Data on impact distribution will assist researchers, athletes and coaches in making necessary adjustments to prevent injuries and improve performance.

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The current study therefore deployed relevant technology and methodology to bridge gaps identified in current literature. The next chapter expounds on the methodological system deployed to answer the relevant questions of the study.

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CHAPTER 3

METHODOLOGY

A. INTRODUCTION

The primary aim of the study was to determine the effects of an eight-week customised endurance-training programme on kinematics and impact distribution associated with fatigue in recreational runners. Secondarily, the study sought to determine how running fatigue and gender influence the magnitude of impact at the tibia and lower back, body load, and running kinematics. This chapter presents the characteristics of the participants, the equipment and instrumentations deployed in the study, and the various experimental procedures, that were used to test the hypothesis of the study. The chapter is concluded with statistical analysis procedures and ethical considerations adhered to, during the study.

B. STUDY DESIGN

This experimental research study was completed in two phases. In both phases, a pre-post interventional design was deployed. Phase 1 focused on the acute changes in running kinematics and running impact parameters (i.e. magnitude of impact, body load, and external distribution of impact) as a result of metabolic fatigue. The participants underwent a fatigue protocol on a motorised treadmill while parameters of interest were assessed immediately before and after the fatigue protocol. In the phase 2, the runners were assigned to either an intervention group or a control group. The intervention group underwent eight-weeks of endurance training whereas the control group continued with their normal training routines. The same fatigue protocol was then administered after the eight weeks to test the “self-optimisation hypothesis”.

C. PARTICIPANTS

Forty recreational runners (19 men and 21 women) were recruited from the Stellenbosch Boland community through flyers and online advertisement on the website of Stellenbosch University for this study to participate in this research study. The number of participants was determined after a power calculation (Gpower 3.1, Kiel, Germany) was done using an α = 0.05 and an effect size of 0.473 determined based on previous similar investigations (see Figure 3.1) and a desired power of 0.80 (β = 0.80). Twenty-seven participants were deemed enough for the phase 1, whereas 30 (intervention = 15, control = 15) participants was found to be enough for the phase 2 of the study. In order to account for dropouts (reported 25% rate) and potential data-collection challenges due to technology failure and other unforeseen circumstances, 40 runners in total were recruited.

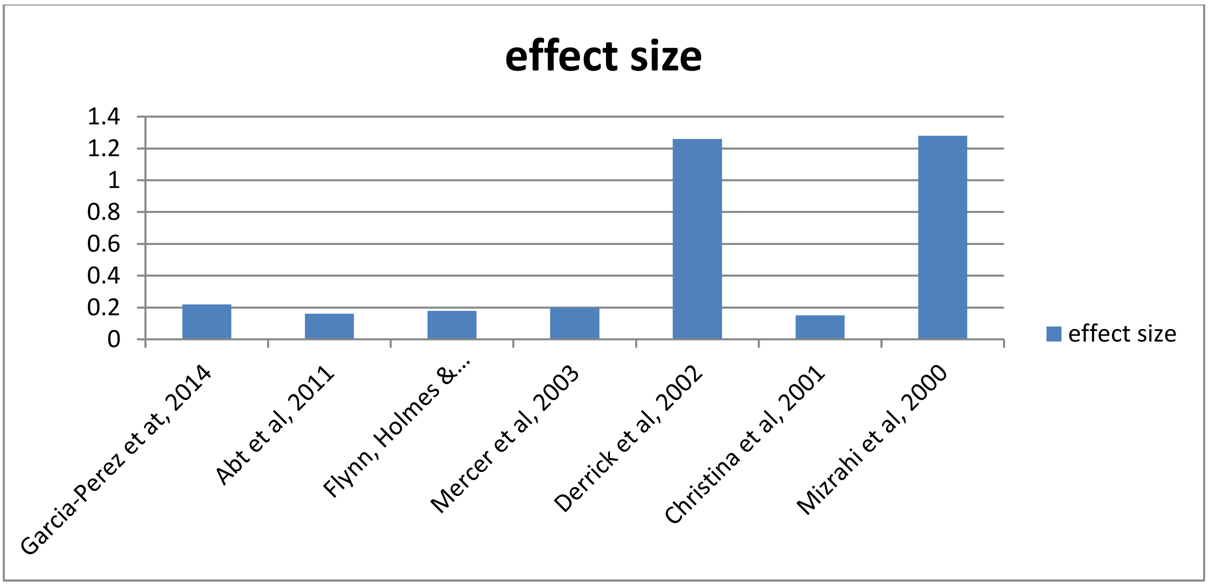

Figure 3.1: Studies and effect sizes of tibia impact realised pre- and post-fatigue.

The ages of the participants ranged between 19 and 30 years. All participants were free from lower-extremity injuries for at least six months prior to the study and were running regularly but recreationally with a mileage of <20 km per week. The participants were informed of the

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experimental procedures and all granted their informed consent (see Appendix F). A pre-participation health history screening questionnaire was completed by all participants prior to data collection to ensure qualification and provide demographic information about the participants (see Appendix G). Runners were excluded if they reported any known history of metabolic, neurological, or cardiovascular disease; recent (six-months prior) surgery or musculoskeletal injury of the lower limbs or back; and any recent (six-months prior) concussion.

D. ETHICS

Ethical clearance was given by the Research Ethics Committee (Humanities), Stellenbosch University (# SU-HSD-002032).

The participants were informed that their participation was voluntarily and that they therefore could withdraw from the study at any time. The participants filled out informed consent forms and a clear explanation of the protocols and procedures was given prior to testing. A basic life support qualified health-care professional available at all times during pre- and post-testing to provide basic medical aid in case of emergencies.

Recorded digital data obtained in connection with this study were stored on a password-protected computer belonging to the primary investigator. A back-up of the digital data was stored on a password protected personal computer of the supervisor. All hard copy files were stored in a locked office at the Department of Sport Science, Stellenbosch University.

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E. RESEARCH PROCEDURES

An appointment was made with the participants who fitted the inclusion criteria, to visit the Exercise Physiology Laboratory at the Department of Sport Science, Stellenbosch University, for the experimental procedures for the phase 1 and after the eight-weeks of intervention for phase 2 of the study.

1. FIRST VISIT

After completion of an informed consent and a health history questionnaire, the participants' anthropometric measurements were taken by the primary investigator for descriptive purposes before administering the fatigue protocol.

All participants wore their own running shoes, were fully rested and had not run at least 24 hours before data collection. The participants were requested to abstain from food and caffeine for at least one and a half hours prior to testing. The tests were performed in the morning, at the same time of the day, under controlled laboratory conditions (temperature = 20–24 °C and relative humidity = 50–60 % at 130 m altitude).

The men wore only running shorts, whereas the women wore crop tops to enable direct placement of reflective markers on bony landmarks of interest.

2. FATIGUE PROTOCOL

The participants were fitted with an adjustable safety harness on a motorised treadmill of known speed (Saturn h/p/cosmos, Nussdorf – Traunstein, Germany). After completion of a warm-up of eight minutes at 9 km/hr or 8 km/hr depending on running experience and individual comfort, the participants completed a discontinuous submaximal incremental test with increments of 1.5 km/hr every four minutes on the motorised treadmill interspersed by a one-minute rest for blood lactate [La]b sampling and RPE reading. The eight minutes' warm-up run was intended to acclimatise the participants to treadmill running and for pre-fatigue analyses. The speed selection (9km/hr for men and 8km/hr) was chosen to enable the runners to run at a steady state, based on previous studies on recreational runners (Garcia-Perez et al., 2013; Mercer et al., 2003; Mizrahi et al., 2000). The treadmill gradient was held at 1% throughout the run to reflect the energetic cost of outdoor running (Jones & Doust, 1996). The increments continued until blood lactate had risen to at least 4 mmol·L-1 from the previous stage.

After [La]b has risen to 4 mmol/L from the previous discontinuous stage, VO2max was determined by a continuous, constant grade (1%) incremental test to volitional exhaustion with increments of 1.5 km/hr every 4 minutes. The 1.5 km/hr speed increments with a 4-minute stage duration was used since it had been found to best assess aerobic fitness, determine peak running speed (Vpeak), and predict endurance performance in recreational runners (Peserico, Zagatto, & Machado, 2015). Consistently across each trial, the participants were verbally encouraged, to exert maximum effort. One minute after the maximal performance, the participants underwent a last four minute 9 km/hr for men and 8km/hr for women submaximal run for post fatigue analysis.

Figure 3.2: Schematic representation of sequence of protocol.

3. INTERVENTION

Participants were taken through eight weeks of endurance training with the aim of improving their fitness and endurance after going through the initial fatigue protocol. To achieve these objectives, the runners were asked to complete four training sessions per week over the eight weeks. The duration of eight weeks was chosen based on previous literature (Lake & Cavagnah, 1996; Mangine et al., 2015; Moore et al., 2012).

The intervention training programme was classified into two sessions: supervised and unsupervised (homework). Two sessions per week were supervised by the primary investigator and two were performed in the participants' own time as "homework". During the supervised sessions, the participants were asked to arrive at the Coetzenburg athletics stadium, Stellenbosch University (refer to Table 3.1).

For week-to-week repeatability, each session started and ended with at least one 400-m lap on the athletics track, with the rest of the sessions performed on concrete road. The participants were provided with feedback to familiarise them with pacing strategies. The participants ran in groups of two – four people who were matched as best possible according to their pre-test performance. Running in groups also served as a strategy for enhancing motivation and adherence to maintain training in the study. During each session (supervised and homework), running parameters were monitored using a mobile application, Strava to acquire training data regarding pace, distance, and time as a 'log book'.

Table 2.1: Training programme

Sessions (Days)	**Session Type**	**Session goal**	**Training**
Session 1 **Monday/ Tuesday**	Supervised	Basic endurance: aims to improve oxidation and utilisation of fats as an energy source while sparing muscle glycogen stores.	60-minute easy run @ 60 -70 % PTS
Session 2 **Wednesday/Thursday**	Supervised	Lactate threshold training: to adapt (raise) the runners' AT	2 x 20 minutes @ LT (~85 % PTS). With 5 minutes of easy run @ 60 % PTS in between.
Session 3	Homework	Aerobic endurance tempo training: designed to build aerobic capacity and speed endurance with moderate volume	45 - minute easy run @70 - 80% PTS
Session 4	Homework	Same as session 3	60 min easy run @ 70-80% PTS
Total	**four training sessions per week (one training session at LT)**		

LT: Lactate threshold, PTS: Pre-test maximal speed

4. CONTROL GROUP

The control group continued with their ““normal”” running routine for the eight weeks. Their running sessions were monitored using Strava to acquire data regarding pace, distance, and time as a ‘log book’. The participants were required to forward such information to the primary investigator immediately after the days’ session.

5. POST-INTERVENTION

After the eight weeks of the intervention, the participants went through post-testing. All procedures administered during the first visit were repeated during the post-intervention. The participants visited the Exercise Physiology laboratory for the second time for post-intervention testing. They wore the same attire and running shoes as during the pre-intervention testing. The same fatigue protocol described previously was administered at the same time of the day and under the same laboratory conditions as the pre-intervention.

G. TEST AND MEASUREMENTS

All test and measurements were repeated at both testing periods (before and after the intervention)

1. ANTHROPOMETRY

Participants’ anthropometric assessments were taken by the same investigator before data collection procedures for descriptive purposes and body fat determination. The International Society for the Advancement of Kinanthropometry (Marfell-Jones et al., 2001) were adhered to during the various anthropometric measurements. Body mass, height, and skin folds at body segments were measured at the Sports Physiology Laboratory in the Department of Sport Science, Stellenbosch University.

Body mass

The body mass of all participants were measured with a standardised electronic scale (UWE BW – 150, 1997 model, Brisbane, Australia). The participants stood at the centre of the scale for evenly distribution of body weight on both legs. The participants were barefoot at the time of measurement.

Height

The height of the participants was determined using a standing stadiometer (Seca, Germany). The participants stood barefoot with their back against the stadiometer and their heels together. The height was recorded from the anterior side of the feet to the vertex of the skull.

Waist and calf circumference

A standard tape measure was used to measure waist circumference. The tape measure was placed directly on the skin, halfway between the lowest rib and the top of the hip bone, roughly in line with the belly button while participants had their hands on opposite shoulders (right hand on left shoulder and vice-versa).

The right and left calf circumferences were also measured. Maximal calf circumference was defined as the maximum girth between the ankle and the knee joint, perpendicular to the long axis of the lower leg. The participants stood with their arms relaxed by their sides. Their feet were separated with their weight evenly distributed. Extra caution was taken to ensure that the measuring tape did not slip or indent the skin while taking the measurement.

Skin folds

Skin fold measurements were taken using a skinfold caliper (Harpenden Skinfold Caliper, England). Measurements were taken from the biceps, triceps, mid-thigh, abdomen, sub-scapular, supra-spinalae, supra-iliac and calf for body fat analysis.

Table 3.2 Skin fold sites and extraction procedures

Skin fold site	**Procedure**
Triceps	Participants assumed a standing position with arms held freely to the side of the body. A vertical pinch, halfway between the acromion (bony point of the shoulder) and olecranon processes (bony point of the elbow) was made. The calliper was then placed just below the pinch for the triceps skin fold measurement.
Biceps	A vertical fold located on the anterior midline of the upper arm over the belly of the biceps muscle was made while participants were standing with arms beside the body. The pinch of the calliper was made 1 cm higher than the level used to mark the triceps site for the biceps skinfold assessment.
Mid-thigh	A vertical pinch was taken at the mid-point of the anterior (front) surface of the thigh, midway between patella (knee cap) and inguinal fold. This measurement was taken with the participant sitting and the knee bent at right angles.
Abdomen	A mark was made 5 cm adjacent to the umbilicus (belly-button), to the right side. The vertical pinch was made at the marked site, and the calliper placed just below the pinch. Care was taken to ensure that the calliper or fingers were not placed inside the navel.
Sub-scapulae	A diagonal pinch located 1 to 2 cm below the inferior angle of the scapula (the bottom of the shoulder blade) on the right was made with the calliper

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	while the participant was standing. For easier identification, participants were made to place their right hand on their left shoulder.
Supra-spinalae	The intersection of a line joining the spinale (front part of iliac crest) and the anterior (front) part of the axilla (armpit) and a horizontal line at the level of the iliac crest was marked. The pinch was directed medially (towards the centre line) and downward, following the natural fold of the skin (at an approximate angle of 45 degrees) at the marked site.
Supra-illiac	A diagonal fold and pinch was made 1 cm above the anterior superior iliac crest (top of the hip bone) for skin fold assessment of the supra-iliac. The various skinfold measurements were used to assess the body fat composition of participants.

2. RUNNING FATIGUE

The pulmonary gaseous exchange of the participants was assessed throughout the fatigue protocol. Breath-by - breath gas exchange was measured with a metabolic cart (Cosmed Quark CPET metabolic system, Rome, Italy). Heart rate was recorded throughout the test with a heart rate monitor (COSMED wireless HR monitor, Italy). An Acchucheck Soft Click (Roche diagnostics, Mannheim, Germany) was also used to prick the finger for a droplet of blood for lactate sampling using the Lactate Pro 2 meter (ARKRAY, Inc. Kyoto, Japan) at the end of every stage.

The runners were considered to have achieved a maximal performance, and therefore reached their VO_{2max}, when at least two of the following criteria were fulfilled (following Howley et al., 1995): 1) plateau in the VO_2, defined as an increase of less than 1.5 ml·kg·min-1 in two consecutive workloads; 2) respiratory quotient (R- value) > 1.15; 3) maximal heart rate value (HR max) > 95% of the age-

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predicted maximum; 4) RPE ≥ 19 on the 6-20 Borg scale (appendix A). The test was also terminated at volitional exhaustion by the test participant. The peak treadmill speed (Vpeak; in m•s-1) was calculated as follows, taking every second into account:

Vpeak = completed full intensity (m/s) + [(seconds at final speed 240 s-1) x 0.42 m•s-1]

3. KINEMATIC PARAMETERS

Lower extremity kinematic parameters (step length, flight time, contact times and stride angle) were measured and recorded with an OptoGait photoelectric system and extracted onto a computer for processing. The OptoGait (Microgate, Italy, 2010) was set up on either side of the treadmill belts (see Figure 3.3) for lower-extremity spatio-temporal measurements.

Figure 3.3: Picture of OptoGait set-up (photograph by R. Venter)

Forward trunk lean and arm carriage were recorded using two cameras (GoPro Hero 4, Black, USA, 2014) for 2-D analysis. The two cameras, one at the front and the other at the side of the treadmill were positioned 200cm from the treadmill for capturing upper extremity running form for 2-D analysis. The cameras were set to sample at 240 frames per second. Kinematic data were recorded at the last 60 seconds of each stage to enable successful capturing of at least 10 consecutive strides for analysis.

Reflective markers (see Figure 3.4) were placed on the sternum, the two anterior superior iliac spines, and the acromio-clavicular processes of the right and left shoulders to serve as the reference points for the determination of the upper extremity parameters. The women were made to run with crop tops to ensure marker placement directly on the skin whereas the men wore only running shorts.

Figure 3.4: Reflective marker placement on participant (photograph by K. Schütte)

4. IMPACT DISTRIBUTION

The participants ran on the motorised treadmill with lightweight wireless tri – axial accelerometers, range ± 16g, sampling at 1,024 Hz, 16-bit resolution, and 23.6g weight, (Dublin, Ireland) attached to the distal anteromedial right and left tibia, lower back and upper back. In accordance with previous studies (García-Pérez et al., 2014, Mercer et al., 2003; Noris et al., 2014), self-adhesive tapes were used to secure the accelerometers for accurate data collection (see Figure 3.5). The accelerometers were securely tightened to individual comfort. Additional self-adhesive bandage (Cipla-Plast, Cipla, South Africa) was applied over the accelerometers to ensure that artefact movement was minimised throughout the test.

Figure 3.5: Pictures of accelerometer placement (photograph by R. Venter).

The body was divided into three segments (trunk, left leg, and right leg) using the four accelerometers. The trunk was defined as the portion of the body between the L3 spinous process and the level of C7-T2 spinal processes. The right and left legs were defined as the segments between the distal portion of the respective tibia and the L3 spinous process. The distribution of impact (Mercer et al., 2003) was determined and calculated as:

$\mathbf{E}\boldsymbol{D} = [\mathbf{1} - (\boldsymbol{upper\ acc} \div \boldsymbol{lower\ acc})] \times \mathbf{100}$ from all the accelerometers:

ED (impact distribution) gives an indication of how much of the impact was distributed at the left and right side of the lower extremity, and the trunk in percentages. Whereas **acc** represents the vector magnitude of the accelerations in all three axes.

5. DATA EXTRACTION AND STATISTICAL ANALYSIS

Forward trunk lean and arm carriage data were extracted using motion analysis software (Kinovea 0.8.15). The average of five consecutive strides was determined and exported into SPSS 23.0 for statistical analysis. The Hopkins spreadsheet was used to assess the inter-rater reliability of 50% of the data on arm carriage and forward trunk lean at three separate trials. Arm carriage was determined

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using the three classifications (Figure 2.5) suggested by Strohrmann et al., (2014). A number scale was used to assign arm carriage of runners to one of three categories (see Table 3.3)

Table 3.3: Arm carriage number scale

1	Arms parallel and driving forward
2	Arms targeting mid-line
3	Arms crossing mid-line

Impact data were collected at the tibia (right and left), lower back, and upper back via the accelerometers attached to the respective sites. Accelerometer data were extracted using the Consensys software (Consensys_v0.4.0, Dublin, Ireland) and exported for offline analysis. Data on impact were analysed using a custom written MATlab program (V.7.1, The Mathworks Inc, Natick, MA, USA). Impact distribution was ascertained from the accelerometers as summarised in Table 3.4. Impact data were extracted in both time and frequency domains. The time domain was acquired by extracting the peak positive vertical impact and peak negative anteroposterior (breaking) accelerations identified between 1% and 20% stance whereas the frequency domain was acquired from the median frequency of vertical impact accelerations of the whole stance phase. This was calculated as the centre of the PSD curves within the 1 – 100Hz range (Shutte et al., 2016).

