The change in postural control in highly trained trail runners following a short, competitive, off-road time trial

by

Nicholas Price

Thesis presented in partial fulfilment of the requirements for the degree

of Master of Science in the Department of Exercise, Sport, and Lifestyle Medicine,

Faculty of Medicine and Health Sciences

at Stellenbosch University

Supervisor: Mr Simon de Waal

Co-supervisor: Ms Sarah Arnold

March 2023

DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

March 2023

PLAGIARISM DECLARATION

I have read and understand the Stellenbosch University Policy on Plagiarism and the definitions of plagiarism and self-plagiarism contained in the Policy on Plagiarism: The use of the ideas or material of others without acknowledgement, or the re-use of one's own previously evaluated or published material without acknowledgement or indication thereof (self-plagiarism or text-recycling). I also understand that direct translations are plagiarism. Accordingly, all quotations and contributions from any source whatsoever (including the internet) have been cited fully. I understand that the reproduction of text without quotation marks (even when the source is cited) is plagiarism.

March 2023

SUMMARY

Research on acute effects of trail running (TR) induced fatigue and postural control (PC) in highly trained trail runners is scarce. Therefore, the aim of this study was to measure the change in select postural control variables following a short, real-world, trail run time trail (26km; +900m) in a sample of highly trained trail runners.

Thirteen (N=13) male, highly trained trail runners (age: 30.00 ± 5.58 years old; weekly running: 65.00 ± 6.45 kilometres) participated in this study. Participants completed five postural control system (PCS) tests before and after a short, real-world, TR time trial (26km +900m ascent). Balance tests included a Modified Clinical Test of Sensory Interaction of Balance (MCTSIB), Single Leg Modified Clinical Test of Sensory Interaction of Balance (SLMCTSIB) and a Star Excursion Balance Test (SEBT). Postural sway and sway frequencies were measured via a Gyko Inertial Measurement Unit (Microgate, Italy) during four different stance conditions; firm surface with eyes open (FO), firm surface with eyes closed (FC), compliant surface with eyes open (CO), and compliant surface with eyes closed (CC). Jump tests included a Countermovement Jump Test (CMJ) and Single-Leg Countermovement Jump test (SLCMJ). Jump height and flight time were measured using OptoJump (Microgate, Italy) and two Logitech web cameras (30 fps). Tests for normality were performed using the Shapiro-Wilk test. A combination of paired samples t-tests and Wilcoxon signed-rank tests were used to identify differences in mean scores before and after the time trial (significance flagged as $p<0.05$).

Statistically significant increases ($p<0.05$) in mediolateral sway were observed in stance conditions FO, FC and CC while anteroposterior sway showed significant increases ($p<0.05$) for stance conditions FO, and CO during the MCTSIB. A statistically significant increase ($p<0.05$) in mediolateral sway was observed in the SLMCTSIB for the FO stance condition. A significant decrease in reach length was observed during the SEBT in the anterior movement only ($p<0.05$) and only on the right foot. No statistically significant changes ($p>0.05$) were observed for maximal and mean jump height and time for CMJ. However, statistically significant decrements ($p<0.05$) were found for all variables during the SLCMJ test.

This study's key finding was that significant changes in select PC variables were observed following a short TR time trial. In conclusion, it appears general TR-induced fatigue negatively impacts PC regulation following a 26km (+900m) trail run time trial. However, a combination of training status, task experience and compensatory strategies appear to limit the magnitude that general neuromuscular fatigue can have on PC regulation. A greater contribution from cognitive resources such as increased awareness and attentional demand could improve sensory detection capabilities needed to identify optimal balance demands via proprioceptive sensory sources. Future studies should measure trail runners of varying training statuses to better understand this phenomenon.

Keywords: Mountain running; Balance; Proprioception; Compensation strategies

OPSOMMING

Navorsing oor die akute gevolge van velsdwedloop atlete (VA)-geïnduseerde moegheid en postuurbeheer (PB) op hoogs opgeleide veldwedloop atlete is skaars. Daarom was die doel van hierdie studie om die verandering in uitgesoekte PB-veranderlikes voor en na 'n kort (<42.2km), mededingende VA-tydtoets (26km; +900m) in 'n groep hoogs opgeleide veldwedloop atlete te bepaal.

Dertien (N=13) manlike, hoogs opgeleide veldwedloop atlete (ouderdom: 30.00 ± 5.58 jaar oud; weeklikse hardloop afstand: 65.00 ± 6.45 kilometer) het aan hierdie studie deelgeneem. Deelnemers het vyf posturale beheerstelsel (PBS) toetse voltooi voor en na 'n kort, werklike, VA-tydtoets (26km +900m styging). Balanstoetse het 'n *Modified Clinical Test of Sensory Interaction of Balance (MCTSIB), Single Leg Modified Clinical Test of Sensory Interaction of Balance (SLMCTSIB)* en 'n *Star Excursion Balance Test (SEBT)* ingesluit. Posturale swaai- en swaaifrekwensies is gemeet via 'n *Gyko Inertial Measurement Unit (*Microgate, Italy*)* tydens vier verskillende houdingstoestande; ferm oppervlak met oë oop (FO), ferm oppervlak met oë toe (FT), voldoenende oppervlak met oë oop (VO) en voldoenende oppervlak met oë toe (VT). Springtoetse het 'n teenbeweging-springtoets (TBS) en enkelbeen-teenbeweging-springtoets (EBJBS) ingesluit. Springhoogte en vlugtyd is gemeet met *OptoJump (*Micorgate, Italië*)* en twee Logitech-webkameras (30 fps). Toetse vir normaliteit is uitgevoer met behulp van die Shapiro-Wilk-toets. 'n Kombinasie van gepaarde steekproewe t-toetse en Wilcoxon-tekenrangtoetse is gebruik om verskille in gemiddelde tellings voor en na die tydtoets te identifiseer (statistiese betekenisvolheid is op $p<0.05$ gestel).