Table 3.4: Impact extraction procedure from the accelerometer.

Parameter	Extraction procedure
Impact and breaking peak amplitudes (g)	Computed from extracted stance phases in the time domain. Acquired by extracting the peak positive vertical (impact) and peak negative anteroposterior (breaking) accelerations identified between 1% and 20 % stance.

PSD	Centre of the PSD curves within the 1 – 100Hz range

The normality of distribution of all data was tested with the SPSS software 23.0 and log transformation (Tabachnick & Fidell, 2007) was performed where data were not normally distributed. Paired t- tests were conducted with the SPSS software 23.0 to ascertain the relationships between pre and post fatigue for individual running kinematics and impact distribution. Bivariate correlation analysis was used to determine the relationship between changes in running kinematics as a result of fatigue on impact distribution. The correlations between pre- and post-intervention kinematic parameters were also statistically determined using bivariate and paired sample t-test analysis.

Table 3.5: Statistical analysis procedures and their conclusions.

Statistics	**Variables**	**Correlation Coefficient**	**α**	**Conclusion (if p < α)**
Descriptive	Spatio-temporal parameters	N/A	0.05	N/A
Paired t-test	Impact pre-post fatigue distribution	Sig. (2-tailed)	0.05	Running fatigue affects impact distribution
Two way ANOVA	Running kinematics and impact distribution		0.05	Changes in running kinematics because of fatigue affects impact distribution
Paired t-test	Running kinematics, pre and post fatigue	Sig. (2-tailed)	0.05	Running fatigue affects kinematics
Paired t-test	Pre and post fatigue	Sig. (2-tailed)	0.05	Running fatigue affects body load
ANOVA'S	All variables, pre and post intervention		0.05	Training influences impact, and running kinematics

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6. SUMMARY

Thirty-two recreational runners were recruited, administered a fatigue protocol and subjected to a customised interventional training programme for eight weeks. ANOVAs and paired sample t-test were conducted to test the hypothesis of the study. Accelerometers were used to collect impact data at body segments, the OptoGait photoelectric system and two cameras were deployed to record kinematic data. Statistical analyses were performed using SPSS 23.0 and Statistica 12 to test the hypothesis of the study.

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CHAPTER 4: ARTICLE 1

This article has been accepted for publication in the International Journal of Applied Exercise Physiology. The article therefore follows the author guidelines and template as recommended by the journal.

Modifications in running kinematics in fatigued running, do not influence the oxygen cost of transport

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ABSTRACT

Changes in oxygen cost of transport (O_2COT) due to fatigue has often been accompanied with alterations in running kinematics. Nevertheless, it is not certain if the changes in the oxygen cost of transport are as a result of the fatigue or the modifications in the kinematics. We therefore sought to understand the correlations between changes in running kinematics O_2COT in fatigued running. Thirty-two recreational (16 men, 16 women) runners underwent a fatigue protocol which involved incremental speed to volitional exhaustion on a motorised treadmill, whiles heart rate, oxygen consumption, blood lactate, and RPE were monitored. Spatio-temporal kinematic data was assessed with an Optogait photoelectric system, and GoPro Hero 4 Black camera was used to capture upper extremity kinematics for offline analysis. Changes in pre-and post-fatigue and the interactions between the changes in kinematic parameters and cost of oxygen transport were assessed. Forward trunk lean increased from 6.81 ± 2.08 ° to 7.95 ± 2.51 °, contact times also increased from 0.33 ± 0.02 to 0.34 ± 0.02 (seconds) and the oxygen cost of transport increased from 234.1 ± 20.1 to 240.8 ± 19.6 ($ml.km^{-1}.kg^{-1}$) at post-fatigue. A negative medium correlation ($r = -0.484$; $p = 0.001$) was found between changes in arm swing and contact time. Running-induced fatigue causes changes in the spatio-temporal and upper extremity kinematics of recreational runners, however, such changes do not correlate with the increase in O_2COT relative to body weight in fatigued running.

KEYWORDS: forward trunk lean; arm carriage; spatio-temporal kinematics; metabolic fatigue; stride angle; oxygen cost of transport

INTRODUCTION

Oxygen cost of transport (O_2COT) is a key determinant of middle and long distance running performance [1]. An inverse relationship exists between oxygen cost of transport and endurance running performance [2]. Physiological and biomechanical factors have been suggested to alter the O_2COT in distance running. Indeed, fatigued runners have been found to show a remarkable increase in their oxygen cost of transport [3,4]. Biomechanical parameters such as contact time, stride angle [5], foot print index (FPI) [1], vertical stiffness (K_{vert}), and ground reaction forces [6] have also been previously reported to affect the O_2COT in running.

Increases in oxygen cost of transport due to fatigue, has often been accompanied with changes in running kinematics [4]. However, it is not clear whether alterations in running kinematics in fatigued running contributes to the rise in the O_2COT.

The main aim of coaches and athletes involved in distance running is to optimise performance i.e. reduce O_2COT especially under fatigued running where runners are more susceptible to inefficiencies, and injuries.

The primary purpose of this study was therefore to assess the role alterations in upper extremity running kinematics and spatio-temporal parameters play in the O_2COT under fatigued running.

We hypothesised that running-induced fatigue would change the spatio-temporal and upper extremity kinematic parameters and that the changes due to fatigue, would negatively affect the O_2COT in running.

METHODS

Thirty-two recreational runners (16males, 16 females, running experience ≥ 5 years, aged 20-26 years, height 1.72 SD 0.07 meters, mass 68. 09 SD 10.98 kg) volunteered to participate in the study. Runners were included if they were running regularly (2 – 4 sessions per week; 15 – 30 km per week) and have experience with treadmill running. Participants were screened to have no known history of metabolic, neurological, cardiovascular disease, or surgery to the back or lower limbs, and were symptom-free of any lower extremity injuries for at least six months before the start of the study. Participants gave informed consent before participation in accordance with the Declaration of Helsinki. The ethics committee for humanities at Stellenbosch University approved the study (# SU-HSD-002032).

Metabolic Fatigue Protocol: Participants were subjected to an incremental speed to exhaustion running test on a motorized treadmill (Satun h/p/cosmos, Nussdorf-Traunstein, Germany). The participants started running at a speed of 8 $km.h^{-1}$ or 9 $km.h^{-1}$ depending on individual comfort and previous experience. After a warm-up session of four minutes at the starting speed. Participants ran discontinuously in increments of 1.5 km/hr every four minutes interspersed with a one-minute break for rating of perceived exertion (RPE 6 – 20 Borg's scale) and blood lactate sampling. The test continued until an RPE ≥ 19, or volitional exhaustion [7, 8].

Immediately after, participants completed another stage of four minutes at their starting speed for post-fatigue analysis. The treadmill gradient was held at 1% throughout the test to reflect the energetic cost of outdoor running [9]. All tests were performed under similar laboratory conditions (20 – 25 ◦C, 50 – 60% relative humidity at altitude of 130m above sea level). The perceived rate of exertion (RPE), and blood capillary samples from the finger (obtained with a portable lactate analyser; Lactate Pro 2 LT-1730, Japan) were obtained immediately after each stage. Participants were fitted with an adjustable safety harness during the entire running test. A decline in the end-tidal carbon dioxide pressure was also used to confirm fatigability of the participants. We hence defined fatigue as not only the inability of the participants to continue the running test but such inability should correspond with an RPE ≥ 19 and a decline in the end tidal carbon dioxide pressure [10].

The cost of oxygen transport: Breath by breath pulmonary gaseous exchange was recorded throughout the run with a metabolic analyser (Cosmed Quark CPET, Rome, Italy). The gas analysers were calibrated as 16% O_2, 4% CO_2 balance N_2. The turbine flow meter was calibrated with a 3L calibration syringe before each test. The average of Oxygen consumption (VO_2) values at the last 30s of the pre-fatigue and post fatigue runs relative to body weight ($mlO_2Km^{-1}Kg^{-1}$) were determined as O_2COT [11].

Spatio-temporal kinematic measures: An optogait photoelectric system (OPTOGait, Microgate S.r.I, Italy, 2010) was used to record spatio-temporal kinematic parameters of the runners at the last minute of each stage for offline analysis. The transmitting and receiving bars were placed on the edges of the motorised treadmill in such a way that the treadmill belt did not obstruct the infrared diodes of the system.

Upper extremity kinematics: Two cameras (Go Pro Hero 4 Black, USA) were positioned, one in front to assess arm carriage and the other by the side to measure forward trunk lean from the hip. The cameras were set to sample at 240frames/s. This sampling rate was chosen for better quality images and assessment [12]. Data were recorded at the last minute of every stage and analysed using an open source video analysis software (Kinovea 0.8.15). Forward trunk lean was defined as the angle between the upper body (referenced at the superior iliac spinous processes) and the vertical as previous described [12]. Reflective markers were placed on the posterior superior iliac spines, anterior superior iliac spine, and the greater trochanter. The average forward trunk lean of ten consecutive strides (5 left; 5 right) at mid-stance from the side camera was used for analysis. The average of the ten recordings was used to obtain the forward trunk lean. Arm carriage for both arms was determined based on a criterion (1 = arms parallel to line of symmetry; 2 = arms towards the line of symmetry; 3 = arms across line of symmetry) previously used [13].

Statistics: All data were checked for normality (Kolmogorov-Smirnov). Analysis of variance was used to determine the influence of metabolic fatigue on forward trunk lean, spatio-temporal running kinematics, and the cost of oxygen transport ($p = 0.05$). Chi-square analysis was conducted on arm carriage to determine pre-post fatigue differences ($p = 0.05$). Pearson correlations were used to ascertain the differences in pre-and post-fatigue ($p = 0.01$), and changes in kinematic parameters and cost of oxygen transport ($p = 0.05$), whereas Spearman correlation was used to determine the relationship between arm carriage and contact times ($p = 0.01$). 2-tailed independent t-test was used to determine gender differences.

STATISTICAL RESULTS

All tests were terminated at volitional exhaustion, and all the participants reached the set criteria for metabolic fatigue: an RPE ≥ 19, a decline in the end-tidal carbon dioxide pressure (PETCO$_2$), and at least 95% of maximum heart rate. All data were normally distributed except for stride angle which was log transformed to ensure normality.

Table 1. Descriptive statistics for participants and running economy parameters

Descriptive	**All runners (n = 3)2)**	**Men (n = 16)**	**Women (n = 16)**
Age (years)	21.75 ± 1.4	21.86 ± 1.88	21.64 ± 0.74
Body mass (kg)	68.18 ± 11.41	74.72 ± 11.24	61.64 ± 7.19
Height (m)	1.73 ± 0.08	1.78 ± 0.08	1.68 ± 0.06
BMI (kg.m^{-2})	22.56 ± 2.48	23.4 ± 2.51	21.72 ± 2.23

Table 2. Descriptive results for running kinematic parameters at pre-and post-fatigue with gender and running economy

Parameters	**Pre-fatigue**	**Post-fatigue**
Contact time (s)	0.216 ± 0.01	0.219 ± 0.01*
Flight time (s)	0.031 ± 0.05	0.028 ± 0.02
Step length (cm)	89.22 ± 5.94	89.73 ± 5.62
Stride angle	0.421 ± 0.64	0.435 ± 0.58
PETCO$_2$	39.65 ± 4.74	30.09 ± 2.79*
Trunk lean	7.17 ± 2.08	8.42 ± 2.51*
O$_2$COT (ml.kg^{-1}.km^{-1})	234.1 ± 20.1	240.8 ± 19.6*

* $p < 0.05$ significantly different between pre-and post-fatigue

Contact times were significantly longer ($p = 0.014$) at the fatigued state compared to the non-fatigued state. Forward trunk lean significantly increased with running fatigue ($p < 0.001$). Forward trunk lean increased to an average of 8.42° at post fatigue. Flight time, stride angle, and step length, on the other hand, were not affected by metabolic fatigue. About 20% of the recreational runners drove their arms more toward the line of symmetry (midline) of the body when fatigued. A negative Spearman correlation ($r^2 = - 0.484$, $p = 0.008$) was found between changes in contact time and arm carriage with metabolic fatigue.

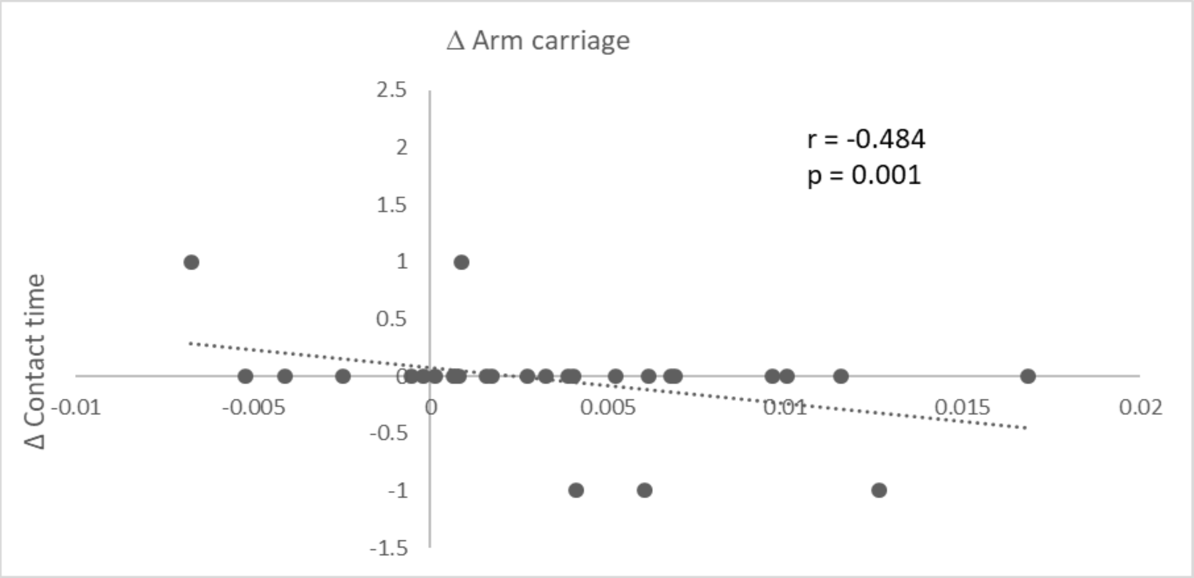

Figure 1. Scatter plot showing the negative correlation between changes in arm carriage and contact time as a result of metabolic fatigue at 95% confidence interval for all participants. /**/ Spearman correlation statistically significant at 0.01 (2-tailed)

There was a significant increase in the cost of oxygen transport relative to body weight ($p = 0.017$) with the onset of metabolic fatigue. However, there were no correlations between the changes observed in the running kinematics and the cost of oxygen transport

DISCUSSIONS

The hypothesis of the current study was that metabolic fatigue would result in changes in spatio-temporal and upper extremity running kinematics and that the changes would negatively affect the oxygen cost of transport under fatigued conditions.

In accordance with our hypothesis, forward trunk lean, and contact time changed (increased) with metabolic fatigue. Our findings build on evidence that running-induced fatigue leads to alterations in running kinematics of recreational runners [15,16,17]. However, the second aspect of the hypothesis was refuted. The changes in the kinematic parameters did not correlate with the oxygen cost of transport under fatigued running. The study was limited to recreational runners within the Stellenbosch Boland area and upper-extremity running kinematics were assessed with 2D video analysis.

Forward trunk lean was the upper extremity running kinematic that significantly changed with fatigue. According to our knowledge, only two studies have assessed the influence of fatigue on forward trunk lean. One of such

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studies was conducted amongst novice runners [18]. The other study [19] investigated how running fatigue influenced forward trunk lean among runners of different levels of experience. However, of the 21 participants used by the researchers, only six might be classified as recreational active runners (according to the reported running mileage per week). The sample size might not be strong enough for generalizable conclusions. The current study is the most exhaustive on recreational runners up to date. The significant increase found by our study as a result of fatigue was above the recommended angle previously reported. A slight increase in forward trunk lean up to about seven degrees reduces is suggested by previous authors to reduce the stress across the patellofemoral joint [20]. The implications of an over exaggerated trunk flexion (i.e. increases beyond 7 °) on the patellofemoral joint and the back muscles are uncertain. It has been demonstrated that too much flexion of the trunk was associated with runners with recurrent low back pain [19]. We therefore recommend that coaches and rehabilitation specialist include interventions and cues that could help runners maintain forward trunk lean posture within the recommended range especially when the runners are fatigued. It has been found to be associated with low back pain and stress on the patellofemoral joint [18, 20]. A hand full of studies available have argued that forward trunk lean increases with respect to fatigue, which our current findings support.

The spatio-temporal kinematic parameter that significantly changed with metabolic fatigue was contact time. An increase in contact time has previously been reported [21]. However, the previous study was among sprinters and endurance athletes. A study among recreational runners [22] reported no significant changes in contact times with the onset of fatigue. Nevertheless, there were some differences between our study and the previous one. Whilst we used a fatigue protocol incremental speeds to exhaustion protocol, the previous researchers made their participants ran at a predetermined speed corresponding to 85% of maximal aerobic speed. We suggest the level of fatigue induced by our protocol could be different from that of the previous study. The previous study was also among a much older population (age = 34.0 ± 7.8 years). In the current study, the runners ran on the treadmill at inclination of 1%. The choice of the inclination was to factor in the energetics of outdoor running, whereas García-Pérez and his colleague did not account for that in their fatigue protocol. It is therefore possible the differences in protocol and descriptive statistics of the runners between our study and that of García-Pérez et al. [22] contributed to the differences in results.

On the other hand, a significant increase in contact times as a result of fatigue was earlier reported [20] amongst elite runners. The previous authors observed that the increase in contact time was accompanied with an increase in the oxygen cost of transport, which our findings support. However, whether one could predict the other (i.e. contact time and cost of oxygen transport) was not investigated by the previous researchers. Our findings show that the change in contact time did not correlate with the oxygen cost of transport under fatigued conditions. The oxygen cost of transport in fatigued running could hence not be used to predict the changes in contact time and vice versa. Again, in contrast with previous authors [12, 20], the increase in the oxygen cost of transport in this study, did not correspond with a reduction in stride angle. Although a similar equipment was used for the measurement of stride angle. It is possible the differences in participant characteristics (i.e. recreational vrs elite runners) contributed to the contradictory findings.

The current study also assessed the relationship between stride angle and the oxygen cost of transport under fatigued conditions which was not the case in the previous studies. According to our knowledge, this is the only study that examined stride angle under such conditions. Stride angle is the angle between the theoretical arc traced by the centre of gravity during the step and the line of the ground (Fig. 2).

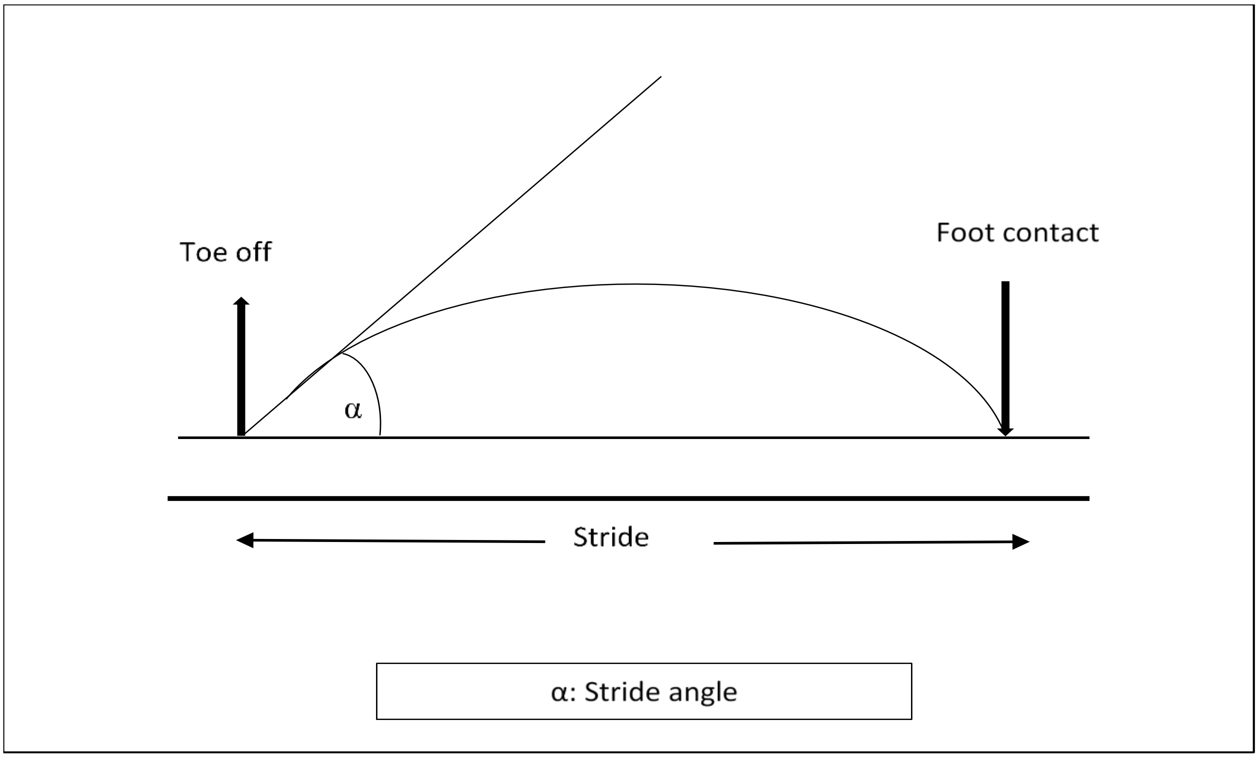

Figure 2. Schematic representation of stride angle (the angle between the parable tangent of the arc of the foot during stride and the ground). Adopted from Santos-Concejero et al. [5].

It has been theorised that an increase in stride angle would result in the release of the elastic energy stored in the Achilles tendon resulting in runners reducing the cost of oxygen transport in running. This theory was supported by Santos-Concejero and his colleagues [5]. They reported strong positive correlations between stride angle and the oxygen cost of transport in long distance athletes independent of fatigue. However, even at the pre-fatigue state, such association was not found in the current study amongst recreational runners. There is evidence to show that Ethiopian and Kenyan distance runners are genetically predisposed to be more efficient [24]. The previous study was amongst Ethiopian long distance runners, hence applicability of the positive correlation between stride angle and oxygen cost of transport by the previous authors to all population of runners (in this case, Southern African runners used in the current study) might not be appropriate. The findings of the current study show that recreational runners do not take advantage of the elastic energy stored in the Achilles tendon to be efficient. Interventions for efficiency in recreational running could consider strategies for optimising the elastic energy in the Achilles tendon.

Some of the runners (about 20%) were found to drive their arms more towards the line of symmetry (midline) when fatigued. Moving the arms towards the midline increases upper body rotation, which could result in an increase in the energy demands of running [25]. The recommended arm carriage posture by the previous researchers was driving the arms forward and parallel to the line of symmetry to support whole body movement and balance [26]. We did not find any correlation between the cost of oxygen transport and driving the arms parallel or towards the midline in both the fatigued and pre-fatigue state. We rather found a negative correlation between change in arm carriage and contact times with fatigue i.e. driving the arms more toward the midline was associated with a reduction in contact time when fatigued. A reduction in the time spent making contact has been found to be beneficial for injury reduction as it affects the impact forces received whilst running [27] It therefore appears driving the arms toward the midline in the fatigued state in distance running could be beneficial for injury reduction. A further study that correlates arm carriage in the three categories and the oxygen cost of transport and running impact variables in the fatigued state could throw more light on the implications of the correlation.

The results of this study showed that metabolic fatigue has significant influence on forward trunk lean, contact time, and the cost of oxygen transport. However, the changes in the kinematics (i.e. forward trunk lean, and contact time) with metabolic fatigue, did not contribute to the increase in the oxygen cost of transport.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of the staff at the Sport Physiology Laboratory, Department of Sport Science Stellenbosch University for assisting in data collection for this study. Saint A. Sackey received masters' scholarship from the Faculty of Allied Health Sciences, Kwame Nkrumah University of Science and Technology, Ghana. The Department of Sport Science, Stellenbosch University, South Africa, provided financial assistance for data collection at the Sport Physiology Laboratory of the University

REFERENCES

1. Lazzer, S., Taboga, P., Salvadego, D., Rejc, E., Simunic, B., Narici, M.V., et. al., *Factors affecting metabolic cost of transport during a multi-stage running race.* The Journal of Experimental Biology 2014. 217, 787-795 doi:10.1242/jeb.091645
2. di Prampero, P. E., Atchou, G., Brückner, J. C. and Moia, C., *The energetics of endurance running*. European Journal of Applied Physiology and Occupational Physiology. 1996. **55**, 259-266
3. Vercruyssen, F., Tartaruga, M., Horvais, N., and Brisswalter, J., *Effects of footwear and fatigue on running economy and biomechanics in trail running.* Medicine in Science in Sports and Exercise, 2016. 48(10): p. 1976.
4. Tam, N., Tucker, R., and Wilson, J.L.A., Effect on oxygen cost of transport on 8-weeks of progressive training with barefoot running. International Journal of Sports Medicine, 2016. 36(13): p. 1100-1105.
5. Santos-Concejero, J., Tam, N., Granados, C., Irazusta, J., Bidaurrazaga-Letona, I., Zabala-Lili J., and Gil, S.M., *Stride Angle as a novel indicator of running economy in well-trained runners*. Journal of Strength Conditioning Research, 2014. 28(7): p. 1889–1895.
6. Morin, J. B., Samozino, P. and Millet, G. Y., *Changes in running kinematics, kinetics, and spring-mass behavior over a 24-h run* Medicine and science in Sports Exerc. 2011. **43**, 829-836.
7. Derrick, T.R., Dereu, D., and Mclean, S.P., *Impacts and kinematic adjustments during an exhaustive run.* Medicine and Science in Sports and Exercise, 2002. 34(6): p. 998–1002.
8. Mercer, J.A., Vance, J., Hreljac, A., and Hamill, J., *Relationship between shock attenuation and stride length during running at different velocities.* European Journal of Applied Physiology, 2003. 87(4–5): p. 403–408.

9. Jones, A.M., and Doust, J.H., *A 1% treadmill grade most accurately reflects the energetic cost of outdoor running.* Journal of Sport Science, 1996. 14(4): p. 321–327.

10. Verbersky, O., Mizrahi, J., Voloshin, A., Treiger, J., and Isakov, E., *Shock transmission and fatigue in human running.* Journal of Applied Biomechanics, 1998 14 (3): p. 300-311.
11. Santos-Concejero, J., Tam, N., Granados, C., Irazusta, J., Bidaurrazaga-Letona, I., Zabala-Lili, J., and Gil, S.M., *Interaction effects of stride angle and strike-pattern on running economy*. International Journal of Sports Medicine 2014; 35(13): p. 1118 – 1123.
12. Souza, R.B., *An evidence-based videotaped running biomechanics analysis*. Physical Medicine and Rehabilitation of Clinics, 2016. 27(1): p. 217–236
13. Strohrmann, C., Harms, H., and Kappeler-setz, C., *Running using body-worn sensors*. IEEE Trans Info Technology Biomedics, 2012 16 (5): 983 - 990.
14. Dierks, T.A., Davis, I.S., and Hamil, J., *The effects of running in an exerted state on lower extremity kinematics and joint timing.* Journal of Biomechanics, 2010: 43(15): p. 2993 – 2998.
15. Miller, R.H., Meardon, S.A., Derrick, T.R., and Gillette, J.C., *Continuous relative phase variability during an exhaustive run in runners with a history of Iliotibial band syndrome*. Journal of Applied Biomechanics, 2008. 24(3): 262–270.
16. Koblbauer, I.F., van Schooten, K.S., Verhagen, E.A., and van Dieën, J.H., *Kinematic changes during running-induced fatigue and relations with core endurance in novice runners*. Journal of Science and Medicine in Sport, 2014. 17(4): p. 419–424.
17. Winter, S., Gordon, S., and Watt, K., *Effects of fatigue on kinematics and kinetics during overground running: A systematic review*. Journal of Sports Medicine and Physical Fitness, 2016. 35(1): p. 887 – 889.
18. Hart, J.M., Kerrigan, D.C., Fritz, J.M., and Ingersoll, C.D., *Jogging kinematics after lumber paraspinal muscle fatigue.* Journal of Athletic Training, 2009. 44 (5): p. 475-481.
19. Strohrmann, C., Harms, H., and Kappeler-setz, C., *Running using body-worn sensors*. IEEE Trans Info Technology Biomedics, 2012 16 (5): 983 - 990.
20. Teng, H.L., and Powers, C.M., *Influence of trunk posture on lower extremity energetics during running*. Medicine in Science in Sports and Exercise, 2015. 47(3): p. 625–630.
21. Nummela, A., Stray-Gundersen, J., and Rusko, H., *Effects of fatigue on stride characteristics during a short-term maximal run.* Journal of Applied Biomechanics, 1996. 12 (2): p. 151–160.
22. García-Pérez, J.A., Pérez-Soriano, P., Llana, S., Martínez-Nova A., Sánchez-Zuriaga, D., *Effect of over ground vs treadmill running on plantar pressure: Influence of fatigue*. Journal of Gait Posture, 2013. 38 (4): p. 929 – 933.
23. Santos-Concejero, J., Granados, C., Irazusta, J., Bidaurrazaga-Letona, I., Zabala-Lili, J., Tam, N., and Gil, S.M., *Differences in ground contact time explain the less efficient running economy in North African runners*. Sport Biology, 2013. 30 (3): p. 181 – 187
24. Wilber, R.L., and Pitsiladis, Y.P., *Kenyan and Ethiopian Distance Runners: What Makes Them so Good?* International Journal of Sports Physiology and Performance, 2012. 7 (2): p. 92-102
25. Arrelano, C., Kram R., *The effects of step width and arm swing on energetic cost and lateral balance during running.* Journal of Biomechanics, 2011. 48(7): p. 1291 – 1295.
26. Strohrmann, C., Seiter, J., Tröster, G., *Can smartphones help with running technique?* Procedia Computer Science, 2013. 19: p. 902 – 907.
27. Hreljac, A., *Impact and Overuse Injuries in Runners*. Medicine and Science in Sports and Exercise, 2004. 36 (5): p. 845-849.

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CHAPTER 5: ARTICLE 2

This article was written in accordance with the guidelines of the Journal of Applied Biomechanics. The article is currently under review. Proof of submission has been attached as Appendix B.

An abstract from the article was accepted for presentation at the World Biomechanics Conference, Dublin, 2018. The proof of acceptance is attached as Appendix C.

TITLE PAGE

October 18, 2018

Body load: A potential indicator of fatigue in distance running

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Conflict of Interest Disclosure: None.

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ABSTRACT

Fatigability has been implicated as a key variable in running-related injury causation models. Biomechanically, the use of running impact variables from tri-axial accelerometers to detect the onset of fatigue has been inconclusive due to contradictory findings. The study on which this article reports assesses the use of accelerometry parameters (body load, and external distribution of impact) as indicators of running-induced fatigue. We also report on the influence of sampling rates of accelerometers in the detection of fatigue. Thirty-two runners (age 21.75 ± 1.4years, height 1.72 ± 0.07m, mileage: between 15km and 25km per week) volunteered to participate in the study. Participants underwent an incremental speed to exhaustion protocol on a motorised treadmill. Tri-axial accelerometers at the tibia, lower-back, and upper back were used to collect data throughout the run. External distribution of impact, vertical tibia impact magnitude, and body load was determined from a customised algorithm in MATLAB (2018a) and analysed before and after fatigue. Body load increased with fatigue ($p = 0.021$; $p = 0.028$ at 100Hz, and 1024Hz respectively. There was a negative correlation ($r = -0.466$, $p = 0.038$) between body load and end-tidal carbon dioxide pressure. This suggests that biomechanical fatigue is related to cardiopulmonary fatigue in distance running.

***Keywords*:** running impact, tibia, accelerometer, L3 spinous process

Word Count: 2092

INTRODUCTION

The quest to understand the physiological, and biomechanical principles behind the high incidence rate of running-related injuries[1, 2], has driven investigations into the reported links to the injuries. Running-induced fatigue[3,4,5,6,7,8,9], has drawn attention due to the changes in fatigue effects in running impact variables (i.e. magnitude, and rate) and kinematics. Running-induced fatigue nevertheless is a complex phenomenon. Researchers have used different pointers, and sometimes a combination of parameters (psychological: rate of perceived exertion [RPE][10]; physiological: heart rate variation [HRV]) [11], end-tidal carbon dioxide pressures [PETCO$_2$] [4]) to indicate the onset of fatigue. Biomechanically, a relationship has been reported between running-induced fatigue and running impact variables from tri-axial accelerometers i.e. magnitude, rate, and attenuation[4, 8]. However, the use of such running impact variables as indicators of running-induced fatigue is questionable due to the reported contradictions in findings. While some researchers reported increases in impact magnitude and rate with fatigue[8], others found no changes[5, 7]. In addition, the validity of using an increase in running impact magnitude as a predictor of injury potential has been cautioned[12]. It has been argued[12] that an increase in impact magnitude may not necessarily result in an increase in the vertical peak ground reaction force and the loading rate, unless it is accompanied by some changes in running kinematics (e.g. less peak knee flexion angle). Tri-axial accelerometers nevertheless present spatial, cost, and ecological advantages in the monitoring of running. We therefore pursued to investigate the use of novel parameters from a tri-axial accelerometer at the lower back, and external distribution of impact (from four accelerometers) as alternative variables for indicating fatigability in distance running. Further, we sought to compare sampling at the traditional 100Hz and at a higher frequency of 1024Hz (the highest commercially available tri-axial accelerometer we could find) and its implications on body load assessment. We also investigated whether the overall impact (i.e. summation of vertical, anterior-posterior, and medio-lateral impact) would be more sensitive to fatigue compared to the use of only the vertical component of the impact. It was hypothesised that running-induced fatigue would result in an increase in body load and the overall impact at the tibia, and alter the external distribution of the impact. We further hypothesised that sampling at the higher frequency (1024Hz) would be superior to the traditional rate (100Hz) in the detection of fatigue with body load.

METHODS

Thirty-two recreational runners (16 women, 16 men; age 21.75 ± 1.4yrs; height 1.72 ± 0.07m) volunteered to participate in the study. All participants were free from lower extremity injuries for at least six months prior to the study and were running regularly but recreationally with a mileage of between 10km and 25 km per week, and also had some treadmill running experience. The participants were informed of the experimental procedures and all granted their informed consent. A pre-participation health history screening questionnaire was completed by all participants prior to data collection to ensure that they fit the criteria and provided demographic information about the participants. Runners were excluded if they reported any known history of metabolic, neurological, or cardiovascular disease; and a recent (six months' prior) surgery or musculoskeletal injury of the lower limbs or back. All experimental procedures were approved by the Research Ethics Committee of Humanities of Humanities, Stellenbosch University. In accordance with the Declaration of Helsinki, all participants completed an informed consent, and a health history questionnaire. All participants wore their own running shoes, were fully rested and had not run at least 24 hours before data collection. Participants abstained from food and caffeine for at least one and a half hours prior to testing. The tests were performed in the morning, at the same time of the day, under controlled laboratory conditions (temperature = 20 – 24 °C and relative humidity = 50 – 60 % at 130 m altitude). The participants were fitted with an adjustable safety harness on a motorised treadmill of known speed (Saturn h/p/cosmos, Nussdorf – Traunstein, Germany). After completion of a warm-up of eight minutes at 9kmhr^{-1} or 8kmhr^{-1} depending on individual comfort, the participants completed a discontinuous submaximal incremental test with increments of 1.5kmhr^{-1} every four minutes on the motorized treadmill interspersed by a one-minute rest for blood lactate [La]b sampling RPE reading until volitional exhaustion. The speed selection (9kmhr^{-1} or 8kmhr^{-1}) was chosen to enable runners run at a steady state, based on previous studies on recreational runners[4,5,7]. The treadmill gradient was held at 1% throughout the run to reflect the energetic cost of outdoor running[16]. Consistently across each trial, the participants were verbally encouraged, to exert maximum effort. One minute after the maximal performance, the participants underwent a last four minutes at 9 kmhr^{-1} or 8kmhr^{-1} (depending on their starting speed) for a submaximal run for post fatigue analysis. The runners were considered to have achieved a maximal performance, and be fatigued when the following criteria were fulfilled[17]: rating of RPE ≥ 19 on the 6-20 Borg scale, a decline in PETCO$_2$, and or volitional exhaustion. Triaxial accelerometers (±16 g range, sampling at 1024 Hz, 16-bit resolution, 23.6 g weight, Shimmer 3, Dublin, Ireland) were securely positioned using a self-adhesive tape over the L3 spinous process of the trunk, left and right distal end of the tibia, and upper back to collect accelerometry data throughout the run. Tri-axial accelerometry data signals were processed using a customised software in MATLAB version 8.3 (The Mathworks Inc. Natick, MA, USA). The accelerations were trigonometrically tilt-corrected prior to extracting outcome measures. The measurements were computed from the final 20 consecutive steps of acceleration signals at the pre-fatigue and post-fatigue runs. Body load was determined from accelerometry data from the lower back, and determined as previously described[18,19]. The reliability of a single accelerometer at the lower back (L3 spinous process) for the estimation of body load[18] with respect to activities involving forward running has been previously determined. The researchers reported a Pearson correlation of between 0.77 and 0.84 at low intensities, and 0.74 and 0.93 at high intensities compared to a standard force plate. Calculations were done from both high- and down-sampled sampling rate conditions, 1024Hz and 100Hz respectively. Accelerations were down-sampled to 100Hz to replicate that used typically in-field and traditionally in previous studies[17,19,20,21]. **External distribution of impact (ED):** The body was divided into three segments (trunk, left leg, and right leg) using four accelerometers. The trunk was defined as the portion of the body between the L3 spinous process and the level of C7-T2 spinal processes. The right and left legs were defined as the segments between the distal portion of the respective tibia and the L3 spinous process. ED was determined and calculated[7] as: $\mathbf{E}\boldsymbol{D} = [\mathbf{1} - (\boldsymbol{upper\ acc} \div \boldsymbol{lower\ acc})] \times \mathbf{100}$ from all the accelerometers: ED gives an indication of how much of the impact was distributed at the left and right side of the lower extremity, and the trunk in percentages, whereas **acc** represents the vector magnitude of the accelerations in all three axes. All data were checked for normality (Kolmogorov-Smirnov). A two factor analysis of variance (ANOVA) was used to determine the influence of running-induced fatigue on running impact magnitude, body load, and external distribution (p = 0.05, 95% confidence intervals).

RESULTS

All runners fulfilled the set fatigued requirements. Therefore, there was a decline in $PETCO_2$, an RPE ≥ 19, and all the tests were terminated by volitional exhaustion. The descriptive statistics and the fatigue criteria are shown in (Table 1). The ANOVA results are shown in (Table 2). The analysis showed a significant increase ($p = 0.021$, $p = 0.028$ at 100Hz and 1024Hz respectively) in body load (regardless of sampling rate) with the onset of fatigue (Figure 1.), and a negative correlation ($r = - 0.466$, $p = 0.038$) between body load fatigue (indicated as a decline in $PETCO_2$) as shown in Figure 2. Vertical impact, and the vector sum of the vertical, anterior-posterior, and medio-lateral accelerations remained unchanged after fatigue. Magnitude of impact at the lower back, and upper back was also not affected by fatigue (Figure 3). External distribution of impact did not change with fatigue. However, it was found that external distribution of impact differed from one runner to the other. Whiles some distributed most of the impact around the lower extremities, others distributed most along the trunk.