Statisties beduidende toenames ($p<0.05$) in mediolaterale swaai is waargeneem in houdingstoestande FO, FT en VT, terwyl anteroposterior swaai beduidende verhogings ($p<0.05$) getoon het vir houdingstoestande FO, en VO tydens die MCTSIB. 'n Statisties betekenisvolle toename ($p<0.05$) in mediolaterale swaai is waargeneem in die SLMCTSIB vir die FO houding toestand. 'n Beduidende afname in reiklengte is tydens die SEBT waargeneem slegs in die anterior beweging ($p<0.05$) en slegs op die regtervoet. Geen statisties betekenisvolle veranderinge ($p>0.05$) is waargeneem vir maksimum en

gemiddelde springhoogte en tyd vir CMJ nie. Statisties betekenisvolle afnames ($p<0.05$) is egter gevind vir alle veranderlikes tydens die SLCMJ-toets.

Die hoofbevinding van hierdie studie was dat betekenisvolle veranderinge in uitgesoekte PBS-veranderlikes waargeneem is na 'n kort VA tydtoets. Ten slotte, dit blyk dat algemene veldwedloop-geïnduseerde moegheid 'n negatiewe impak op rekenaarregulering het na 'n 26km (+900m) tydtoets. 'n Kombinasie van opleidingstatus, taakervaring en kompenserende strategieë blyk egter die omvang te beperk wat algemene neuromuskulêre moegheid kan hê oor rekenaarregulering. 'n Groter bydrae van kognitiewe hulpbronne soos verhoogde bewustheid en aandagvraag kan sensoriese opsporingsvermoëns verbeter wat nodig is om optimale balanseise via proprioseptiewe sensoriese bronne te identifiseer. Toekomstige studies moet veldwedloop atlete met verskillende opleidingstatusse meet om hierdie verskynsel beter te verstaan.

Sleutelwoorde*: Berg draf; Balans; Propriosepsie; Vergoedingstrategieë*

ACKNOWLEDGEMENTS

I would like to thank the following individuals for their respective contributions to the process of completing this thesis. Furthermore, I'd like to express my gratitude to each and every one of them for the role they have played in this chapter of my life.

My parents, **Lesley and Kevin**, for their unconditional love and support. Without them, my academic career would not have been possible. To my brother, Jason, for always being open to chat, listen and hand out advice like a wise old sibling.

Simon de Waal, for his academic guidance and support, as well as the tireless motivation throughout the entire thesis process. It has been quite a journey and it would not have been possible without him.

Sarah Arnold, for her hawk-eye attention to detail, endless knowledge of postural control and for investing so much time into helping me achieve this goal.

Camryn Simpson, for her endless love, and support and for standing next to me through this rollercoaster experience.

My **participants**, for their commitment to the study and their willingness to push themselves to the red zone without complaining and always with a smile. Their patience during the process was much appreciated.

Research study assistants, firstly **Wikus Strydom**, for his patience, commitment and help through the entire process and secondly, **Mark Landman**, for his contribution in assisting the many equipment training sessions.

Tonya Esterhuizen, from the Department of Epidemiology and Biostatistics, for her help and statistical guidance.

TABLE OF CONTENTS

APPENDICES

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

°C	:	Degrees Celsius
%	:	Percentage
<	:	Less than
>	:	More than
3D	:	Three dimensional
Am	:	after meridian (morning)
AP	:	Anteroposterior
ASIS	:	Anterior Superior Iliac Spine
B.C	:	Before Christ
BMI	:	Body Mass Index
CC	:	Compliant surface, eyes closed
CMJ	:	Counter movement Jump
CO	:	Compliant surface, eyes open
COG	:	Centre of Gravity
COP	:	Centre of Pressure
DR	:	Downhill running
et al.	:	*et alia (“and others”)*
Etc.	:	etcetera
FC	:	Firm surface, eyes closed
FO	:	Firm surface, eyes open
FR	:	Familiarisation run
Hrs	:	Hours
Hz	:	Hertz
ICF	:	Informed Consent Form
IMU	:	Inertial Measurement Unit
ITRA	:	International Trail Running Association
KHz	:	Kilohertz
Km	:	Kilometres

$km.h^{-1}$	:	Kilometres per hour
LR	:	Level running
m	*:*	*Meters*
m/s	*:*	*Meters per second*
MCTSIB	:	Modified Clinical Test of Sensory Interaction of Balance
ML	:	Mediolateral
mm	:	Millimetres
n	:	Sample size
PC	:	Postural control
PCS	:	Postural control system
RPE	:	Rate of perceived exertion
RR	:	Road running
SEBT	:	Star Excursion Balance Test
SLCMJ	:	Single leg Counter Movement Jump
SLMCTSIB	:	Single Leg Modified Clinical Test of Sensory Interaction of Balance
TR	:	Trail running
TT	:	Time trial
UR	:	Uphill running
USA	:	United States of America
vs.	:	Versus

CHAPTER OVERVIEWS

Chapter One: This chapter includes an introduction to the thesis with regard to all relevant topical information. It also contains the purpose of the study, problem statement, research questions, aims, objectives and hypotheses of the study.

Chapter Two: This chapter summarises the existing literature regarding trail running, postural control and exercise-induced acute neuromuscular fatigue. Furthermore, it explores the relationship between postural control and trail running with reference to the influence of acute neuromuscular fatigue on postural control.

Chapter Three: This chapter explains the methodology for this research study. It explains the study design, participants, study overview, ethical aspects, tests and measurements, data analysis and statistical analysis.

Chapter Four: This chapter includes a research article titled *Postural control changes in highly trained trail runners following a short, competitive off-road time trial.* This chapter was written in accordance with the guidelines provided by Elsevier Gait & Posture Journal. Consequently, the referencing style for this chapter is in differs from that of the rest of this thesis in order to accommodate the preferred referencing style of the Elsevier Gait & Posture Journal. The primary focus of this article was to observe the change in postural control variables following a short, real-world, trail run time trial.