DISCUSSION

We sought to assess the detection of running-induced fatigue using body load, running impact at the tibia, and the external distribution of impact in distance runners. We also determined the influence of sampling rate of accelerometers on fatigue detection with respect to body load. It was hypothesised that running-induced fatigue would lead to an increase in body load and the overall impact at the tibia, and change the external distribution of the impact. We hypothesised that sampling at the higher frequency of 1024Hz would be superior to the traditional rate of 100Hz in the detection of fatigue with body load. In accordance with our hypothesis, body load significantly increased with running-induced fatigue among the group regardless of the sampling rate, with a negative correlation between $PETCO_2$ and body load. This is the first study according to our knowledge that investigated the relationship

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between running-induced fatigue and body load from a single tri-axial accelerometer in distance running. Our results affirm that a single accelerometer at the lower back of a runner could give an indication of exhaustion (i.e. fatigability). Accelerometers are lightweight and could be used to monitor loads outdoors over long periods, presenting ecological advantages over force platforms. The use of body load as an indicator of fatigue could address a limitation (the possibility of runners prematurely quitting a running fatigue protocol due to the subjectivity of RPE and volitional exhaustion) reported by previous authors[7] in the detection of fatigue. The magnitude of load has previously been linked to running-related injuries[13]. The higher the load, the higher the possibility of injuries[22]. The study elucidated the potential of using an accelerometer at the lower back to measure the accumulation of internal biomechanical loading and fatigability. The findings could therefore serve as a foundation for biomechanical monitoring of load in the outdoor settings for fatigue detection, and possible reduction of injuries in distance running. Most of the commercially available load monitoring systems concentrate on physiological load (i.e. heart rate measures), to the neglect of biomechanical loading. Our findings show that body load as a single parameter could predict PETCO$_2$ (a physiological indicator of fatigue) and hence could be a useful variable in ecological monitoring of load and fatigue in distance running. The traditional sampling rate (100Hz), and the higher sampling rate (1024Hz) were both able to detect running-induced fatigue. However, the traditional rate (100Hz) is preferred for the detection of fatigue, due to the lesser computations involved with the traditional rate and hence presents better real-time feedback application.

In agreement with some previous studies, the vertical impact at the tibia did not change with fatigue[7,23]. Nevertheless, it contradicted the findings of other studies[4,8,9]. The current results and contradictions in the previous studies reiterate the need for the use of other impact parameters such as body load as an indicator of running-induced fatigue. The available

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literature[4,5,6,7,8] looked at how impact is reduced as it travels along the body during running, often referred to as impact attenuation. The current study attempted to understand where, and how the impact is distributed externally in the body under fatigued conditions. Although the results showed that external distribution of impact does not change with fatigue, the nature of the distribution was individualistic. Whiles some of the runners distributed most of the impact around the lower extremities, others distributed around the trunk. The participants wore their own running shoes during testing. It is unclear whether that could have contributed to the distribution. The scope of this study was limited to the determination of whether fatigue influences the distribution of impact. Future studies on the implications of external load distribution (i.e. lower extremity or trunk) could help shed more light on the mechanisms behind running-related injuries at specific injury sites.

The physical and physiological demand on runners (body load) increases with fatigue. The higher sampling rate (1024Hz) was not superior to the traditional sampling rate (100Hz). Therefore, in the detection of fatigue the traditional rate is preferred, due to the fact that fatigue could be detected at a lower computational demand and therefore has better real-time application. However, absolute figures (i.e. the magnitude of the load) should be interpreted with respect to the sampling rate. Running-induced fatigue does not affect the magnitude of running impact and external distribution of impact in running.

ACKNOWLEDGEMENT

The authors would like to acknowledge the contributions of the staff at the Sport Physiology Laboratory, Department of Sport Science Stellenbosch University, South Africa for assisting with data collection for this study. Saint A. Sackey received a master’s scholarship from the Faculty of Allied Health Sciences, Kwame Nkrumah University of Science and Technology, Ghana. The Department of Sport Science, Stellenbosch University, South Africa,

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provided financial assistance for data collection at the Sport Physiology Laboratory of the University.

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REFERENCES

1. Buist I, Bredeweg SW, Lemmink KAPM et al. Predictors of running-related injuries in novice runners enrolled in a systematic training program: A prospective cohort study. *Am J Sports Med 2010*, 38(2), 273–280
2. Taunton JE, Ryan MB, Clement DB et al. A prospective study of running injuries: the Vancouver sun run “in training” clinics. *Br J Sports Med 2003*, 37(3), 239–244.
3. Koblbauer IF, van Schooten KS, Verhagen EA et al. Kinematic changes during running-induced fatigue and relations with core endurance in novice runners. *J Sci Med Sport 2014*, 17(4), 419–424.
4. Mizrahi J, Verbitsky O, Isakov E, et al. E€ ect of fatigue on leg kinematics and impact acceleration in long distance running. *Hum Mov Sci 2000*, 19 (2000) 139 – 15. PII: S 0 1 6 7 - 9457(00)00013-0
5. Garcı´a-Pe´rez JA, Pe´rez-Soriano P, Llana S et al. Effect of overground vs treadmill running on plantar pressure: Influence of fatigue. *J Gait Posture 2013,* 38 (4), 929 – 933.
6. Abt JP, Sell TC, Chu Y. et. al. Running kinematics and shock absorption do not change after brief exhaustive running. *J Strength Cond Res 2011*, 25(X): 001– 007.
7. Mercer JA, Vance, J, Hreljac A et al. Relationship between shock attenuation and stride length during running at different velocities. *Eur J Appl Physiol 2002*, 87(4–5), 403–408.
8. Derrick TR, Dereu D, & Mclean SP. Impacts and kinematic adjustments during an exhaustive run. *Med. Sci. Sports Exerc 2002*, 34(6), 998–1002.
9. Verbitsky O, Mizrahi J, Voloshin A et al. Shock transmission and fatigue in human running. *J Appl Biomech 1998*, 14 (3), 300-311.
10. Dierks TA, Davis IS, & Hamil J. The effects of running in an exerted state on lower extremity kinematics and joint timing. *J Biomech 2010*, 43(15), 2993 – 2998.

Stellenbosch University https://scholar.sun.ac.za

11. Nascimento EMF, Kiss MADPM, Santos TM, et al. Determination of Lactate Thresholds in Maximal Running Test by Heart Rate Variability Data Set. *Asian J Sports Med 2017*, http://dx.doi.org/10.5812/asjsm.58480
12. Derrick TR. The effects of knee contact angle on impact forces and accelerations. *Med Sci Sports Exerc 2004*, 36(5):832-7.
13. Bertelsen ML, Hulme A, Petersen J, et al. A framework for the etiology of running- related injuries. *Scand J Med Sci Sports 2017*, 27:1170–1180
14. Soligard T, Schwellnus M, Alonso JM, et al. How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. *Br J Sports Med. 2016*, 50:1030-1041
15. Magnusson SP, Langberg H, Kjaer M. The pathogenesis of tendinopathy: balancing the response to loading. *Nat Rev Rheumatol. 2010*, 6:262-268
16. Jones AM, & Doust JH. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. J Sport Sci 1996, 14(4), 321–327.
17. Howley ET, Bassett DR, Welch HG. Criteria for maximal oxygen uptake: review and commentary. *Med Sci Sports Exerc 1995*, 27 (9) 1292 – 1301.
18. Hollville E, Coutirier A, Guilhem G, et al. Minimaxx player load as an index of the center of mass displacement? A validation study. *33rd International Conference on Biomechanics in Sports, Poitiers, France, June 29 - July 3, 2015*
19. Boyd LJ, Ball K, Aughey RJ. The reliability of MinimaxX accelerometers for measuring physical activity in Australian football. *Int J Sports Physiol Perform 2011*, 6(3):311-21.
20. Dalen T, Jørgen I, Gertjan E, et al. Player load, acceleration, and deceleration during forty-five competitive matches of elite soccer. *J Strength Cond Res 2016*, 30(2): 351–359.

21. Bailey JA, Gastin PB, Mackey L, et al. The Player Load Associated with Typical Activities in Elite Netball. *Int J Sports Physiol Perform 2017*. DOI: https://doi.org/10.1123/ijspp.2016-0378
22. Malisouxa L, Nielsenb RO, Urhausen A, Theisen D. A step towards understanding the mechanisms of running-related injuries. *J Sci Med Sport 2015*, 18. 523–528.
23. García-Pérez JA, Pérez-Soriano P, Belloch SL, et al. Effects of treadmill running and fatigue on impact acceleration in distance running. *Sport Biomech 2014*, 13 (3) 259 – 266.

TABLES

Table 1. Descriptive statistics for participants and running economy parameters

<table>
<tr><th>Descriptive</th><th colspan="2">All runners (n = 32)</th><th>Men (n = 16)</th><th colspan="2">Women (n = 16)</th></tr>
<tr><td>Age (years)</td><td colspan="2">21.75 ± 1.4</td><td>21.86 ± 1.88</td><td colspan="2">21.64 ± 0.74</td></tr>
<tr><td>Body mass (kg)</td><td colspan="2">68.18 ± 11.41</td><td>74.72 ± 11.24</td><td colspan="2">61.64 ± 7.19</td></tr>
<tr><td>Height (m)</td><td colspan="2">1.73 ± 0.08</td><td>1.78 ± 0.08</td><td colspan="2">1.68 ± 0.06</td></tr>
<tr><td>BMI (kg.m^{-2})</td><td colspan="2">22.56 ± 2.48</td><td>23.4 ± 2.51</td><td colspan="2">21.72 ± 2.23</td></tr>
<tr><td colspan="6">Fatigue parameters</td></tr>
<tr><td>Parameters</td><td colspan="3">Pre-fatigue</td><td colspan="2">Post-fatigue</td></tr>
<tr><td>RPE</td><td colspan="3">6.5 ± 0.51</td><td colspan="2">19.00 ± 1.0*</td></tr>
<tr><td>PETCO$_2$</td><td colspan="3">39.65 ± 4.74</td><td colspan="2">30.09 ± 2.79*</td></tr>
</table>

/*/Statistically significant difference between pre-post fatigue ($p < 0.05$

Table 2. Mean and standard deviations of impact parameters, and body load at pre-post fatigue

Parameters	**Pre-fatigue**	**Post-fatigue**	***P* value (0.05)**
Tibia impact (g)			
Tibia (vertical)	4.03 ± 1.33	4.42 ± 2.18	0.822
Tibia (vector sum)	6.14 ± 2.13	6.15 ± 3.71	0.981
Lower back	2.21 ± 1.40	2.32 ± 1.39	0.831
Upper back	1.19 ± 0.54	1.19 ± 0.56	0.842
Body Load (au)			
Body load 100Hz	69.61 ± 19.65	72.66 ± 21.83	0.021*
Body load 1024Hz	380.76± 115.97	396.46±128.03	0.028*

/* /Significant difference between pre-post fatigue ($p < 0.05$). Body load was extracted from the accelerometer at the lower back (L3 spinous process)

FIGURE CAPTION

Figure 1 - Diagramatic representation of the changes in body load calculated from an acceleromter at the L3 spinous process at pre-post fatigue (for all the participants at 95% confidence interval levels).

Figure 2 - Scatter display of the correlation between changes in body load (100Hz) and PETCO$_2$ due to fatigue

Figure 3 – Spider-plot display, showing the individualistic nature of the external distribution of impact.

FIGURES

Figure 1

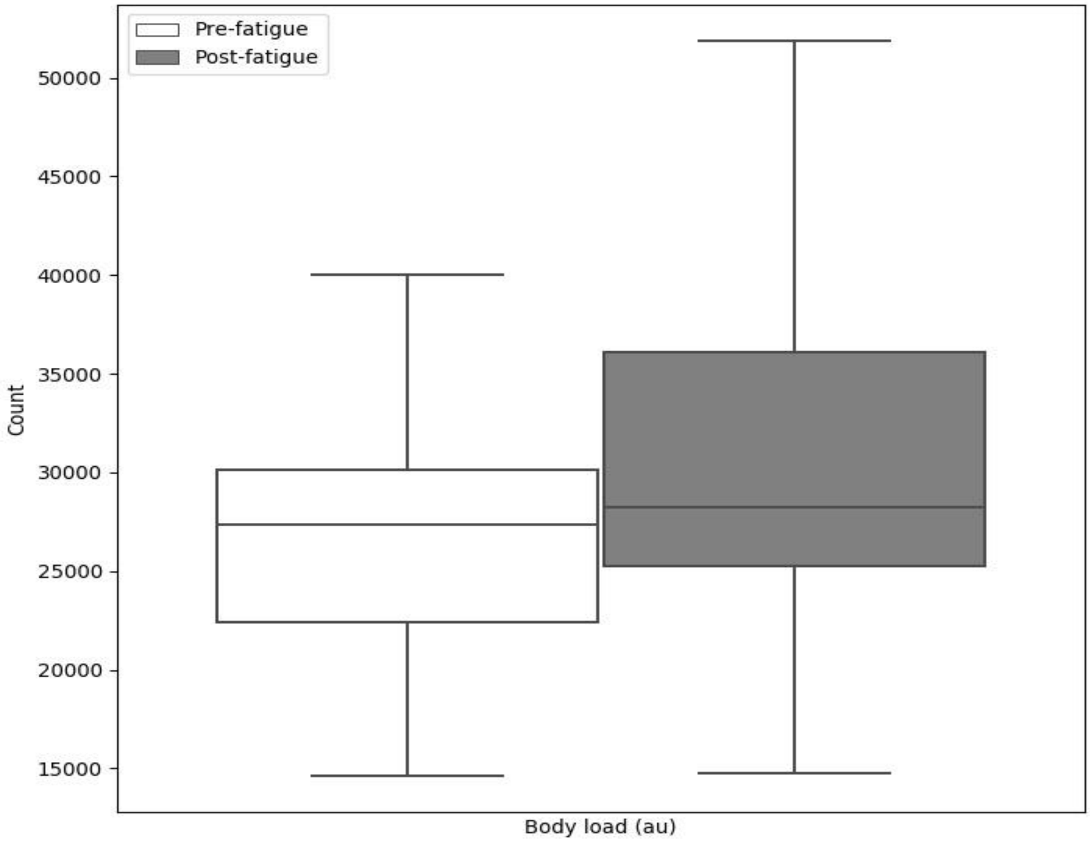

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Figure 3

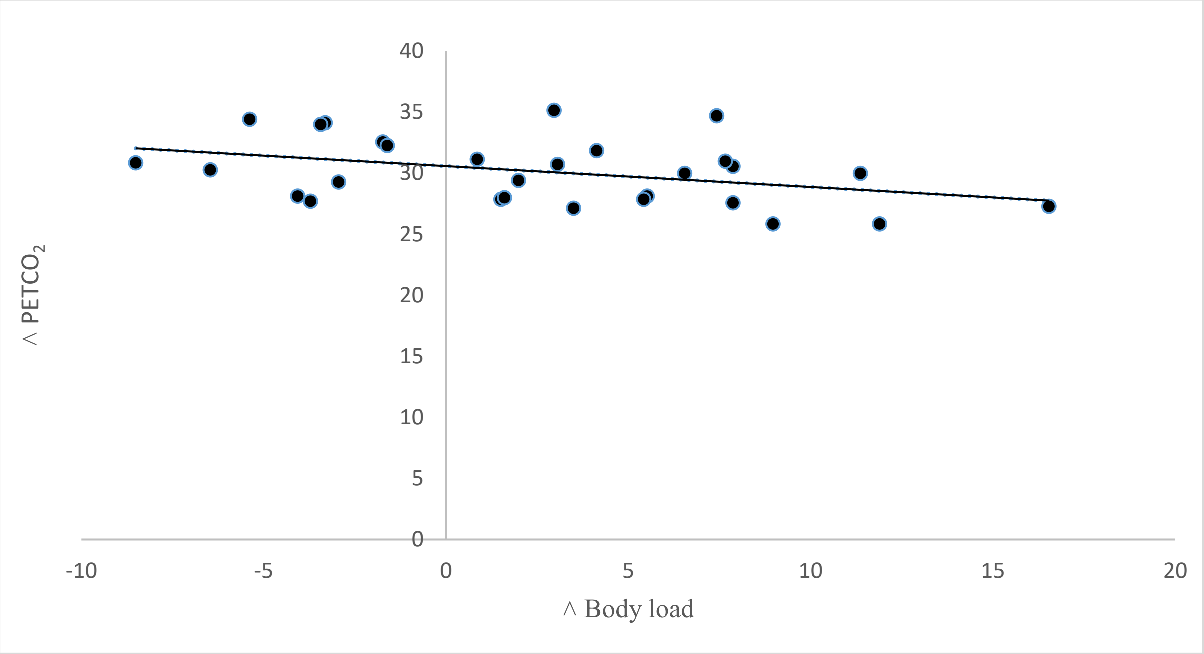

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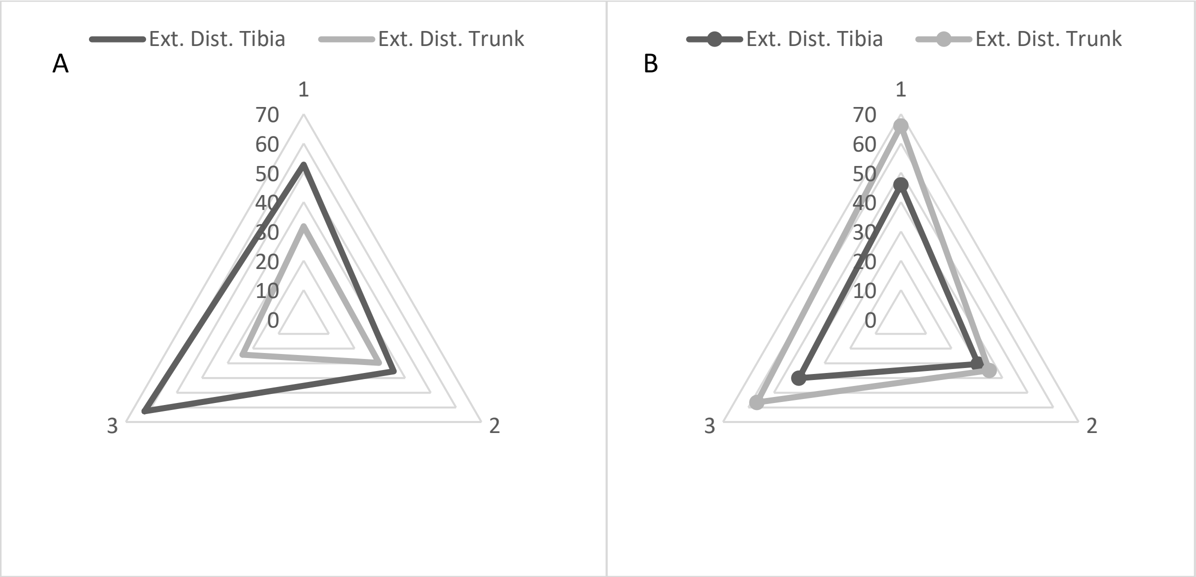
Figure 3.



/A/ the impact was mainly distributed around the lower extremity, whereas in /B/ the impact was mainly distributed around the trunk.

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CHAPTER 6: ARTICLE 3

An abstract for this article was accepted for oral presentation at South African Sports Medicine Association Conference, 2017 (Appendix D).

The full article was submitted to the Journal of Strength and Conditioning Research for review and publication. The reviewers requested revisions for further consideration. The revised article has been resubmitted for consideration. Attached in Appendix E is the proof of resubmission. The article hence follows the requirements and recommendations of the journal.

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TITLE PAGE

Manuscript Title: **Runners self-optimize their kinematics in response to running-induced fatigue after eight weeks of endurance training**

Running head: **Endurance training and self-optimization**

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ABSTRACT

Novice and recreational runners are less efficient and prone to injuries compared to well-trained elite runners. It has been theorized that a brief exposure of runners (recreational and novice) to training could lead to automatic fine-tuning of running kinematics for better efficiency. However, only a hand full of studies have tested this theory. The reported findings have also been contradictory. It is again not clear whether the theory holds under fatigued conditions. We therefore investigated the influence of endurance training on running kinematics, running impact variables, and the oxygen cost of transport (O_2COT) under fatigued conditions in recreational running. Twenty recreational runners were recruited and subjected to eight-weeks endurance-training program. Before and the training program, participants underwent a running fatigue protocol whilst O_2COT was monitored. Running impact variables and body load were assessed with tri-axial accelerometers and analyzed using a custom written algorithm in MATLAB 2018a. Spatio-temporal, and upper extremity kinematics were also quantified with an OptoGait photoelectric system whereas 2-D video analysis was deployed in the determination of upper extremity kinematics. The oxygen cost of transport was significantly lower after the intervention when the runners were fatigued but remained unchanged at pre-fatigue. The reduction in O_2COT was accompanied with reductions in step length ($p = 0.03$), contact time ($p = 0.015$), and forward trunk lean ($p = 0.006$), whereas step frequency increased ($p = 0.004$). It was concluded that eight weeks of endurance results in modifications in running kinematics for self-optimization in recreational running under fatigued conditions.

Keywords: fatigue; running; kinematics; tibia; accelerometer; endurance training

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INTRODUCTION

It has been hypothesized that runners subconsciously alter their running technique after a brief exposure to some level of training to be more efficient (16). It is not certain whether this theory holds for recreational runners, due to the paucity of knowledge and the contradictory findings in English literature (1,10,16). Different training interventions, duration of training programs, characteristics of the participants used i.e. novice, recreational, or elite, and biomechanical parameters considered (10,16, 19), are some of the reasons for the differences in findings.

In a recent review on running economy and running kinematics, the author submitted that experienced runners are able to alter their biomechanical parameters (i.e. kinematics) in accordance with their physiological state for efficiency (18). It is well documented that novice and recreational runners lose control of their musculoskeletal system, alter their running biomechanics, and become less efficient under fatigued conditions (9,15,26). In line with the self-optimization hypothesis, one would think that exposing recreational runners to training would lead to modifications that would make them more efficient under both fatigued and unfatigued conditions. However, the contradictions in the self-optimization theory, coupled with the fact that no study has ascertained the influence of training on running kinematics under fatigued conditions among recreational and novice runners, make such thoughts only speculative. There are questions on which kinematic and spatiotemporal parameters are optimized (if any) in response to training. It is further unclear whether endurance training leads to any modifications in running form and running impact relevant for better efficiency, and injury reduction. The current study therefore investigated the “self-optimization hypothesis” on spatio-temporal, running kinematics, and impact variables under fatigued and unfatigued conditions. We hypothesized that, the endurance training program would alter the spatiotemporal and upper extremity kinematics of runners, and running impact variables (i.e. impact magnitudes, and body load), and that such changes would be accompanied with a reduction in O_2COT.

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METHODS

Experimental approach to problem

Participants were subjected to a running induced fatigue protocol before and after eight weeks of training geared towards improving endurance and fitness. During the training period, the participants were requested not to participate in any other sessions of training or competitions. Upper-extremity kinematics, spatio-temporal parameters, running impact variables, and O_2COT were assessed before and after the fatigue run to ascertain whether alterations in running form due to endurance training would make the runners more efficient (i.e. a reduction in O_2COT).

Subjects

Twenty recreational runners (age 21.75 SD 1.4 years, height 1.72 SD 0.07 meters, mass 68. 09 SD 10.98 kg) were recruited to participate in the study. The subjects were informed of the risks and benefits of the study prior to data collection. After an approved informed consent document and a health history questionnaire were completed, subjects' anthropometric measurements were taken by the primary investigator for descriptive purposes. The Research Ethics Committee Humanities at Stellenbosch University approved the study (# SU-HSD-002032). All subjects wore their own running shoes, were fully rested, and had not run at least 24 hours before data collection. The subjects were instructed to abstain from food and caffeine for at least one and a half hours prior to testing. The tests were performed in the morning, at the same time of the day, under controlled laboratory conditions (temperature = 20–24 °C and relative humidity = 50–60 % at 130 m of altitude). Men wore only running shorts whereas women wore crop tops to enable direct placement of reflective markers on bony landmarks of interest. Runners were included if they were running regularly (2 – 4 sessions per week; 15 – 30 km per week) and had experience in treadmill running. The participants were screened to have no known history of metabolic, neurological, or cardiovascular disease, or surgery to the back or lower limbs, and were symptom-free of any lower extremity injuries for at least six months before the start of the study.

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Procedures

The subjects were subjected to an incremental speed to exhaustion running test on a motorized treadmill (Satun h/p/cosmos, Nussdorf-Traunstein, Germany) to induce fatigue. The participants started running at a speed of 8 km.h^{-1} or 9 km.h^{-1} depending on individual comfort and previous experience. After a warm-up session of four minutes at the starting speed, the participants ran in increments of 1.5 km.hr^{-1} every four minutes interspersed with a one-minute break for rating of perceived exertion (RPE 6 – 20 Borg's scale) and blood lactate (obtained with a portable lactate analyzer; Lactate Pro 2 LT-1730, Japan) sampling. The test continued until an RPE $\geq$ 19, a maximum heart rate of at least 95%, and a decline in $PETCO_2$ was reached, and or volitional exhaustion (9,17,26). Immediately thereafter, subjects completed another stage of four minutes at their starting speed for post-fatigue analysis. The treadmill gradient was held at 1% throughout the test (14). The participants were fitted with an adjustable safety harness during the treadmill running test. The metabolic fatigue protocol was administered before after the intervention with the runners wearing the same running shoes, clothing, at the same time of the day, and under the same conditions as far as possible.

During the intervention, the subjects were taken through eight weeks of endurance training with the aim of improving their aerobic fitness and endurance. To achieve these objectives, the runners were asked to complete four training sessions per week over the eight weeks. The duration of eight weeks was chosen based on previous literature (16,19,11). The training program was classified into two sessions, supervised and unsupervised. Two sessions per week were supervised by the primary investigator and two were performed in the participants' own time as '"homework"'. The training program is detailed in Table 1.

Table 1 should be place here

For week-to-week repeatability, each supervised session started and ended with at least one 400 m lap on the athletics track (Coetzenburg stadium, Stellenbosch), with the rest of the session performed on concrete road. Subjects ran in groups of two to four persons who were matched as best as possible according to their pre-test performance. During each session (supervised and homework), running parameters were monitored using a mobile application Strava to acquire training data regarding pace, distance, and time as a ‘log book’.

Breath-by-breath pulmonary gaseous exchange was recorded throughout the run with a metabolic analyzer (Cosmed Quark CPET, Rome, Italy). The gas analysers were calibrated as 16% O_2, 4% CO_2 balance N_2. The turbine flow meter was calibrated with a 3L calibration syringe before each test. O_2COT was determined as previously described (21,24) from the VO_2 (mlO2·kg^{-1} ·min^{-1}) values collected during the last 30 s of the pre-post run.

An OptoGait photoelectric system (OptoGait, Microgate S.r.I, Italy, 2010) was used to record spatio-temporal kinematic parameters of the runners at the last minute of each stage for offline analysis. The transmitting and receiving bars were placed on the edges of the motorized treadmill in such a way that the treadmill belt did not obstruct the infrared diodes of the system.

Two cameras (Go Pro Hero 4 Black, USA) were positioned, one in front to assess arm carriage and the other by the side to measure forward trunk lean from the hip. The cameras were set to sample at 240frames/s. This sampling rate was chosen for better quality images and assessment (22). Data were recorded at the last minute of every stage and analyzed using an open source video analysis software (Kinovea 0.8.15). Forward trunk lean was defined as the angle between the upper body (referenced at the superior iliac spinous processes) and the vertical as shown by previous authors (22). Reflective markers were placed on the posterior superior iliac spines, anterior superior iliac spine, and the greater trochanter for identification of reference points. The average forward trunk lean of 10 consecutive strides (five left; five right) at mid-stance from the side camera was used for analysis. The average of the 10 recordings was used to obtain the forward trunk lean. Arm carriage for both arms was determined based on a criterion (1 = arms parallel to line of symmetry; 2 = arms towards the line of symmetry; 3 = arms across line of symmetry) previously used (23).

Triaxial accelerometers (±16 g range, sampling at 1024 Hz, 16-bit resolution, 23.6 g weight, Dublin, Ireland) were securely positioned using a self-adhesive tape over the L3 spinous process of the trunk, left and right distal end of the tibia, and upper back (between C7-T2 spinal processes) to collect

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accelerometer data throughout the run. Tri-axial accelerometer data signals were processed using a customized software program, MATLAB version 2018a (The Mathworks Inc. Natick, MA, USA). The accelerations were trigonometrically tilt-corrected prior to extracting outcome measures. The acceleration signals were low-pass filtered with a cut-off frequency of 50 Hz to remove artifact noise. The measurements were computed from the final 20 consecutive steps of acceleration signals at the pre-fatigue and post-fatigue rans. Body load was determined from accelerometer data from the lower back, and determined as previously described (3,5). The reliability of a single accelerometer at the lower back (L3 spinous process) for the estimation of body load (3) with respect to activities involving forward running has previously been determined. Calculations of body load were done from both high- and down-sampled sampling rate conditions, 1024Hz and 100Hz respectively. The frequency of 100Hz was chosen to replicate that used traditionally in previous studies (2,3,5,7).

Statistical analysis

All data were checked for normality (Kolmogorov-Smirnov). Analysis of variances (ANOVAs) and paired sample test were performed on the data to test the hypothesis of the study.

RESULTS

Four runners could not complete the intervention due to injuries and other reasons. Their data were hence not included in the pre-post intervention analysis. The ANOVA results of the remaining 16 participants at pre-post intervention are illustrated in Table 2.

Table 2 should be placed here

There were significant reductions in step length ($p = 0.03$), contact time ($p = 0.015$), and forward trunk lean ($p = 0.006$) after the endurance training at post fatigue with a significant increase in step frequency ($p = 0.004$). Flight time, stride angle, and arm carriage did not change after the training ($p > 0.05$) under fatigued conditions. There were also no differences in running impact magnitude at the tibia, and body load at pre-post fatigue before and after the intervention ($p > 0.05$). However, O_2COT was significantly lower ($p = 0.029$) after the intervention in the fatigued condition. Independent of fatigue, forward trunk lean significantly reduced ($p = 0.01$) after the intervention.

DISCUSSIONS

The hypothesis of the study was that an eight-week endurance training program would lead to modifications in running kinematic and spatiotemporal parameters and that such changes would be accompanied by a reduction in O_2COT under fatigued conditions. In accordance with our hypothesis, runners modified their contact time, step frequency, step length, and forward trunk lean after the intervention at post-fatigue. The changes were accompanied by a significant reduction in the O_2COT.

The current study showed that recreational runners sub-consciously fine tune the length and the rate of their step to be more efficient after an endurance training program when fatigued. Manipulation of step length and rate has been used in previous studies for improvement of economy and efficiency. Reducing step/stride length by about 3% has been proposed as efficient for trained runners (8,20). In the current study, the runners reduced their step length for about 3.9% after the intervention when they were fatigued. However, studies (6,20) that consciously allowed the participants to reduce their step/stride length by such percentages did not report improvements in the economy of their runners. It is unclear why such discrepancy exist. Nevertheless, it that appears alterations at the subconscious level i.e. “” self-optimization”” and individualization rather than whole-sale prescription of “correct” running technique (i.e. step length vs rate) is the way forward in the quest for better performance, and efficiency. The trained runner is able to optimize his/her running style under unfavorable conditions such as fatigue. The results of this study support claims that trained runners could subconsciously fine-tune their running kinematics in response to their physiological state (18).

Smaller contact times has previously been linked to better economy. Spending lesser time during ground contact accompanied a reduction in the O_2COT in previous studies (21), which the current study supported in the fatigued state. A reduction in contact time has been alluded to result in reductions in tibia accelerations (12). However, the reduction in contact times experienced by the runners in the fatigued state did not accompany smaller impact acceleration magnitudes. Reductions in impact of magnitude and rate has been reported as possible injury reduction strategies (13). We therefore suggest that in the fatigued state, the reduced contact times exhibited by our runners after the training intervention was towards better economy (reduction in O_2COT), but not strong enough for reductions in running-related injuries as shown by the no significant reduction in running impact variables. It is possible that the duration of the training program was not long enough to elicit substantial alterations in running impact variables.

Sixteen weeks of training previously (1) resulted in reductions in vertical ground reaction forces (which is closely associated with running impact magnitude from accelerometers). The training program of these authors was aimed towards investigating the long-term effects of training on running technique, whiles the current study looked at the acute effects. The training program of the previous authors also differed in many aspects from the current study. In the previous study, the participants underwent 16-weeks of barefoot training whereas in our study, the endurance training was administered shod. The choice of our running program was to assess whether endurance training would make runners subconsciously alter their kinematics without necessarily suggesting to them through some specific training on their technique, hence it was not expedient to make them run barefoot. The sub-maximal speed (8km.hr^{-1} or 9km.hr^{-1}) used for pre-post fatigue analysis in our study was similar to the speed used for analysis by the previous authors. However, Azevedo and colleagues made their participants ran for 10 minutes for the analysis whereas ours ran for four minutes. It is not certain, whether changes in running impact variables would have been seen at a much longer duration. Nevertheless, as our data were collected under fatigued conditions, it was not possible to make the participants ran much longer after the fatigue protocol. Future studies could consider the “self-optimization” hypothesis on running impact at different speeds and durations, and in different training programs.

The training intervention also resulted in a forward trunk lean favourable for the reduction of injuries. Forward trunk lean of between 3° and 7° has been reported as capable of reducing the stress across the patello-femoral joint during running (25). Before the training, runners increased their trunk lean beyond the recommended angle when fatigued. The findings support claims that untrained runners tend to overexaggerate their trunk flexion when fatigued (15). However, the training led to the runners maintaining the angle within the range appropriate for possible injury reductions on the patello-femoral joint.

The self-optimization hypothesis did not hold when the runners were not fatigued. This was in agreement with some previous studies (16,24), but was at odds with others (19). Tam and colleagues (24) found no changes in the O_2COT after eight weeks of barefoot training when they tested the runners shod. Although we cannot make direct comparisons between the current study and the previous one due to differences in the training program, the current findings nevertheless add to the body of knowledge that eight weeks of endurance training does not affect the O_2COT at pre-fatigue. However, the significance of acute training for optimization still holds as there were modifications in running kinematic parameters with a significant reduction in the O_2COT under fatigued conditions. In another study amongst female beginner runners, the researchers found improvements in running economy after 10 weeks of training, whereas we found the improvements only after our participants were fatigued. The two studies agree on optimization after exposure to training, the only difference being the period of improvement (i.e. pre-fatigue or post-fatigue). The previous authors used female participants who had had no running experience prior to testing whereas our participants were active recreational runners. As a similar training program was used by the previous authors, we suggest that training to improve endurance and fitness is key for improvements in running economy for both recreational and novice runners. However, in recreational runners, the gains are more apparent under fatigued conditions.

CONCLUSIONS

The findings of this study demonstrate that training at certain anaerobic thresholds to improve endurance leads to modifications in running kinematic and spatiotemporal parameters of recreational runners in fatigued running which are beneficial for reductions in O_2COT. Runners self-optimize their running kinematics in response to a brief exposure to endurance training to be more economical in response to fatigue.

PRACTICAL IMPLICATIONS

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- Eight-weeks of endurance training effects modifications in running technique, beneficial for reductions in O_2COT during fatigued running
- Improvement in endurance and fitness in distance running should take precedence over running technique modification
- Endurance training at 70% to 80% of peak treadmill speeds could be beneficial for efficiency in distance running
- Reducing step length and increasing step rate are beneficial for reducing O_2COT in fatigued running

REFERENCES

1. Azevedo APDS, Mezêncio B, Amadio AC, Serrão JC. 16 weeks of progressive barefoot running training changes impact force and muscle activation in habitual shod runners. PLoS ONE; 11(12): e0167234, 2016. doi:10.1371/ journalpone.0167234 PMID: 27907069
2. Bailey JA, Gastin PB, Mackey L, Dwyer DB. The player load associated with typical activities in elite netball. Int J Sports Physiol Perform 12 (9):1218-1223, 2017. doi: 10.1123/ijspp.2016-0378
3. Barreira P, Robinson MA, Drust B, et al. Mechanical Player Load™ using trunk-mounted accelerometry in football: Is it a reliable, task- and player-specific observation? J Sport Sci 35(17):1674–1681, 2017
4. Bertelsen ML, Hulme A, Petersen J, Brund RK, Sørensen H, Finch CF, et al. A framework for the etiology of running- related injuries. Scand J Med Sci Sports 27:1170–1180, 2017. DOI: 10.1111/sms.12883
5. Boyd LJ, Ball K, Aughey RJ. The reliability of MinimaxX accelerometers for measuring physical activity in Australian football. Int J Sports Physiol Perform 6(3):311-21, 2011.

6. Connick MJ, Li FX. Changes in timing of muscle contractions and running economy with altered stride pattern during running. Gait Posture 39(1):634-637, 2014. doi: 10.1016/j.gaitpost.2013.07.112
7. Dalen T, Jørgen I, Gertjan E, Hjelde GH, Wisløff U. Player load, acceleration, and deceleration during forty-five competitive matches of elite soccer. J Strength Cond Res 30(2): 351–359, 2016.
8. de Ruiter CJ, Verdijk PW, Werker W, Zuidema MJ, de Haan A. Stride frequency in relation to oxygen consumption in experienced and novice runners. Eur J Sport Sci 14(3):251-258, 2014. doi: 10.1080/17461391.2013.783627
9. Dierks TA, Davis IS, Hamil J. The effects of running in an exerted state on lower extremity kinematics and joint timing. J Biomech 43(15): 2993 – 2998, 2010.
10. González-Mohíno F, González-Ravé JM, et al. Effects of continuous and interval training on running economy, Maximal aerobic speed and gait kinematics in recreational runners. J Strength Cond Res. 30(4):1059-66, 2016. doi: 10.1519/JSC.0000000000001174
11. Gomez-Molina J, Ogueta-Alday A, Camara J, Stickley C, Garcia-Lopez J. Effect of 8 weeks of concurrent plyometric and running training on spatiotemporal and physiological variables of novice runners. Eur J Sport Sci 18(2): 162 – 169, 2018.
12. Grubera AH, Boyera KA, Derrick TR, Hamill J. Impact shock frequency components and attenuation in rearfoot and forefoot running. J Sport Health Sci 3(2): 113-121, 2014. https://doi.org/10.1016/j.jshs.2014.03.004
13. Hreljac, R.N. Marshall, P.A. Hume. Evaluation of lower extremity overuse injury potential in runners. Med Sci Sports Exerc 32: 1635-1641, 2000.
14. Jones AM, Doust JH. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. J Sport Sci 14(4): 321–327, 1996.
15. Koblbauer IF, van Schooten KS, Verhagen EA, van Dieën JH. Kinematic changes during running-induced fatigue and relations with core endurance in novice runners. J Sci Med Sport 17(4): 419–424, 2014.

16. Lake MJ, Cavanagh PR. Six weeks of training does not change running mechanics or improve running economy. Med Sci Sports Exerc 28(7): 860 – 869, 1996.