Chapter Five: This chapter briefly concludes the thesis by referring to the various research hypotheses. Furthermore, the chapter includes the limitations of the study as well as recommendations for future research

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND INFORMATION

Human locomotion can be viewed as a seemingly straightforward task when it is simplified to be understood as the way in which individuals propel themselves in order to satisfy a purpose of movement in the most economically effective way possible (Abu-Faraj et al., 2015). However, the task of walking and running is far more complex than one may think. Such simple tasks are influenced by numerous factors (anatomy, ground surface, the weather or the intended outcome of movement) that could disrupt movement economy (Novacheck, 1998). Humans use bipedal locomotion every day for different reasons. Such reasons vary from occupational commuting to that of leisurely activities for exercise and overall well-being (Lee et al., 2017). Over the past decade-and-a-half, locomotion for exercise has seen a dramatic increase in popularity and participation, with walking and running being the most popular forms of bipedal locomotion (Fredericson and Misra, 2007).

Walking and running should be understood as natural progressions and regressions from one another when the speed of movement changes. Walking succeeds that of a stationary position where a progression in forward momentum is capped at a movement threshold of 2.3m/s. Beyond this speed, the action of running is initiated. Running is the natural progression of bipedal movement when the speed of forward (or backward) momentum increases to a point where walking becomes too uncomfortable to maintain as well as biomechanically inefficient for the required task. For human beings, a threshold speed appears to occur around 2.4m/s whereby locomotion intuitively changes from walking to a more comfortable running motion (Bartlett and Kram, 2008).

Other than the change in velocity resulting in the transition period between walking and running, one is able to differentiate between walking and running through their biomechanical differences. Walking should be understood as planned, repeated limb movements which act to move the body in a forward direction, while simultaneously maintaining stance stability (Kharb et al., 2011). In terms of gait, walking technically comprises of only two phases: (1) a stance phase, and (2) a swing phase (Novacheck, 1998). However, these phases are further divided to account for specific limb actions through a single gait cycle. The walking subphases can be broken down as follows: initial contact, loading response, midstance, terminal stance, pre-swing, rear foot toe-off, initial swing and terminal swing (Kharb et al., 2011). The key characteristic of walking is the period of double stance (or double limb support) where both feet are in contact with the ground between initial contact of the one foot and toe-off of the other (Bartlett and Kram, 2008; Kharb et al., 2011). This biomechanical characteristic is one of the main differentiating characteristics between walking and running.

The transition between walking and running is primarily identified when the double stance support phase while walking is replaced with a flight phase (also known as a float phase) which sees a period of time where no limbs have any contact with the ground (Novacheck, 1998). In terms of phases, running consists of four phases: (1) stance phase (2) early flight phase (3) swing phase (4) late flight phase (Chapman, 2013). As the movement strategy transitions from walking to running, the body is placed under different and more taxing circumstances. These circumstances are, increased ground reaction forces, a decreased centre of gravity as speed increases, the need for greater joint range of motion and the need for greater muscle contractions (Dugan and Bhat, 2005).

The benefits associated with recreational running vary from physical to psychological, with running for exercise recently prescribed as medicine for overall well-being and longevity (Lee et al., 2017). Consequently, running for the purpose of exercise and race participation has become increasingly popular over the past 10 to 15 years, with a greater emphasis on healthy living (Fredericson and Misra, 2007; Hoffman et al., 2010).

As recreational running and participation in races continue to increase in popularity, so too do the different types of running and running races. Off-road running is a fairly new type of running, with participation numbers climbing exponentially over recent years to reach a 2017 total of 9.1 million participants in the United States alone (Malliaropoulos et al., 2015; Scheer et al., 2020). Several categories of off-road running currently exist, with trail running (TR) being the largest and most popular category (Scheer et al., 2020). When compared to road running (RR), TR is characterised foremost by the environment in which it takes place and the ground surfaces associated with that environment. It makes use of the natural environment (forests, parks and nature reserves etc.) where asphalt roads are absent and dirt trails are solely prominent (Hoffman et al., 2010). There has been a recent demand for a universal language of description within off-road running, where guidelines have been proposed to easily distinguish between the different types of off-road running. To meet this demand, this thesis will follow all guidelines of description based on the latest TR literature by Scheer et al. (2020). For descriptive clarity, TR and the races associated with TR, will be defined in the article as follows:

“Trail running, the most popular discipline of off-road running, is defined as a foot race in a natural environment including mountains, deserts, forests, coastal areas, jungles/rainforests, grassy or arid plains over a variety of different terrains (e. g. dirt road, forest trail, single track, beach sand, etc.) with minimal paved or asphalt roads, not exceeding 20–25 % of the total race course” (Scheer et al., 2020, pg.27).

Further differentiating characteristics of TR include the possibility of extensive race durations, large variance in vertical displacement and hence, increased eccentric muscle contractions on prolonged downhill segments (Easthope et al., 2010). All factors considered, participation in TR and TR events (distance and duration dependent) can put a considerable amount of stress on the body that may inevitably lead to acute neuromuscular fatigue (Baiget et al., 2018; Millet et al., 2022). Running requires the coordination and facilitation of various sources of sensory information which initiate motor patterns that control muscle activations (Abu-Faraj et al., 2015).

Considering the complex nature of running, it is understood that in the simplest form, the brain needs to coordinate a series of body segments in a way that optimises neuromuscular control and joint segment orientation in order to optimise running biomechanics and maintain an efficient dynamic equilibrium (Millet et al., 2011). The postural control system (PCS) is responsible for regulating the ability to maintain dynamic balance and movement coordination, thus contributing towards the maintenance of an efficient upright posture during running (Paillard, 2012).

Postural control (PC) is described as a complex and constant process of re-establishing a balance equilibrium (Paillard, 2012). Where balance is known to be the task of maintaining the centre of mass over the base of support, PC essentially controls how and when the process of balance must be re-established (Massion, 1994). The PCS is initiated with the perception of external stimuli that are recognised via the following systems: visual, vestibular, somatosensory and proprioception (Massion, 1994). These systems contribute to the interpretation of the stimuli and the subsequent initiation of appropriate postural responses.