17. Mercer JA, Vance J, Hreljac A, Hamill J. Relationship between shock attenuation and stride length during running at different velocities. Eur J Appl Physiol 87(4–5): 403–408, 2003.

18. Moore IS. Is There an Economical Running Technique? A review of modifiable biomechanical factors affecting running economy. Sports Med 46:793–807, 2016. doi 10.1007/s40279-016-0474-4

19. Moore IS, Jones AM, Dixon SJ. Mechanisms for improved running economy in beginner runners. Med Sci Sports Exerc 44(9):1756-63, 2012. doi: 10.1249/MSS.0b013e318255a727

20. Moore IS, Jones AM, Dixon SJ. The pursuit of improved running performance: can changes in cushioning and somatosensory feedback influence running economy and injury risk? Footwear Sci 6:1–11, 2014.

21. Santos-Concejero J, Tam N, Granados C, et al. Interaction effects of stride angle and strike pattern on running economy. Int J Sports Med 35(13): 1118 – 1123, 2014.

22. Souza RB. An evidence-based videotaped running biomechanics analysis. Phys Med Rehabil Clin. 27(1): 217–236, 2016.

23. Strohrmann C, Harms H, Kappeler-setz, C. Running using body-worn sensors. IEEE Trans Info Technol Biomed 16 (5): 983 – 990, 2012.

24. Tam N, Tucker R, Wilson JLA, Santos-Concejero J. Effect on oxygen cost of transport from 8-weeks of progressive training with barefoot running. Int J Sports Med 36(13): 1100-1105, 2015. DOI: 10.1055/s-0035-1548888

25. Teng HL, Powers CM. Influence of trunk posture on lower extremity energetics during running. Med Sci Sports Exerc 47(3): 625–630, 2015.

26. Verbitsky O, Mizrahi J, Voloshin A, Treiger J, Isakov E. Shock transmission and fatigue in human running. J Appl Biomech 14 (3): 300-311, 1998.

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TABLES

Table 1. Training program

Sessions (Days)	Session Type	Session goal	training
Session 1 Monday/ Tuesday	Supervised	Basic endurance: aims to improve oxidation and utilization of fats as an energy source while sparing muscle glycogen stores.	60 minutes easy run @ 60-70 % PTS
Session 2 Wednesday/Thursday	Supervised	Lactate threshold training: to adapt (raise) the runners anaerobic threshold	2 x 20 minutes @ LT (~85 % PTS). With 5 minutes of easy run @ 60 % PTS in between.
Session 3	Homework	Aerobic endurance tempo training: designed to build aerobic capacity and speed endurance with moderate volume	45 minutes easy run @70-80% PTS
Session 4	Homework	Same as session 3	60 minutes easy run @ 70-80% PTS
Total	**4 training sessions per week (1 training session at LT)**		

LT: Lactate threshold, PTS: Pre-test maximal speed

Table 2. ANOVA results showing parameters at pre-post-fatigue, before and after the training intervention

	Pre-fatigue				**Post-fatigue**			
Parameter	**Pre-Int**	**Post- Int**	***p* value**	**Effect size**	**Pre-Int**	**Post-Int**	***p* value**	**Cohen's d**
Contact time	0.37±0.02	0.35±0.09	0.170	0.306	0.38±0.03	0.35±0.02	0.015*	0.631
Step length (cm)	89.23±5.58	88.53±6.00	0.618	0.121	89.22±6.46	85.72±5.28	0.051*	0.593
Step frequency	79.97±4.64	80.84±3.85	0.471	0.204	80.18±4.08	82.56±2.69	0.004**	0.688
Tibia impact (g)	6.14±2.13	6.15±3.71	0.579	0.003	6.59±2.11	7.43±4.59	0.118	0.207
Body load (au)	46421.54±9529.26	45037.05±13508.14	0.572	0.118	44571.47±10294.02	54300.96±19584.32	0.131	0.621
O_2COT ($ml.kg^{-1}.km^{-1}$)	234.13±20.10	231.51±20.64	0.224	0.103	240.81±19.62	229.23±18.69	0.029*	0.685
$PETCO_2$	38.94±3.56	39.39±3.91	0.379	0.120	30.01±2.39	29.46±2.91	0.291	0.206

Trunk lean (°)	7.43±2.08	6.52±2.55	0.072	0.391	8.76±2.55	6.97±2.49	0.006**	0.710

/*/**/Statistically significant difference, p value < 0.05, p value < 0.01 at 95% confidence interval respectively. /INT/Intervention.

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CHAPTER 7

DISCUSSION

A. INTRODUCTION

The primary aim of this study was to determine the influence of metabolic fatigue on running kinematics, running impact, and body load among recreational runners using wearable technology applicable to outdoor settings. The second aim of the study was to assess the effects of a customised endurance training intervention on running kinematics, impact, body load and external distribution of impact under fatigued conditions in recreational running.

The hypothesis that running induced fatigue would result in an increase in the magnitude of impact at the tibia, and lower back, step length, and arm carriage, and a reduction in stride angle was rejected. Nevertheless, forward trunk lean, contact time, and body load, increased in accordance with the hypothesis of the study. The researcher further hypothesised that the runners would fine-tune their kinematics to be more efficient under fatigued conditions after eight weeks of endurance training. This was supported by the results of the current study. For a global perspective of the whole study, the key points from the articles are summarised in this section. The findings with respect to Objective 1 are analysed and discussed in Article 1 of this dissertation. Objectives 2 and 6 are discussed in Article 3, whereas Objectives 4, 5 and 7 are covered in Article 3. The results with respect to Objective 3 as shown in Appendix I were not included in any of the articles. Objective 3 is hence discussed separately in this chapter. A discussion of the comparisons between the control and the intervention groups concludes the chapter.

Objective 3: To assess the effects of gender on running kinematics and impact variables under fatigued conditions.

It was hypothesised that running kinematic parameters and impact variables of female recreational runners would differ from that of their male counterparts due to the reported differences in injury profiles. The findings of this study showed that the female runners had shorter steps, higher step frequency, smaller contact time, and higher vertical tibia impact compared to their male counterparts at the submaximal speed. Nevertheless, no fatigue by gender interactions were found in contrast with our hypothesis. Previous authors (Sean et al., 2016; Sinclair & Taylor, 2014; Sinclair, 2012) have also reported significant differences in running kinematics with respect to gender. The kinematic parameters of interest between the previous studies and the current study were different. The previous authors investigated running mechanics, joint kinematics, and tibia-calcaneal kinematics using VICONS and force platforms. The current study was the first to extensively look at spatio-temporal, upper extremity, and running impact variables using cost effective, and wearable technology. The finding of the current study adds to the body of knowledge on the kinematics that are influenced by gender.

According to my knowledge, only one study in the English literature (Wilson et al., 2015) have previously reported on differences due to gender on running kinematics under fatigued conditions. In agreement with the current study, the previous authors report no gender interactions with step length after an exhaustive run but in contrast found longer steps for all participants irrespective of gender after the exhaustive ran. The contradictions in the findings could be as a result of the differences in the fatigue protocol and the determination of fatigue. In the Wilson et al. (2015) study, the participants were made to run at a constant speed of 12.5kmhr^{-1} until an RPE of $\geq$ 18. Mercer et al. (2003) suggested it was possible for participants to prematurely end a running fatigue test, hence the need for more indicators in the measurement of fatigue. In the current study, $PETCO_2$ in addition to RPE were considered to overcome the Mercer et al. (2003) limitation. Although smaller contact time, shorter step length and higher step frequency often leads to smaller running impact magnitudes, that was not realised in this study with regards to the women. The vertical impact magnitude at the tibia was higher in the women compared to the men. Higher load and impact magnitudes have been cited as links to running related injuries (Berterlsen et al. 2017). The results of the current study provide some understanding of the underlying principles behind the different injury profiles of men and women. For instance, patellofemoral pain syndrome has been found to be more prevalent in women than men. Some authors have reported knee miss-alignment and cartilage malfunction due to stress as causative factors (Witvrouw et al., 2014). There is evidence to support that vertical tibia impact is absorbed and attenuated by structures such as cartilages and tendons as it travels through the body in order to maintain a consisted brain function (Hamill et al., 1995; Mercer et al., 2003). Higher impacts would therefore require the cartilages and tendons to absorb higher impacts and stress in order to shield the brain. This could potentially be an underlying factor for the reported cartilage malfunction that accompanied patellofemoral pain in women.

A further analysis of the results revealed that almost all the women ran at $8kmhr^{-1}$ (except one) whereas the men ran at $9kmhr^{-1}$ for the pre-post fatigue analyses. One could argue that the differences in the spatio-temporal running kinematic parameters were as a result of the different running speeds. However, the fact that the vertical impact magnitudes were higher in the females despite the gains in the spatio-temporal kinematics is a concern. It is possible the impact magnitude would have been much higher if the women were able to run at the same submaximal speed as the men. Future study at similar speeds could shed more light on whether women would have higher impacts and loads than men.

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Article 1

It had been shown previously that runners alter their kinematics, and increase the O_2COT when they are fatigued. Whether the changes in the kinematics contributed to the increase in O_2COT was unclear.

This article addressed two issues: the influence of running-induced fatigue on spatio-temporal and upper extremity kinematics, and how changes in the running kinematics due to fatigue affects O_2COT. The results of the article showed that running-induced fatigue increased forward trunk lean, contact time, and the cost of oxygen transport. However, the changes in the kinematics (i.e. forward trunk lean, and contact time), did not contribute to an increase in the O_2COT under fatigued conditions. Refer to Chapter 4 for the full discussion.

Article 2

Article 2 assessed the use of accelerometry parameters for the estimation of running induced fatigue. In accordance with previous studies, impact magnitude was not sensitive to fatigue. It was nevertheless demonstrated that body load could be used for monitoring fatigue. Refer to Chapter 5 for the full discussion.

Article 3

Self-optimisation has been proposed by previous authors as a means for efficiency in running. The study demonstrated that training at certain ATs to improve endurance and fitness leads to modifications in running kinematic and spatiotemporal parameters of recreational runners in fatigued running which is beneficial for reductions in O_2COT. In contrast to previous authors, the optimisation i.e. the reduction in oxygen cost was only seen under fatigued conditions. Refer to Chapter 6 for the full discussion.

B. CONTROL AND INTERVENTION GROUP COMPARISON

It was hypothesised that the eight weeks of a customised endurance training intervention would lead to automatic modifications in running kinematics and impact relevant for gains in running economy i.e. "self-optimisation". In agreement with Lake and Cavanagh (1996), this hypothesis did not hold when we compared the two groups i.e. control group versus intervention group (table 10), but contradicted that of González-Mohíno et al. (2016).

However, when a within group analysis was made, it was found that the eight-week endurance training resulted in modifications in running kinematics at post fatigue which were accompanied with a significant reduction in the O_2COT (refer to article 3). There is paucity of knowledge to compare this finding. Nevertheless, it affirms an earlier observation, that trained runners could subconsciously fine-tune their running kinematics in response to their physiological state (Moore, 2016). Deducing from the fact that studies have found trained runners to be more resistant to changes in kinematics due to fatigue compared to untrained runners (Strohrmann et al., 2012), the findings of the current study alludes that exposing recreational runners to a structured endurance training programme could lead to self-optimisation under fatigued conditions. The results of this study bridges a gap that was apparent in the available literature i.e. is self-optimisation applicable under fatigued conditions, and adds to the body of knowledge on whether an endurance training programme is relevant for self-optimisation.

In one of the earlier reports (Lake & Cavanagh, 1996), the researchers found no changes in running kinematics after six weeks of training. The current study differs in methodology with the previous authors. In the current study, participants were subjected to eight weeks of training whilst six weeks was deployed in the earlier study. The current study also examined the runners

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at both pre- and post-fatigue conditions. In the pre-fatigue condition, the results were in agreement with that of Lake and Cavanagh (1996) hence the differences in the duration of the training programme was irrelevant. The previous authors did not examine their participants under fatigued conditions hence a comparative analysis could not be made with respect to self-optimisation under such conditions.

González-Mohíno et al. (2016) on the other hand exposed their participants to eight weeks of training. The authors found differences in running kinematics after the training intervention whereas in the current study, the changes were found only after fatigue. The sample sizes of the groups (control = five, intervention = six) were also small and may not be good enough for generalisable conclusions compared to the current study. The current study according to our knowledge is the most extensive on self-optimisation under both pre-post fatigue conditions.

Recreational runners lose control of their musculoskeletal system under fatigued conditions resulting in changes in running form (Mizrahi et al. 2000; Verbesky et al., 1998). A brief exposure of the recreational runners to endurance training to improve fitness makes them more resilient to fatigue and are able to subconsciously alter their running kinematics to be economical in response to their physiological state.

Again, in comparison with the control group, the peak treadmill speed of the intervention group was significantly higher (table 9) whereas the RER remained similar. This implies that at the end of the eight weeks, the training programme was able to result in a remarkable increase in the fitness levels of the participants. It has been argued that training could lead to changes in RER and hence substrate utilisation (Lindlein et al., 2018; Fletcher et al., 2010) which may influence the use of oxygen cost of transport as a marker for running economy. In the current study, the RER values did not differ much between the control group and the intervention group although there was a significant difference in the peak treadmill (Vpeak) speed between the two groups. However, the effect size change in Vpeak after the intervention was medium (*Cohen's d* = 0.51). It is suggested that the change was not strong enough to elicit a significant alteration in substrate utilisation. Data was also captured at similar speeds for the pre-post fatigue analysis for both groups (Control and Intervention). RER has been found to be more sensitive to varying speeds (Fletcher et al., 2010).

CONCLUSION

Running-induced fatigue resulted in increases in contact time, forward trunk lean, and body load. Running impact magnitude at the tibia and the lower back, arm carriage, step length and flight times on the other hand remained unchanged. The kinematic parameters that changed with respect to fatigue have been linked to running related injuries, and economy.

The use of running impact variables i.e. impact magnitude, attenuation, and rate as indicators of fatigue in running has been a subject of debate. The current study confirms the uncertainty of the direction of change of running impact variables. The study however, presents body load as an alternative accelerometry parameter for outdoor monitoring of fatigue in distance running. Another strength of the use of body load is that it can be extracted ecologically without interfering with the running pattern of runners. The current study again shed light on some of the possible underlying biomechanical principles behind the different injury profiles of male and female runners. Coaches, women runners, and other industry players should take into account the higher vertical impact to which women runners are predisposed to at the tibia in the choice of interventions (shoe cushioning, training etc) for injury reduction.

Eight weeks of endurance training resulted in modifications in the running kinematic parameters of the recreational runners, which was also accompanied with a reduction in the O_2COT at the fatigued state. The study showed that training at certain ATs with the aim of

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improving fitness and endurance could make recreational runners more efficient when they are fatigued. The study was novel in showing the viability of the “self-optimisation” hypothesis under fatigued conditions.

Coaches and recreational runners could adopt the training programme used in this study to improve fitness and optimise their running form in response to running-induced fatigue.

LIMITATIONS

The current study was limited to recreational runners in the Stellenbosch Boland community for convenience. The use of 2D video analysis for the determination of upper extremity kinematics could be subjective. The 2-D video analysis were not validated against the gold standard (3D) due to financial and logistical constraints. Running shoes were not standardised in the determination of external distribution of impact. Although all the participants met the inclusion criteria, it appears that the men were more experienced than the women, who hence could not run at the same starting speed.

SUGGESTED FUTURE RESEARCH

Different fatigue protocols have been used for inducing fatigue. It would be beneficial to investigate the different fatigue protocols to establish a standardised running protocol for inducing fatigue.

The effects of the different categories of arm carriage on running impact variables, and running energetics are still uncertain. It would be beneficial to understand what constitutes an active swing and its implications on running efficiency.

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Self-optimisation and gait retraining have been hypothesised as ways of improving efficiency and economy. It would be expedient to concurrently validate the two hypothesises among different levels of runners to provide a holistic view of interventions for better performance and injury reduction.

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REFERENCES

The general referencing of this dissertation follows the **Harvard referencing style**.

Abt, J.P., Sell, T.C., Chu, Y., Lovalekar, M., Burdett, R.G., Lephart, S.M. 2011. Running kinematics and shock absorption do not change after brief exhaustive running. *Journal of Strength Conditioning Research*. 25(X): 001– 007.

Anderson, T., 1996. Biomechanics and running economy. *Sports Medicine*. 22:76–89.

Arrelano, C., & Kram, R. 2011. The effects of step width and arm swing on energetic cost and lateral balance during running. *Journal of Biomechanics*. 48(7): 1291 – 1295.

Arellano, Christopher J. & Kram, Ro. dger, 2014. The metabolic cost of human running: is swinging the arms worth it? *Journal of Experimental Biology*, 217(14): 0115637.

Azevedo, A.P.S., Mezêncio, B., Amadio, A.C., & Serrão, J.C. 2016. 16 weeks of progressive barefoot running training changes impact force and muscle activation in habitual shod runners. PLoS ONE. 11(12): e0167234. doi: 10.1371/journal.pone.0167234 PMID: 27907069

Bailey, J.A., Gastin, P.B., Mackey, L., et al. 2017. The player load associated with typical activities in elite netball. *International Journal Sports Physiology and Performance*. DOI: https://doi.org/10.1123/ijspp.2016-037810.1123/ijspp.2016-0378

Baker, R. 2009. Gait analysis methods in rehabilitation. *Journal of Neuro Engineering and Rehabilitation*, 3(4):1–10.

Bertelsen, M.L., Hulme, A., Petersen, J., et al. 2017. A framework for the ethology of running-related injuries. *Scandinavian Journal of Medicine and Science in Sports*, 27:1170–1180. DOI: 10.1111/sms.12883

Boyd, L.J., Ball, K. & Aughey, R.J. 2011. The reliability of MinimaxX accelerometers for measuring physical activity in Australian football. *International Journal of Sports Physiology and Performance*, 6(3):311–321.

Buist, I., Bredeweg, S.W., Lemmink, K.A., vVan Mechelen, W. &, Diercks, R.L. 2010. Predictors of running-related injuries in novice runners enrolled in a systematic program: A prospective cohort study. *American Journal of Sport Medicine*. 38(2): 273 – 280.

Chen, Y., Fredericson, M., Matheson, G. & Phillips, E. 2013. Exercise is medicine. *Current Physical Medicine and Rehabilitation Reports*, 1(1):48–56.

Christina, White & Gilchrist, 2001. Effect of localized muscle fatigue on vertical ground reaction forces and ankle joint motion during running. *Human Movement Science*. 20(3): 257–276.

Cifrek, M., Medved, V., Tonković, S., & Ostojić, S. 2009. Surface EMG based muscle fatigue evaluation in biomechanics. *Clinical Biomechanics*, 24(4): 327–340.

Connick, M.J. & Li, F.X. 2014. Changes in timing of muscle contractions and running economy with altered stride pattern during running. *Journal of Gait Posture*, 39:634–637.

Dalen, T., Jørgen, I., Gertjan, E., Hjelde, G.H., Wisløff, U., 2016. Player load, acceleration, and deceleration during forty-five competitive matches of elite soccer. *Journal of Strength and Conditioning Research*. 30(2): 351–359.

Dallam, G.M., Wilber, R.L., Jadelis, K., Fletcher, G., & Romanov, N. 2005. Effect of a global alteration of running technique on kinematics and economy. *Journal of Sports Sciences*. 23(7): 757–764.

Derrick, T.R. 2004. The effects of knee contact angle on impact forces and accelerations. *Medicine and Science in Sports and Exercise*. 36(5):832-–837. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/15126718 [Accessed 10 November, 2017].

Derrick, T.R., Dereu, D., & Mclean, S.P. 2002. Impacts and kinematic adjustments during an exhaustive run. *Journal of Medicine and Science in Sports and Exercise*. 34(6): 998–1002.