TR is a sport where the external environment is ever-changing. This means that athletes are constantly having to overcome postural disturbances with each step. As previously mentioned, TR is further classified by variations in vertical displacement, meaning increased eccentric muscle contractions and thus intensified acute neuromuscular fatigue. This type of fatigue has been documented to influence PC and the PCS as seen through increased postural sway in either an anterior-posterior or mediolateral direction (Degache et al., 2014). Furthermore, neuromuscular fatigue negatively influences the ability of the PCS to initiate smooth and coordinated movement responses (Paillard, 2012).

Trail running endurance events that consist of longer durations, increased intensity and eccentric muscular contractions can result in muscle damage which may impair muscle functioning and the systems regulating neuromuscular feedback (Byrne et al., 2004; Dabbs and Chander, 2018). Consequently, there may be an increase in postural sway and overall PC may be affected. When acute neuromuscular fatigue is present, the increase in postural sway during TR can be attributed to certain declines in muscular performance as measured through greater fatigue identified in the ankle plantar and dorsiflexor muscles as well as the hip adductors and abductors (Degache et al., 2014). Furthermore, literature shows that following an ultra-length trail race, athletes have great difficulty controlling motor tasks – suggesting reduced PC as an index of fatigue (Degache et al., 2014).

Research into PC during “mountain ultra-marathons” appears to confirm two things: (1) acute neuromuscular fatigue deteriorates postural control, and (2) alterations in postural control follow a bi-phasic pattern after 100km (Degache et al., 2019). The bi-phasic nature of PC found in the above-mentioned study explains that PC variables deteriorated until a point. After this point, changes in PC appeared to plateau, thus indicating the presence of compensatory strategies that serve to limit the impact of fatigue on PC. Alterations in postural sway are the largest prior to 100km, meaning that the first phase of the competition is vital in terms of the extent to which PC degrades before anticipatory strategies limit the degradations thereof (Degache et al., 2019). It is yet to be established whether similar changes in neuromuscular performance and possible compensatory strategies will occur when runners are not exposed to altitude, sleep deprivation and other demands associated with ultra-distances. However, Baiget et al. (2018) found smaller declines in neuromuscular efficiency during a 21.1km trail event. Thus, motivating further research into the effect of short-distance (<42.2km) trail events on neuromuscular performance and the consequential effects on postural control.

Therefore, an investigation into the changes in PC after a short distance maximal effort time trial may provide vital information on the importance of PC in TR and further contribute to the lack of field-based literature associated with TR.

1.2 PROBLEM STATEMENT

The sport of TR is characterised by uneven ground surfaces, large variations in vertical displacement, potentially extreme environmental conditions and over various durations and distances (Biaget et al, 2018; Easthope et al., 2010; Scheer et al., 2019) . As ground surface inclines vary to such an extent, there is an increased prevalence of repeated eccentric muscle contractions over the course of a race which can contribute to the onset of acute neuromuscular fatigue which may negatively influence PC regulation. It is therefore important to determine how PC is influenced during these races to better understand the value that PC training (specifically proprioceptive training) may have in improving overall performance. It is clear that the PCS is a vital facilitation system for effectively navigating TR environments, however, the sensory inputs and feedback pathways are susceptible to fatigue (Paillard, 2012). The degree to which acute neuromuscular fatigue potentially decreases postural control performance is unclear. The efficiency of the processing systems needed for PC maintenance is reduced due to the effect exercise-induced fatigue can have on muscle functioning, and proprioceptive and neuromuscular feedback systems. A decline in the ability of the PCS to effectively facilitate sensory inputs and neural feedback could lead to an increased risk of falling or injury prevalence due to affected running mechanics or reduced overall performance. An investigation into the extent to which PC is affected by acute neuromuscular fatigue could prove beneficial in highlighting the importance of PC in TR as well as lead to possible recommendations with regard to injury prevention and even performance enhancement. Furthermore, this study will contribute to the lack of TR-specific research as well as research regarding the impact of acute neuromuscular fatigue on postural control in the sport of TR (Easthope et al., 2010; Scheer et al., 2019).

1.3 PURPOSE OF STUDY

The purpose of this study was to observe the impact of a short, real-world, trail run time trial on postural control in a sample of highly trained trail runners.

1.4 STUDY SIGNIFICANCE AND MOTIVATION

Researching the change in postural control following a short, real-world trail running time trial could provide valuable information regarding the possible need for the recommendation of postural control training in TR training programs. Thus, highlighting possible methods for TR performance enhancement. This study could contribute to the area of TR literature with specific regard to TR, fatigue and postural control. The findings of this study could contribute towards a need for both runners and industry professionals to understand the importance of postural control in TR.

1.5 RESEARCH QUESTIONS

1. How does a short, real-world, trail running time trial (26km; +900m) affect postural control in highly trained trail runners?

1.6 AIMS AND OBJECTIVES

RESEARCH AIM

The research aim of this study was to measure the change in select postural control variables following a short, real-world, trail run time trail (26km; +900m) in a sample of highly trained trail runners.

OBJECTIVES

1. To measure the change in postural control ability in highly trained trail runners following a short, real-world trail run time trial (26km; +900m) using the Modified Clinical Test of Sensory Interaction on Balance Test (MCTSIB) and Single Leg Modified Clinical Test of Sensory Interaction of Balance Test (SLMCTSIB) measured with Gyko (Microgate, Italy) inertial accelerometer.

Variables:

a. Mediolateral sway (mm)

b. Anteroposterior sway (mm)
c. Centroidal frequency of medial later sway (Hz)
d. Centroidal frequency of anteroposterior sway (Hz)
e. Mean frequency of mediolateral sway (Hz)
f. Mean frequency of anteroposterior sway (Hz)

2. To measure the change in relative reach distance (cm) in highly trained trail runners following a short, real-world trail run time trial (26km; +900m) using the Star Excursion Balance Test (SEBT).

3. To measure the change in jump performance (CMJ and SLCMJ) in highly trained trail runners following a short, real-world trail run time trial (26km; +900m) as measured by OptoJump transmitting and receiving panels (Microgate, Italy).

Variables:

a. Maximum jump height (cm)
b. Mean jump height (cm)
c. Maximum flight time (s)
d. Mean flight time (s)

1.7 HYPOTHESES

Research hypothesis one (H_1): Postural control for the study sample will be significantly reduced for all variables across all tests following a short, real-world, trail run time trial compared to baseline results.

Null hypothesis one (H_0): There will be no significant change in postural control across all tests for the entire study sample when comparing pre-post time trial results.

1.8 VARIABLES

The table below summarises the variables examined within this research study

Table 1.1: Summary of all variables examined within this research study.

Dependent Variables	Independent Variable	Control Variables
Medial lateral sway (length ML) (mm)	26km trail run time trail	Time trial distance (km)
Anterior posterior sway (length AP) (mm)		Time trial route
Centroidal frequency of medial later sway (Hz)		Time trial elevation gain (m)
Centroidal frequency of anterior posterior sway (Hz)		Weather conditions
Reach (cm)		Sex (male or female)
Maximum jump height (cm)		Age (years)
Mean jump height (cm)		Runner training status (highly trained)
Maximum flight time (s)		Type of runner (trail runner)
Mean flight time (s)		

1.9 ASSUMPTIONS

Certain assumptions were made regarding the participants and the recruitment process, data collection and the study as a whole. It was assumed that the participants answered the questionnaire honestly, thus providing honest and accurate answers regarding their training status, average weekly mileage, as well as all injury and health statuses. The advertisement used for the recruitment process clearly stipulated the inclusion and exclusion criteria of the study. The researchers did their best to ensure that all familiarisation attempts, word prompts and personnel present during test days were as similar as possible.

CHAPTER 2: THEORETICAL CONTEXT

2.1 INTRODUCTION

Bipedal locomotion has evolved in conjunction with the evolution of human anatomical structure, which allows humans to move in a bipedal and upright manner (Rothschild, 2012). As locomotion became competitive in the form of running, the environment in which running stereotypically took place began to expand outside of city walls. Human running is a sequence of repetitive movements which serve to move the body where a person needs to go. Understanding these sequences is vital to understand the impact that off-road terrains have on the mechanisms of running and how the alterations in sequences can affect the ability to maintain dynamic equilibrium. Postural control (PC) is an important ability for maintaining an upright equilibrium, which is utilised for tasks ranging from daily chores to running on rocky mountain trails (Paillard, 2012). The system which coordinates this ability is complex and could be challenged by the nature of trail running (TR) and the level of exercise-induced acute neuromuscular fatigue associated with TR (Easthope et al., 2010).

The popularity of off-road running grows daily, however, it appears that scientific interest and contribution to the sport of TR is not progressing at the same rate (Scheer et al., 2020). This chapter will first explore the sport of TR through existing literature which includes the human gait cycle, and the influences off-road terrain has on these mechanisms. Secondly, this chapter will expand on fatigue and the relationship between fatigue and postural control within the sport of TR. Finally, the chapter concludes with typical tests and measures of PC, related equipment and the validity and reliability of the tests and associated equipment.

2.2 TRAIL RUNNING DEFINED

Bipedal movement has been used by human beings as a form of locomotion for almost two million years (Rothschild, 2012). The anatomical structure associated with bipedalism meant that early humans were able to make use of what has been labelled “primitive running” (Rothschild, 2012). The skeletal structure and muscular orientation of these early humans allowed them to utilize this form of running to scavenge for food and retreat to safety when needed (Rothschild, 2012). As evolution guided the progression of the modern human, so too evolved the action of running. Running became a competitive sport during the Ancient Olympic Games in 776 B.C (Rothschild, 2012). Fast forward to the 21st century, running has continued to evolve and progress in terms of competitiveness, distances, equipment, technique and even the type of environment running takes place in. As the popularity of running races continues to increase, so too does the number of individuals choosing to substitute road running for that of off-road running (Hoffman et al., 2010). Scheer et al. (2020) confirm that the number of off-road running participants increased from 4.8 million people in 2009 to 9.1 million people in 2017 in the USA alone. Despite this rise in popularity, trail running (TR) research remains scarce and its description becomes lost in translation through a lack of universally accepted terminology (Scheer et al., 2020). As the academic interest within trail running grows, it is important to ensure the highest level of clarity when describing trail running within the literature. Having a firm understanding of trail running, trail running races and trail running athletes from an academic perspective will assist in identifying the population to which this thesis is directed.

As TR research evolves, so too should the understanding that TR falls under the umbrella term of “off-road running”. There are serval sub-classifications of *off-road running* that are defined primarily based on the environment in which they take place and their respective distances (Scheer et al., 2020). Care must be taken when defining TR specifically, as not all off-road running and running events are full under the trail running classification (Scheer et al., 2020). There exists a number of recognized off-road running disciplines such as sky running, mountain running, fell running, cross-country running, orienteering and ultramarathon running. However, recent classification requirements of each discipline have seen a handful become mutually exclusive to that of TR, with minimal overlap between them. The most noteworthy overlap being between that of ultramarathon running and trail running (Scheer et al., 2020).