De Ruiter, C.J., Verdijk, P.W., Werker, W., et al. 2013. Stride frequency in relation to oxygen consumption in experienced and novice runners. *European Journal of Sport Science*, 14:251–258.

Dierks, T.A., Davis, I.S., & Hamil, J. 2010. The effects of running in an exerted state on lower extremity kinematics and joint timing. *Journal of Biomechanics.* 43(15): 2993 – 2998.

Di Michele & Merni, 2014. The concurrent effects of strike pattern and ground-contact time on running economy. *Journal of Science and Medicine in Sport.* 17(4): 414–418.

Dutto, D.J., & Smith, G.A. 2002. Changes in spring-mass characteristics during treadmill running to exhaustion. *Medicine & Science in Sports & Exercise*. 34(8): 1324–1331.

Enoka, R.M. & Duchateau, J. 2008. Muscle fatigue: what, why and how it influences muscle function. *Journal of Physiology*. 586(1): 11–23.

Eskofier, B., Hoenig, F., & Kuehner, P. 2008. Classification of perceived running fatigue in digital sports. Pattern Recognition, 2008. ICPR 2008. 19th International Conference on, Pattern Recognition. 1–4.

Farley, T., Claire, & González, O. 1996. Leg stiffness and stride frequency in human running. *Journal of Biomechanics*. 29: 181-–186. doi: 10.1016/0021-9290(95)00029-1.

Farley, C.T. &, McMahon, T.A., 1992. Energetics of walking and running: insights from simulated reduced-gravity experiments. *Journal of Applied Physiology*. 73:2709–2712.

Stellenbosch University https://scholar.sun.ac.za

Fletcher, J.R., Shane P. Esau, S.P., & MacIntosh, B.R., 2010. Changes in tendon stiffness and running economy in highly trained distance runners. *European Journal of Applied Physiology*. 110 (5): 1037–1046.

Flynn, Holmes & Andrews, 2004. The effect of localized leg muscle fatigue on tibial impact acceleration. *Clinical Biomechanics*. 19(7): 726–732.

Fong, D.T., & Chan, Y. 2010. The use of wearable inertial motion sensors in human lower limb biomechanics studies: A systematic review. *Sensors(Basel*). 10(12): 11556–11565.

Gabbett, T.J. 2016. The training-injury prevention paradox: Should athletes be training smarter and harder? *British Journal of Sports Medicine*. 50(5): 273.

Gabbett, T.J., & Jenkins, 2011. Relationship between training load and injury in professional rugby league players. *Journal of Science and Medicine in Sport*. 14(3): 204–209.

García-Pérez, J.A., Pérez-Soriano, P., Belloch, S.L., et al. 2014. Effects of treadmill running and fatigue on impact acceleration in distance running. *Sport Biomechanics*. 13 (3): 259 – 266. https://doi: .org/10.1080/14763141.2014.909527

García-Pérez, J.A., Pérez-Soriano, P., Llana, S., Martínez-Nova, A., & Sánchez-Zuriaga, D. 2013. Effect of over ground vs treadmill running on plantar pressure: Influence of fatigue. *Journal of Gait and Posture*. 38 (4): 929 – 933.

Gomez-Molina, J., Ogueta-Alday, A., Camara, J., Stickley, C., & Garcia-Lopez J. 2017. Effect of 8 weeks of concurrent plyometric and running training on spatiotemporal and physiological variables of novice runners. *Journal of Applied Sport Science*. 162 – 169. https://doiorg.ez.sun.ac.za/10.1080/17461391.2017.1404133doi: 10.1080/17461391.2017.1404133

González-Mohíno, F., González-Ravé, J.M., Juárez, D., et al. 2016. Effects of continuous and interval training on running economy, maximal aerobic speed and gait kinematics in recreational runners. *Journal of Strength and Conditioning Research*. 30(4):1059-–1066. doi: 10.1519/JSC.0000000000001174.

Grubera, A.H., Boyera, K.A., Derrick, T.R., & Hamill, J. 2014. Impact shock frequency components and attenuation in rearfoot and forefoot running. *Journal of Sports and Health Science.* 3(2): 113—121. https://doi.org/10.1016/j.jshs.2014.03.004doi: 10.1016/j.jshs.2014.03.004

Hagginson, B. 2009. Methods of Running Gait Analysis. *Current Sports Medicine Reports*. 8(3): 136-–141.

Hamill, Derrick & Holt, 1995. Shock attenuation and stride frequency during running. *Human Movement Science*. 14(1): 45–60.

Hart, J.M., Kerrigan, D.C., Fritz, J.M., & Ingersoll, C.D. 2009 Jogging kinematics after lumber paraspinal muscle fatigue. *Journal of Athletic Training*. 44 (5): 475-–481.

Hollville, E., Coutirier, A., Guilhem, G., et al. 2005. Minimaxx player load as an index of the center of mass displacement? A validation study. *33rd International Conference on Biomechanics in Sports, Poitiers, Franc*e, 29 June – 23 9 - July 3, 2015.

Howley, E.T., Bassett, D.R., & Welch, H.G. 1995. Criteria for maximal oxygen uptake: rReview and commentary. *Medicine and Science in Sports and Exercise*. 27 (9): 1292 – 1301.

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

Johnston, C.A.M., Taunton, J.E., Lloyd-Smith, D.R. &, McKenzie, D.C. 2003. Preventing running injuries. Practical approach for family doctors. *Canadian Family Physician*. 49:1101-–1109.

Jones, A.M., & Doust, J.H. 1996. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. *Journal of Sport Science*. 14(4): 321–327.

Kadono, H., & Michiyoshi, A.E. 2015. Changes in the running motion with fatigue during middle-distance running. *33rd International Conference on Biomechanics in Sports.*

Karamanidis, K., Arampatzis, A., & Brugemann, G. 2004. Reproducibility of electromyography and ground reaction force during various running techniques. *Journal of Gait and Posture*. 19(2): 115-–123.

Kellis, E., & Liassou, C., 2009. The effect of selective muscle fatigue on sagittal lower limb kinematics and muscle activity during level running. *Journal of Orthopaedics, Sports and Physical Therapy*. 39(3):210-–220.

Killian, M.L. 2007. The effect of downhill running on impact shock and asymmetry. Published master's MA thesis. Montana State University. Retrieved from URL [Accessed 01 September 2017 [online].

Koblbauer, I.F., Van Schooten, K.S., Verhagen, E.A., & Van Dieën, J.H. 2014. Kinematic changes during running-induced fatigue and relations with core endurance in novice runners. *Journal of Science and Medicine Sport*. 17(4): 419–424.

Kyröläinen, H. et al. 2000. Effects of marathon running on running economy and kinematics. *European Journal of Applied Physiology*, 82(4): 297–304.

Lafortune, M.A., Henningt, E., & Vallant, G.A. 1995. Tibial shock measured with bone mounted transducers. *Pergamon. Journal of Biomechanics*. 28(8): 989-–993.

Lake, M.J., & Cavanagh, P.R. 1996. Six weeks of training does not change running mechanics or improve running economy. *Medicine and Science in Sports and Exercise*. 28(7): 860 - –869.

Lazzer, S., Taboga, P., Salvadego, D., Rejc, E., Simunic, B., Narici, M.V., et. al., 2014. Factors affecting metabolic cost of transport during a multi-stage running race. *The Journal of Experimental Biology*. 2(17), 787-–795 doi: 10.1242/jeb.091645

Leinhard, K., Schneider, D., & Maffiuletti, N.A. 2013. Validity of the OptoGait photoelectric system for the assessment of spatiotemporal gait parameters. *Medical Engineering & Physics*. 35(4): 500-–504.

Lindleina, K., Zechc, A., Zochd, A., Braumanna, K.M., & Hollander, K., 2018. Improving running economy by transitioning to minimalist footwear: a randomised controlled trial. *Journal of Science and Medicine in Sports*. 21 (2018): 1298–1303.

Lobo, J., & Dias, J. 2007. Relative pose calibration between visual and inertial sensors. The *International Journal of Robotics Research*. 26(6). https://doi: .org/10.1177%2F0278364907079276

Lorist, M.M., Kernell, D., Meijman, T.F. & Zijdewind, I. 2002. Motor fatigue and cognitive task performance in humans. *Journal of Physiology*, 545(1):313–319.

Lucas-Cuevas, A.G., Baltich, J., Enders, H., Sandro Nigg, S. & Nigg, B. 2015. Ankle muscle strength influence on muscle activation during dynamic and static ankle training modalities. *Journal of Sports Sciences*, 34(9):1–8.

Lucas-Cuevas, A.G., Priego Quesada, J., Giménez, J.V., Aparicio, I., Jimenez-Perez, I. &, Pérez-Soriano, P. 2016. Initiating running barefoot: Effects on muscle activation and impact accelerations in habitually rearfoot shod runners. *European Journal of Sport Science*. 16(8): 1145–1152.

Magnusson, S.P., Langberg, H. &, Kjaer, M. 2010. The pathogenesis of tendinopathy: Balancing the response to loading. *National Reviews Rheumatology*. 6:262-–268.

Mangine, G.T., Hoffman, J.R., Gonzalez, A.M., Townsend, J.R., Wells, A.J., et al. 2015. The effect of training volume and intensity on improvements in muscular strength and size in resistance-trained men. *Physiological Reports*. 3(8): e12472.

Markell-Jones, 2001. International standards for anthropometric assessment. International Society for the Advancement of Kinanthropometry. Retrieved from http://www.ceap.br/material/MAT17032011184632.pdf [10th December 2017].

Maykut, J., & Ford, K. 2015. Concurrent validity and reliability. *The International Journal of Sports Physical Therapy*. 10(2): 136-–146.

McKenna, M., & Riches, P.E. 2007. A comparison of sprinting kinematics on two types of treadmill and over-ground. *Scandinavian Journal of Medicine & Science in Sports*. 17(6): 649–655.

Mercer, J.A., Vance, J., Hreljac, A., & Hamill, J. 2003. Relationship between shock attenuation and stride length during running at different velocities. *European Journal of Applied Physiology*. 87(4/–5): 403–408.

Miller, R.H., Meardon, S.A., Derrick, T.R., & Gillette, J.C. 2008. Continuous relative phase variability during an exhaustive run in runners with a history of iliotibial band syndrome. *Journal of Applied Biomechanics*. 24(3): 262–270.

Mizrahi, J., Verbitsky, O., Isakov, E., & Daily, D. 2000. Effect of fatigue on leg kinematics and impact acceleration in long distance running. *Human Movement Science.* 19 (2000): 139 – 15. PII: S 0 1 6 7 - 9457(00)00013-0

Morin, J.B., Samozino, P., Zameziati, K., & Belli, A. 2007. Effects of altered stride frequency and contact time on leg-spring behavior in human running. *Journal of Biomechanics*. 40 (15): 3341 – 3348.

Moore, I.S. 2016. Is there an economical running technique? A review of modifiable biomechanical factors affecting running economy. Sports Medicine. 46:793–807. doi 10.1007/s40279-016-0474-4.

Moore, I.S., Jones, A.M., & Dixon, S.J. 2014. The pursuit of improved running performance: can changes in cushioning and somatosensory feedback influence running economy and injury risk? *Footwear Science*. 6:1–11.

Moore, I.S., Jones, A.M., & Dixon, S.J. 2012. Mechanisms for improved running economy in beginner runners. *Medicine and Science in Sports and Exercise*. 44(9):1756-–1763. doi: 10.1249/MSS.0b013e318255a727

Moore, I.S., Jones, A.M. & Dixon, S.J. 2014. The pursuit of improved running performance: Can changes in cushioning and somatosensory feedback influence running economy and injury risk? *Footwear Science*, 6:1–11.

Morin, J.B., Samozino, P., Zameziati, K. & Belli, A. 2007. Effects of altered stride frequency and contact time on leg-spring behavior in human running. *Journal of Biomechanics*, 40(15):3341–3348.

Nagel, A., Fernholz, F., Kibele, C., & Rosenbaum, D. 2008. Long distance running increases plantar pressures beneath the metatarsal heads: A barefoot walking investigation of 200 marathon runners. *Journal of Gait and Posture*. 27(1): 152-–155.

Nascimento, E.M.F., Kiss, M.A.D.P.M., Santos, T.M., et al. 2017. Determination of lactate thresholds in maximal running test by heart rate variability data set. *Asian Journal of Sports Medicine.* http://dx.doi.org/10.5812/asjsm.58480doi: 10.5812/asjsm.58480

Nielsen, R.O., Buist, I., Parner, E.T., Nohr, E.A., Sørensen, H., Lind, M., & Rasmussen, S. 2013. Predictors of running-related injuries among 930 novice runners: A 1-year prospective follow-up study. *Orthopaedic Journal of Sports Medicine*. 1(1): 2325967113487316.

Norris, M., Anderson, R. & Kenny, I.C. 2014. Method analysis of accelerometers and gyroscopes in running gait: A systematic review. Proceedings of the Institution of Mechanical Engineers, Part P: *Journal of Sports Engineering and Technology*, 228(1): 3–15.

Nummela, A., Stray-Gundersen, J., & Rusko, H. 1996. Effects of fatigue on stride characteristics during a short-term maximal run. *Journal of Applied Biomechanics*. 12 (2): 151–160.

Old Mutual Two Oceans Marathon. 2017. Retrieved from http://www.twooceansmarathon.org.za [Accessed 25 December 2017].

Peserico, C.S., Zagatto, A.M., & Machado, F.A. 2015. Evaluation of the best-designed graded exercise test to assess peak treadmill speed. *International Journal of Sports Medicine*. 1–6. doi: 10.1055/s-0035-1547225

Pipkin, A., Kotecki, K., Hetzel, S., & Heiderscheit, B. 2016. Reliability of a qualitative video analysis for running. *Journal of Orthopaedics in Sports and Physical Therapy*, .46(7):556-–561. doi: 10.2519/jospt.2016.6280

Pontzer, H., Holloway, J.H., Raichlen, D.A., & Lieberman, D.E. 2009. Control and function of arm swing in human walking and running control and function of arm swing in human walking and running. *Journal of Experimental Biology*. 212(4): 523–534.

Reinisch, M., Schaff, P., Hauser, W., & Rosemeyer, B. 1991. Treadmill versus field trial movement analysis and pressure distribution in the athletic shoe. Sportverletz Sportschaden. 5: 60–73.

Roe, G., Halkier, M., Beggs, C., Till, K., & Jones, B. 2016. The use of accelerometers to quantify collisions and running demands of rugby union match-play. *International Journal of Performance Analysis in Sport*. 16(2): 590–601.

Sallis, R. 2009. Exercise is medicine and physicians need to prescribe it! *British Journal of Sports Medicine*, 43(1):3–4.

Santos-Concejero, J., Granados, C., Irazusta, J., Bidaurrazaga-Letona, I., Zabala-Lili. J., Tam, N., & Gil, S.M. 2013. Differences in ground contact time explain the less efficient running economy in North African runners. *Sport Biology*. 30 (3): 181 - –187.

Santos-Concejero, J., Tam, N., Granados, C., Irazusta, J., Bidaurrazaga-Letona, I., Zabala-Lili, J., & Gil, S.M. 2014. Stride Angle as a novel indicator of running economy in well-trained runners. *Journal of Strength and Conditioning Research*. 28(7): 1889–1895.

Santos-Concejero, J., Tam, N., Granados, C., Irazusta, J., Bidaurrazaga-Letona, I., Zabala-Lili, J., & Gil, S.M. 2014a. Interaction effects of stride angle and strike-pattern on running economy. *International Journal of Sports Medicine*. 2014; 35(13): 1118 – 1123.

Santos-Concejero, J., Tam, N., Granados, C., Irazusta, J., Bidaurrazaga-Letona, I., Zabala-Lili, J. & Gil, S.M. 2014b. Stride angle as a novel indicator of running economy in well-trained runners. *Journal of Strength and Conditioning Research*, 28(7):1889–1895.

Schache, A.G., Blanch, P., Rath, D., Wrigley, T., & Bennel, K. 2002. Three-dimensional angular kinematics of the lumber spine and pelvis during running. *Human Movement Science*. 21(2): 273-–293.

Schütte, K.H., Maas, E.A., Exadaktylos, V., Berckmans, D., & Vanwanseele, B. 2015. Wireless tri-axial trunk accelerometry detects deviations in dynamic center of mass motion due to running-induced fatigue. *PLoS One*. 1–12. doi: 10.1371/journal.pone.0141957

Sean, T., Clermont, C., Ferber R., et al. 2016. Gender differences in gait kinematics in competitive and recreational runners. *Running injury clinic*. 0-1.

Shorten, M.R., & Winslow, D.S. 1992. Spectral analysis of impact shock during running. *International Journal of Sport Biomechanics*. 8: 288–303.

Sinclair, J., Greenhalgh, A., Edmundson, C., Brooks, D., & Hobbs, S. 2012. Gender differences in the kinetics and kinematics of distance running: Implications for footwear design. *International Journal of Sports Science and Engineering*. 6. 118-–128.

Sinclair, J., Shore, H.F., Taylor, P.J. & Atkins, S. 2015. Sex differences in limb and joint stiffness in recreational runners. Human Movement, 16(3):137–141.

Sinclair, J.K., Chockalingam, N. & and Vincent, H., 2014. Gender differences in multi-segment foot kinematics and plantar fascia strain during running. *Foot and Ankle Online Journal*. 7(4).

Sinclair, J., Shore, H.F., Taylor, P.J. and Atkins, S., 2015. Sex differences in limb and joint stiffness in recreational runners. *Human Movement*. 16(3):137-141.

Soligard, T., Schwellnus, M., Alonso, J.M., et al. 2016. How much is too much? (Part 1): International Olympic Committee consensus statement on load in sport and risk of injury. *British Journal of Sports Medicine*. 50:1030-–1041.

Souza, R.B. 2016. An evidence-based videotaped running biomechanics analysis. *Physical Medicine Rehabilitation Clinic*. 27(1): 217–236.

Strohrmann, C., Harms, H., & Kappeler-sSetz, C. 2012. Running using body-worn sensors. *IEEE Trans Info Technol Biomedical*. 16 (5): 983 - –990.

Strohrmann, C., Seiter, J., & Tröster, G. 2014. Feedback provision on running technique with a smartphone. JUSPN. 5: 25 – 31.

Tabachnick, B. G., & Fidell, L. S. 2007. Using multivariate statistics. Fifth edition. (5th ed.). Boston, MA: Allyn & Bacon/Pearson Education.

Tam, N., Tucker, R., & Wilson, J.L.A. 2016. Effect on oxygen cost of transport on 8-weeks of progressive training with barefoot running. *International Journal of Sports Medicine*. 36(13):1100-–1105.

Taunton, J.E., Ryan, M.B., Clement, D.B., McKenzie, D.C., Lloyd-Smith, D.R., & Zumbo, B.D. 2003. A prospective study of running injuries: The Vancouver sun run “in training” clinics. *British Journal Sports Medicine*. 37(3): 239–244.

Teng, H.L., & Powers, C.M. 2015. Influence of trunk posture on lower extremity energetics during running. *Medicine Science in Sports and Exercise*. 47(3): 625–630.

Verbitsky, O., Mizrahi, J., Voloshin, A., Treiger, J., & Isakov, E. 1998. Shock transmission and fatigue in human running. *Journal of Applied Biomechanics*. 14 (3): 300-–311.

Vercruyssen, F., Tartaruga, M., Horvais, N., & Brisswalter, J. 2016. Effects of footwear and fatigue on running economy and biomechanics in trail running. *Medicine Science in Sports and Exercise*. 48(10):1976.

Verniba, D., Vergara, M.E., & Gage, W.H. 2015. Force plate targeting has no effect on spatiotemporal gait measures and their variability in young and healthy population. *Journal of Gait and Posture.* 41(2): 551-–556.