Prior to the push for a universal language of description, the literature regarding TR and TR races appeared to have several common denominators with regard to their description. These commonalities included; (a) the fact the sport of TR takes place in natural environments where surfaces are rough, uneven and disregard that of paved roads (Malliaropoulos et al., 2015; Ehrstrom et al., 2017; Giandolini et al., 2017), (b) TR is associated with large variations in elevation (Ehrstrom et al., 2017; Giandolini et al., 2017; Biaget et al, 2018; Degache et al, 2019), and (c) the classification of distances and duration within TR and TR races have an open variance, ranging from short distances (<42.2km/1.5-4hrs) to ultralong distances (>100km/± 24hrs) (Easthope et al., 2010; Ehrstrom et al., 2017; Scheer et al., 2019). As TR and TR races continue to increase in popularity and participation, the definition thereof becomes less blurred and the confusion between off-road running disciplines dissipates. However, for the purpose of this thesis, as well as for the sake of continuing to build a universal language of trail running terminology, the accepted definition of trail running in this thesis will be in accordance with the latest literature in TR which provides specific guidance in this regard.

The descriptive guidance provided by Scheer et al. (2020) recommends this discipline of off-road running (trail running), be described in accordance with five underlying factors: (1) environmental conditions (2) terrain (3) distance covered (4) altitude change and (5) competition rules and standards of the respective governing bodies. The sport of TR is governed by the International Trail Running Association (ITRA) who, in 2017, released the following basic description of TR and TR races:

"… a pedestrian and off-road race conducted in a natural environment (e.g. mountain) with minimal possible paved or asphalt road (<20% of the total duration race)" - (Ehrstrom et al., 2017, p. 580).

Albeit short and sweet, the above definition remains to be the crux of defining TR. However, half a decade later, the latest literature has progressed the understanding of this definition in the direction of creating a universal language in terms of defining TR. The most recent definition to date states that:

"Trail running, the most popular discipline of off-road running, is defined as a foot race in a natural environment including mountains, deserts, forests, coastal areas, jungles/rainforests, grassy or arid plains over a variety of different terrains (e. g. dirt road, forest trail, single track, beach sand, etc.) with minimal paved or asphalt roads, not exceeding 20–25 % of the total race course" (Scheer et al., 2020, pg.277)

Furthermore, it is worthwhile to note that due to route profiles, distances and trail difficulty, participants in TR races are required to be self-sufficient between aid stations in terms of food, water and clothing (Scheer et al., 2020). The nature of TR allows routes to be set in some of the most isolated locations and for this reason, the safety of runners holds the highest level of importance. In the case of an emergency, all participants are required to have several safety items on their person at all times. It is the responsibility of the race organizers to ensure that the route is well-marked so that no runner could get lost en route. Then, in accordance with the descriptive guidance provided by Scheer et al. (2020), race classification is to be based on a "km-effort formula" that includes both distance covered as well as the change in altitude/elevation. This is expressed as a sum of the total distance (km) plus the vertical gain (m) divided by 100. For example, should the race be 65km in length with 3500m worth of elevation, the equation would read: 65+ 3500/100 = 100.

With all of the above in mind, whenever this thesis mentions TR, it is referring to the definition recommended by the literature of Scheer et al (2020). It is vital to understand that both the updated definition as well as the accepted call for a universal language of understanding of TR terminology is barely a year old. Therefore, it is noteworthy to mention that the definition of TR and TR races within this thesis will differ from the majority of TR research published before the year 2020. This chapter will highlight existing literature on the topics of running and walking gait, how the nature of TR may influence gait, postural control, fatigue and the influence fatigue can have on running biomechanics and the PCS.

2.3 GAIT CYCLE AND THE INFLUENCE OF OFF-ROAD GROUND SURFACES

Understanding the Gait Cycle

The biomechanical movements associated with walking and running are characterized by a series of cyclical joint motions that together, form a pattern of movement known as a gait cycle (Lohman III et al., 2011). For both walking and running, respective phases and noteworthy points in time are identified within each gait cycle (Bartlette and Kram, 2008). At face value, the tasks of walking and running appear seemingly straightforward when understood as a bipedal locomotive method of moving from point A to point B. However, these tasks are complex and require constant and immediate readjustments in order to maintain stability in motion (Kharb et al., 2011). Walking and running gait can be influenced by numerous factors (anatomy, ground surface, environmental conditions or the intended outcome of movement) that could disrupt the economy of movement (Novacheck, 1998). The following section explores the existing literature regarding walking and running gait and secondly, highlights the effect of off-road ground surfaces and elevation changes on running gait and biomechanics.

It is vital to have a thorough understanding of both walking and running gait in order to prevent acute and chronic injuries as well as correct major gait discrepancies for the purpose of improving running efficiency and performance. Walking and running should be understood as natural progressions and regressions from one another when the velocity of movement exceeds 2.3m/s (Bartlette and Kram, 2008). Bipedal locomotive gait intuitively adjusts between walking and running in response to environmental factors (such as ground surface, elevation and temperature) and intrinsic physiological factors (such as exhaustion, dehydration and muscle soreness) to ensure locomotion is as biomechanically comfortable as possible. Kharb et al. (2011) define a gait cycle, in terms of walking bipedalism to be the time interval between two successive gait events. The *event* refers to the period between one foot coming into contact with the ground and the same foot making ground contact again. (Kharb et al., 2011; Novacheck, 1998). This allows us to understand the gait cycle for both walking and running as the period between two successive moments of initial contact of the same foot.

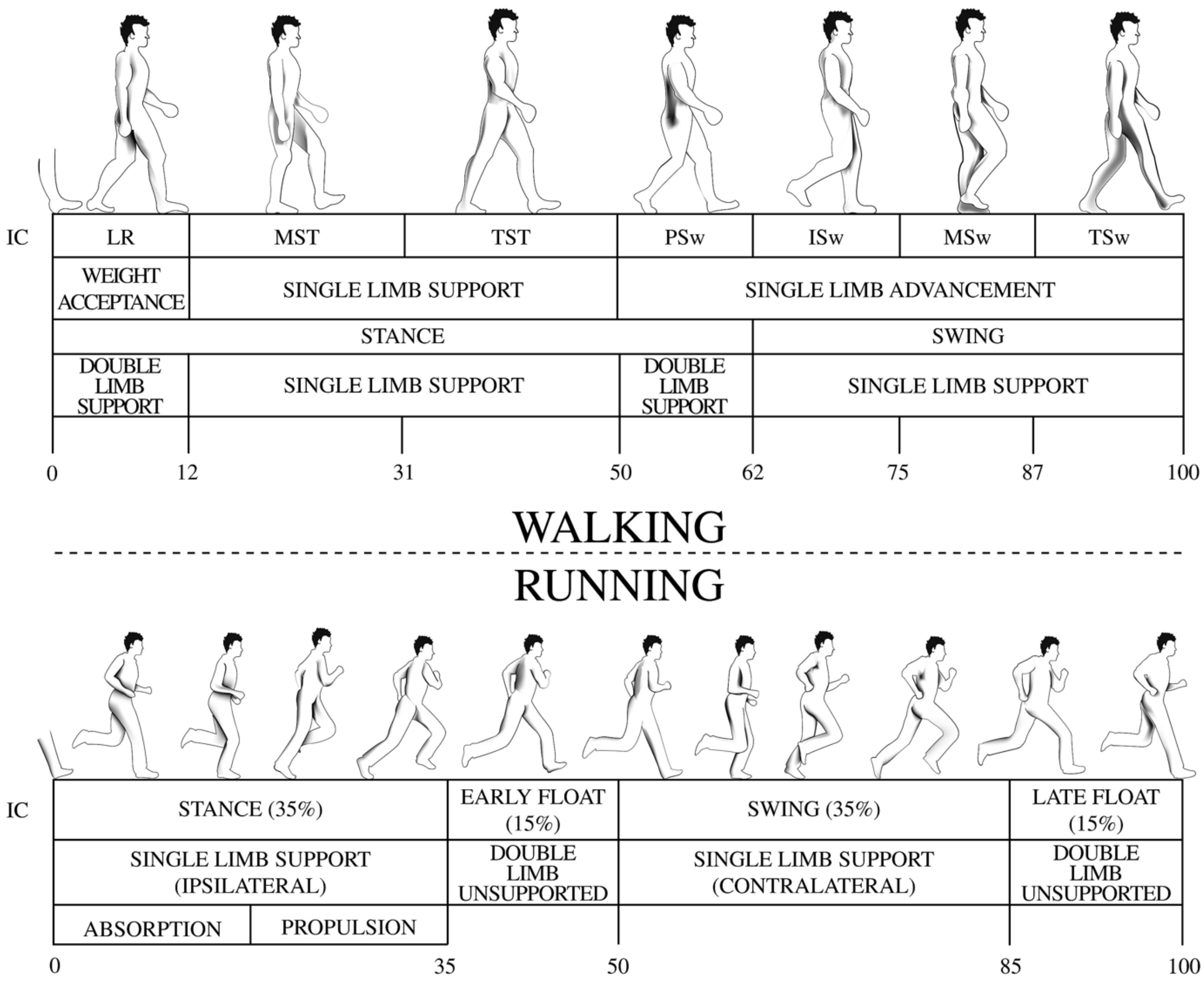
Walking Gait

Human bipedal walking gait walking is divided into two main phases: (1) the stance phase and (2) the swing phase (Novacheck, 1998). These two phases can be further divided to account for seven periods of time, where the stance phases consist of four periods and the swing phase consists of three periods (Kharb et al., 2011). *"Stance"* is the term given to the instance within the walking gait cycle in which a foot is in contact with the ground, providing support and stability for the initiation of the next phase (Lohman III et al., 2011). Stance, as well as the beginning of the walking gait cycle, starts with initial contact of a lower limb with the ground (i.e. the point when the heel first makes contact with the ground). The periods within this phase are: (1) loading response (2) mid stance (3) terminal stance (4) pre-swing. *"Swing"* refers to the moment in time when the non-supporting limb is in the air for the purpose of limb advancement (i.e. the next step forward) and consists of the three remaining periods that complete a full gait cycle: (5) initial swing (6) mid-swing (7) terminal swing (Kharb et al., 2011). A primary characteristic of walking is the presence of a double support phase. This means that within *"stance"* there is a moment in time when both feet are in contact with the ground at the same time. This primary characteristic of walking is also the major differentiating factor between walking and running, where the periods of double support are replaced by moments in time called a *“float phase”* where neither limb has contact with the ground and is initiated by an increase in velocity of movement (Lohman III et al., 2011; Kharb et al., 2011; Novacheck, 1998).

Running Gait

A running gait does not differ in terms of its cyclic starting point and shares the definition with that of a walking gait, which sees a gait cycle (walking or running) as the time interval of initial contact on one foot through to the time this foot makes contact with the ground again. Although similar in periods and events, running gait is primarily associated with a *“float phase”* as well as more time spent within the swing phase as velocity increases (Novacheck, 1998). The phases within running are as follows: (1) stance phase (2) early flight (3) swing phase (4) late flight (Lohman III et al., 2011).

Following initial contact of the right heel, the right lower limb immediately enters a period of single-leg support within the stance phase. Here the knee, ankle and hip joint perform two biomechanical tasks in order for the current forward momentum to be maintained (Novacheck, 1998). First, there is a need to absorb the downward force of impact upon initial contact and second, to effectively coordinate muscular contractions in order to control downward force absorption (eccentric muscle contraction) and then to immediately propel the body, and opposite limb forward into the next phase of gait (concentric muscle contractions) (Lohman III et al., 2011). The phase proceeding stance phase is called the early flight phase. This is where forward momentum propels the stabilizing lower limb into the air through the toe-off period of the right foot (Novacheck, 1998). At the same time, the opposite lower limb (left leg) is at the final stages of terminal swing and for a short period, both lower limbs are in the air with zero contact with the ground (Lohman III et al., 2011). The right lower limb now enters the swing phase as the left lower limb makes contact with the ground and becomes the new stabilizing single limb. As the right lower limb leaves the ground, the same propulsion function performed by the knee, ankle and hip joint of the first stance phase acts to lift the body into the final



phase of the gait cycle. The late flight phase occurs as the left lower limb enters its second float phase and the body prepares to absorb another round of downward force. As the right lower limb makes contact with the ground once more, a full running gait cycle has been completed and can now repeat itself many times over (Lohman III et al., 2011). The walking and running gait cycle are illustrated in Figure 2.1 below.