Wearing, S.C., Urry, S.R., & Smeathers, J.E. 2000. The effect of visual targeting on ground reaction force and temporo-spatial parameters of gait. *Clinical Biomechanics*. 15(8): 583-–591.

Weist, R.., Eils, E., & Rosenbaum, D. 2004. The influence of muscle fatigue on Eelectromyogram plantar pressure patterns as an explanation for the incidence of metatarsal stress fractures. *American Journal of Sports Medicine*. 32(8): 1893-–1898.

106. Wilber, R.L., & Pitsiladis, Y.P. 2012. Kenyan and Ethiopian distance runners: What makes them so good? *International Journal of Sports Physiology and Performance*. 7 (2): 92-–102.

Williams, K.R., Snow, R., & Agruss, C., 1991. Changes in distance running kinematics with fatigue. *International Journal of Sports Biomechanics*. 7(2): 138-–162.

Willson, J.D., Loss, J.R., Willey, W.R., & Meardon, S.A. 2015. Sex differences in running mechanics and patellofemoral joint kinetics following an exhaustive run. *Journal of Biomechanics*. 48(15): 4155-–4159.

Winter, S., Gordon, S., & Watt, K. 2016. Effects of fatigue on kinematics and kinetics during over-ground running: A systematic review. *Journal of Sports Medicine and Physical Fitness*. 35(1):887 – 889.

Vollestad, N. 1997. Measurement of muscle fatigue. *Journal of Neuroscience Methods*. 74(2): 219-–227.

APPENDIX A: PROOF OF ACCEPTANCE OF ARTICLE ONE

IJAEP
International Journal of Applied Exercise Physiology
2322-3537 www.ijaep.com
Vol.8 No.1
Received: November 2018, Accepted: December 2018, Available online: March 2019

DOI: 10. 30472 /ijaep.v8i1.327

Modifications in running kinematics in fatigued running, do not influence the oxygen cost of transport

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ABSTRACT

Changes in oxygen cost per a given distance of running due to fatigue has often been accompanied with alterations in running kinematics. Nevertheless, it is not certain if the changes in the cost of oxygen transport are as a result of the fatigue or the modifications in the kinematics. We therefore sought to understand the correlations between changes in running kinematics and cost of oxygen transport in fatigued running. Thirty-two recreational (16 men, 16 women) runners underwent a fatigue protocol which involved incremental speed to volitional exhaustion on a motorised treadmill, whiles heart rate, oxygen consumption, blood lactate, and RPE were monitored. Spatio-temporal kinematic data was assessed with an Optogait photoelectric system, and GoPro Hero 4 Black camera was used to capture upper extremity kinematics for offline analysis. Changes in pre-and post-fatigue and the interactions between the changes in kinematic parameters and oxygen cost of transport were assessed. Forward trunk lean increased from 6.81 ± 2.08 ° to 7.95 ± 2.51 °, contact times also increased from 0.33 ± 0.02 to 0.34 ± 0.02 (seconds) and the oxygen cost of transport increased from 234.1 ± 20.1 to 240.8 ± 19.6 ($\text{ml.km}^{-1}.\text{kg}^{-1}$) at post-fatigue. A negative medium correlation ($r = -0.484$; $p = 0.001$) was found between changes in arm swing and contact time. Running-induced fatigue causes changes in the spatio-temporal and upper extremity kinematics of recreational runners, however, such changes do not correlate with the increase in oxygen cost of transport in fatigued running.

KEYWORDS: forward trunk lean; arm carriage; spatio-temporal kinematics; metabolic fatigue; stride angle; oxygen cost of transport

INTRODUCTION

Oxygen cost for a given distance is a key determinant of middle and long distance running performance [1]. An inverse relationship exists between oxygen cost of transport and endurance running performance [2]. Physiological and biomechanical factors have been suggested to alter the oxygen cost of transport in distance running. Indeed, fatigued runners have been found to show a remarkable increase in their oxygen cost of transport [3,4]. Biomechanical

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APPENDIX B: PROOF OF SUBMISSION, JOURNAL OF APPLIED BIOMECHANICS

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- **Journal of Applied Biomechanics** <onbehalfof@manuscriptcentral.com>

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Oct 19 at 1:06 PM

19-Oct-2018

Dear Mr. Sackey:

Your manuscript entitled "Body load: a potential indicator of fatigue in distance running" has been successfully submitted online for consideration of publication in the Journal of Applied Biomechanics.

Your manuscript ID is JAB.2018-0404.

Please mention the above manuscript ID in all future correspondence or when calling the office for questions. If there are any changes in your street address or e-mail address, please log in to Manuscript Central at https://mc.manuscriptcentral.com/hk_jab and edit your user information as appropriate.

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Thank you for submitting your manuscript to the Journal of Applied Biomechanics.

Sincerely,

Journal of Applied Biomechanics Editorial Office

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APPENDIX C: PROOF OF ACCEPTANCE FOR PRESENTAION AT THE WORLD BIOMECHANICS CONGRESS: ARTICLE 2

WCB 2018 <support@oxfordabstracts.com>

To:saintandrewss@yahoo.com

Mar 13 at 12:14 PM

Dear Saint Sackey,

The review process for World Congress of Biomechanics 2018 has now concluded and I am pleased to inform you that your abstract, reference number 1276, entitled 'Body load: A potential indicator for detecting running-induced fatigue and in distance', has been accepted as a poster presentation at the 8th World Congress on Biomechanics 2018.

We received an unexpectedly high number of abstract submissions and as space is limited, the number of abstracts accepted for poster presentations exceeds those accepted for oral presentations. However, plans are being developed to highlight certain posters with 'lightning talks' during the Congress. These details are still being worked out. Likewise, guidelines for presentations will shortly be posted on the Congress website and you will be notified when these are available.

Please note the presenting author indicated on your submission must be registered by 29th March 2018; otherwise the contribution may be removed from the Congress programme. If your presenting author has changed, please notify us immediately. Furthermore, if your plans have changed and you must withdraw your presentation, we ask that you contact us immediately.

Registration must be done online through the link on the congress website available at http://wcb2018.com/registration/. We would like to advise that while large accommodation blocks have been held for Congress delegates in local hotels, Dublin city is very busy over the Congress dates, so early booking is recommended. Tickets for social events are also limited so again, please book early to avoid disappointment.

We look forward to seeing you in The Convention Centre, Dublin from 8th - 12th July.

With best wishes,

David Vorp, WCB18 co-Program Chair, on behalf of
Damien Lacroix, WCB18 co-Program Chair

Danny Kelly, WCB18 Co-Chair
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APPENDIX D: ARTICLE 3, ACEPTANCE FOR SASMA, 2017 ORAL PRESENTATION

Carina Du Plessis <carina@londocor.co.za>

To:saintandrewss@yahoo.com

Sep 8, 2017 at 1:54 PM

RE: SASMA CONGRESS 2017

24 – 27 OCTOBER 2017, CENTURY CITY CONVENTION CENTRE, CAPE TOWN

ACCEPTANCE OF ABSTRACT

To: Mr. Saint Sackey

Affiliation: Department of Sport Science, Stellenbosch University, South Africa

Dear Mr. Sackey,

On behalf of the Scientific Committee we have pleasure confirming that your abstract entitled:

“Runners self-optimize their kinematics in response to running-induced fatigue after eight weeks of endurance training”

Has been accepted for a ORAL. The date and time of your presentation will be forwarded to you next week once the abstracts have been allocated to the programme.

We attach the preliminary scientific programme for your information.

Registration and Accommodation details are available on the website www.sasma2017.co.za

Please do not hesitate to contact us for any further information or assistance.

Kindest regards

Sonja du Plessis / Kea Poulton / Carina du Plessis

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APPENDIX E: PROOF OF SUBMISSION OF THE REVISED VERSION OF ARTICLE 3 TO JOURNAL OF STRENGTH AND CONDITIONING RESEARCH

JSCR Submission Confirmation for JSCR-08-11950R1

Yahoo/Inbox

- **Journal of Strength and Conditioning Research** <em@editorialmanager.com>

To: Saint Andrews Sackey

Nov 18 at 8:40 PM

Nov 18, 2018

Dear Mr Sackey,

The Journal of Strength and Conditioning Research has received your revised submission JSCR-08-11950R1 entitled, "Runners self-optimize their kinematics in response to running-induced fatigue after eight weeks of endurance training."

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Your username is: Saint Sackey

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Journal of Strength and Conditioning Research

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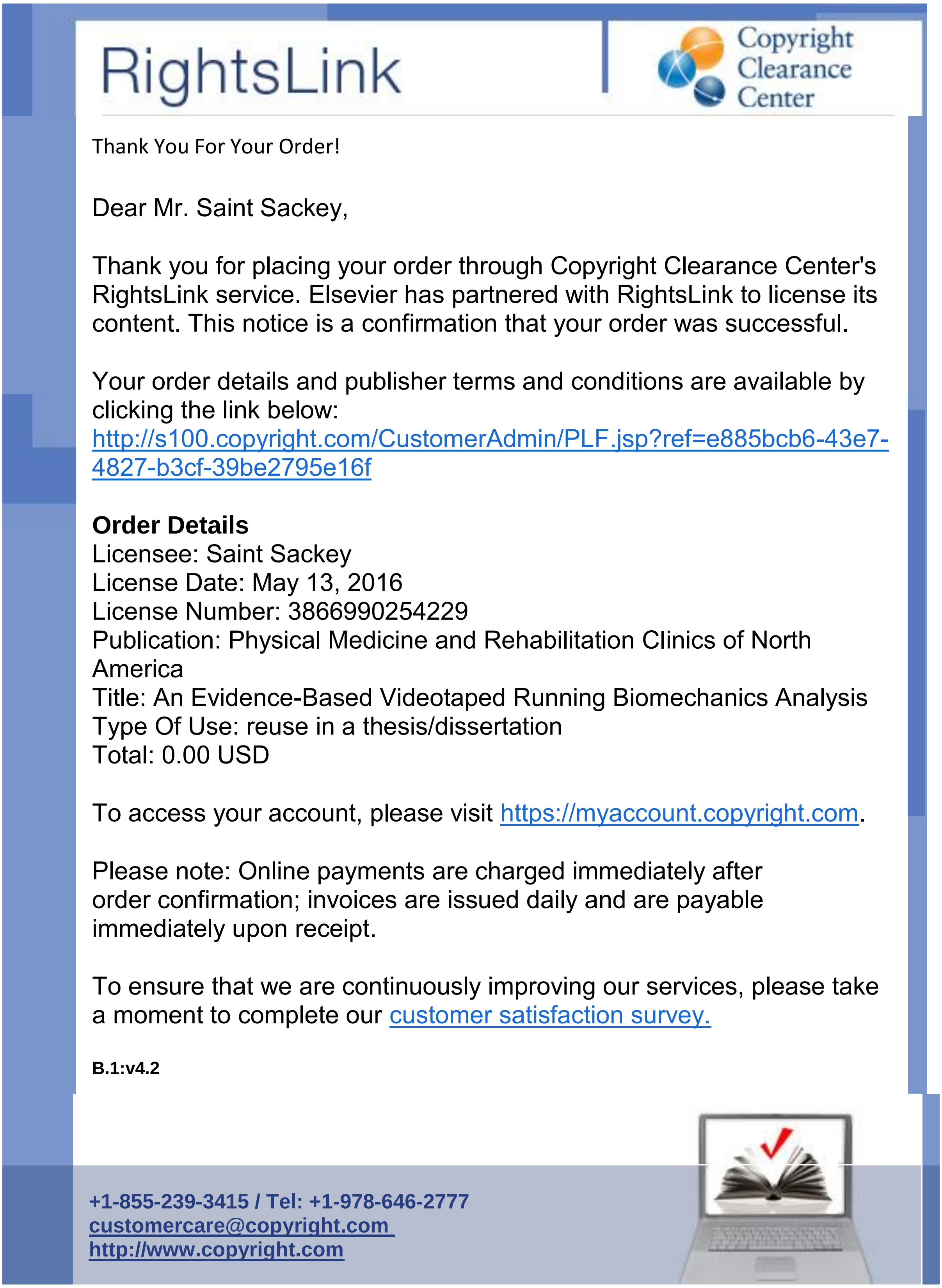
APPENDIX F: PERMISSION TO USE FIGURE 2.2.



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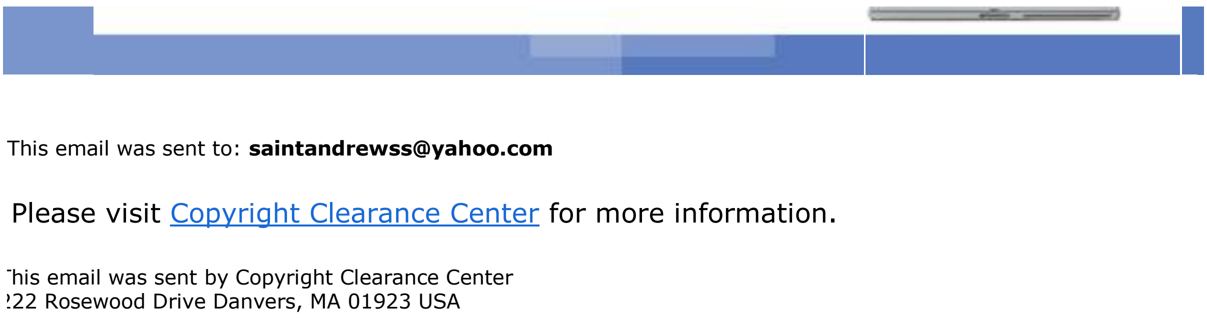

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APPENDIX G: PERMISSION TO USE FIGURE 2.3.

Jordan Santos <jordan.santos@ehu.es>
To:saintandrewss@yahoo.com
May 10, 2016 at 12:20 PM

Dear Saint Andrews

You can use the figure. No problem at all as long as you cite the source.

Regards

Jordan

De: Saint andrews Sackey [mailto:saintandrewss@yahoo.com]
Enviado el: martes, 10 de mayo de 2016 11:47
Para: jordan.santos@ehu.eus
Asunto: PERMISSION TO USE FIGURE

Dr Santos-Concejero,

I am a. student at the Department of Sports Science, University of Stellenbosch, South Africa. I am currently working on a thesis that involves running kinematics. I would be grateful, if you could grant me the permission to use "Fig. 1. Schematic representation of Stride angle" from your publication, Stride Angle as a Novel Indicator of Running Economy in Well-Trained Runners, in my thesis.

kind regards,

Saint Andrews Sackey

student No. 20266863

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APPENDIX H: ADDITIONAL RESULTS

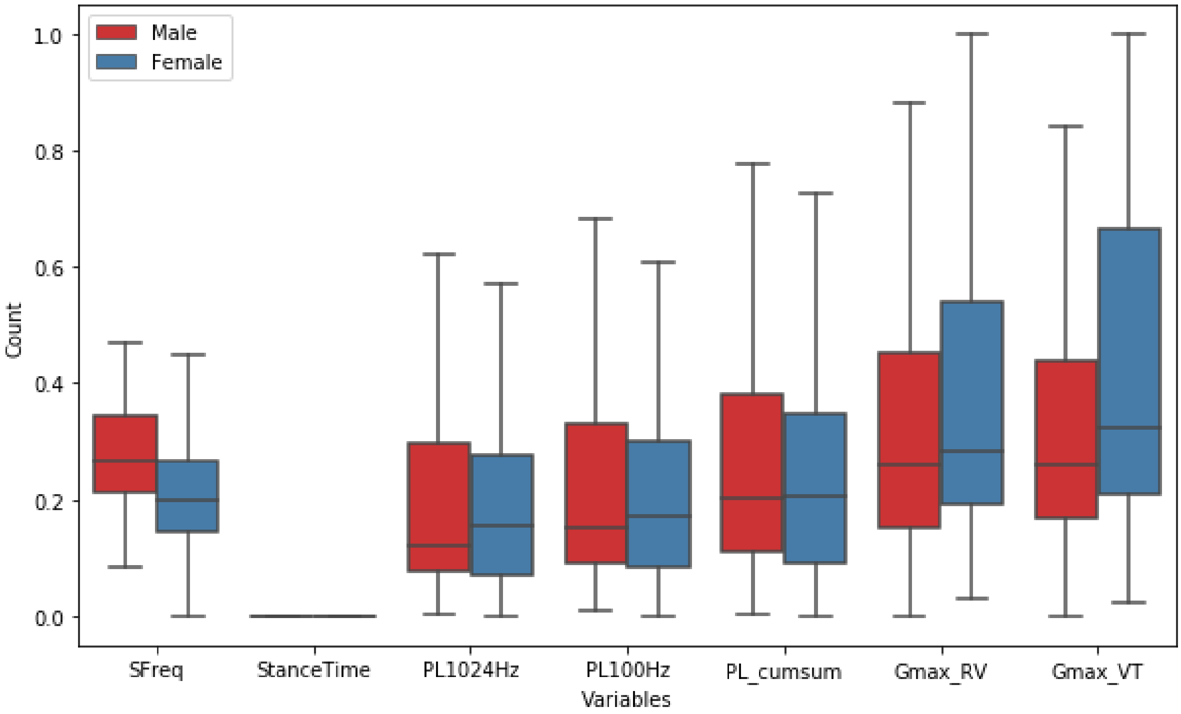

Figure 11. Differences in accelerometer parameters between male and female recreational runners

Table 7. Descriptive statistics of the male and female participants

Descriptive	**All runners (n = 48)**	**Males (n = 24)**	**Females (n = 24)**
Age (years)	21.75 ± 1.4	21.86 ± 1.88	21.64 ± 0.74
Body mass (kg)	68.18 ± 11.41	74.72 ± 11.24	61.64 ± 7.19
Height (m)	1.73 ± 0.08	1.78 ± 0.08	1.68 ± 0.06
BMI (kg.m^{-2})	22.56 ± 2.48	23.4 ± 2.51	21.72 ± 2.23

Table 8. Differences in spatio-temporal and upper extremity kinematics between male and female recreational runners

	Male		**Females**	
Parameters	**Pre-fatigue**	**Post-fatigue**	**Pre-fatigue**	**Post-fatigue**
Contact time (s)	0.219 ± 0.01	0.220 ± 0.01	0.214 ± 0.01	0.215 ± 0.01
Step length (cm)	91.37 ± 5.22	92.06 ± 4.96	86.76 ± 5.92	87.24 ± 5.34
Flight time (s)	0.028 ± 0.07	0.025 ± 0.01	0.025 ± 0.02	0.031 ± 0.03
Stride angle (°)	0.402 ± 0.65	0.314 ± 0.46	0.446 ± 0.71	0.557 ± 1.48
Trunk lean (°)	7.81 ± 2.39	8.86 ± 3.02	6.51 ± 1.56	7.96 ± 1.91

Table 9. Comparison of fitness levels of the control and intervention group, before and after the eight weeks.

	Control group		Intervention group	
Parameters	Before	After	Before	After
Vpeak	4.15±0.54	4.32±0.61	4.15±0.58	4.46±0.62*
RER	0.95±0.03	0.95±0.02	0.95±0.03	0.96±0.04

//Statistically significant difference ($p \leq 0.05$); /RER/ Respiratory exchange ratio; /Vpeak/ Peak treadmill speed.*

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Table 10. Descriptive results at pre-post fatigue of the Control (Cont.) and Intervention (INT) groups after the eight weeks

	Pre-fatigue			Post-fatigue		
Parameters	Cont. group	INT	p value	Cont. group	INT	p value
Contact time(s)	0.36±0.08	0.35±0.09	0.68	0.36±0.06	0.35±0.02	0.44
Step length(cm)	88.97±6.56	88.53±6.00	0.81	87.51±6.15	85.72±5.28	0.28
Trunk lean(°)	6.81±2.61	6.52±2.55	0.69	7.12±2.52	6.97±2.49	0.81
Tibia Impact(g)	6.32±3.46	6.15±3.71	0.87	7.48±4.66	7.43±4.59	0.97