Figure 2.1: Schematic representation of the phases of the walking and running cycles with special attention to the presence of double float in running: Initial Contact (IC), Midstance (MSt), Terminal Stance (TSt), Pre-swing (PSw), Initial-swing (ISw), Mid-swing (MSw), and Terminal-swing (TSw). With permission from Lohman III, Sackiriyas and Swen (2011).

The Effect of Velocity on Gait

Velocity directly influences the proportion of time spent in each phase of the gait cycle (Lohman III et al., 2011). The following running statistics are based off a pace of 6.5m/h regarded as “training pace”, however, these numbers will almost certainly vary between individuals (Lohman III et al., 2011). If the walking gait cycle is taken as a reference of comparison, literature highlights that the stance phase makes up about 60% of the cycle, with the double stance phase accounting for 10% of that amount. Thus, the swing phase accounts for the remaining 40% (Kharb et al., 2011). When examined in terms of ratios, stance-to-swing ratios of walking is said to be approximately 62:38, thus substantiating the percentages suggested by Kharb et al. (2011) (Lohman III et al., 2011). It is understood that for running to commence, velocity needs to increase to a point where it is no longer physiologically efficient to maintain a walking movement. When this occurs, locomotive biomechanics adapt to accommodate the change in velocity and a running gait is initiated. The stance-to-swing ratio now becomes 35:65 with less time spent within the stance phase and more time spent in the swing phase (Lohman III et al., 2011). As previously mentioned, the primary difference between walking and running is the double stance/support phase while walking being replaced with a float phase during running. Early and late float take up approximately 15% of the entire gait cycle respectively while stance and swing phases account for 35% of the remaining gait cycle (Lohman III et al., 2011).

Several spatiotemporal variables are also influenced by an increase in velocity which all affect the speed and overall gait duration (Dugan and Bhat, 2005). The following terms are important to understand exactly *how* velocity increases: (1) cadence, (2) stride length, and (3) step length (Dugan and Bhat, 2005). Cadence is described as the number of steps per unit of time (usually recorded in steps per minute, while stride length is the distance covered between two successive initial contacts of the same foot and finally, step length is measured as the distance between initial contact of the one foot and the following initial contact of the opposite foot (Dugan and Bhat, 2005). In terms of answering the question of *how* velocity is increased, it is understood that velocity increases when step lengths increase which is followed by an increase in cadence. As these adjustments take place, and velocity increases, more time is spent in the float phase. Step and stride lengths are a function of anatomical leg length and total height, with the relationship seen to be between the ability to increase these lengths proportionally to an increase in velocity. (Dugan and Bhat, 2005)

With sufficient knowledge of the locomotive mechanisms underlying both walking and running gait cycles, it is possible to further explore how running surfaces can influence gait cycles, causing possible disruptions in running biomechanics, the importance of the postural control system in regulating sensory inputs in order to facilitate anticipatory responses to postural disruptions, and the implications of fatigue on all of the above.

2.4 THE NATURE OF TRAIL RUNNING

Research shows that TR and TR events (distance and duration dependent) place a considerable amount of stress on the body that inevitably leads to acute neuromuscular fatigue, subsequent decrements in muscular performance and impaired regulatory functioning of the PCS (Paillard, 2012; Degache et al., 2014). Uneven ground surfaces present the need to overcome frequent environmental disruptions. However, it appears that PCS could be sceptical to fatigue and thus, factors such as incline variability could contribute to a decreased processing ability of the PCS to facilitate various sensory inputs in a fatigued state.

Ground Surface Variability

Simply through its definition, we learn that the environment in which TR takes place presents a host of challenges in the form of different ground surfaces (Easthope et al., 2010; Scheer et al., 2018). Trail running literature offers several descriptive terms which are used to describe the type of ground surfaces that are associated with TR and TR environments. The most recent literature describes TR terrain to be natural environments (dirt roads, forests and beach sands for example) with environmental locations that can vary from mountains to grassy plains and even deserts (Scheer et al., 2020). Various other TR literature outline ground surfaces (or terrain), where all share common descriptive factors that point in the direction of an agreed-upon universal language of all aspects relating to trail running: *"…Rough terrain."* (Scheer et al., 2018, pg.6); *"…rocky and root-covered…"* (Ehrstrom et al., 2017, pg.580); *"…mountain, dessert or forest…"* (Malliaropoulos et al., 2015, pg.52); *"… mountain trails…"* (Degache et al., 2014, pg.2); *"… unstable ground…"* (Degache et al., 2019, pg.8).

Over recent years, literature on the effect of varying ground surfaces on human biomechanics has begun to increase (Schutte, 2016). There appears to be a consensus that highlights the fact that uneven ground surfaces have a number of different impacts on human bipedal locomotion. Firstly, uneven running surfaces have been reported to lead to greater energy expenditure when compared to that of smooth surfaces running (Voloshina and Ferris, 2015):

The reason behind increased energy expenditure when running on natural surfaces is multifaceted, however, literature points towards two primary factors namely, disruptions in muscle activation patterns and mechanical factors. For example, research conducted on the effect of uneven terrain on various biomechanical variables found that running efforts on sand led to overall greater muscle activity in the lower limbs as well as greater hip and knee motion when compared to running on hard, smooth ground surfaces (Voloshina and Ferris, 2015; Schutte, 2016). It is thus clear that with uneven ground surfaces comes disruptions in running gait caused by the need to constantly adjust step parameters in order navigate these types of surfaces. This leads to the second significant finding based on the work of Grimmer et al. (2008) and Voloshina and Ferris (2015): running on uneven terrain causes changes in step parameter variability and thus, contributes to the larger energy expenditure associated with running on uneven ground surfaces. Despite the literature reporting no significant changes in mean step parameters (step width, length and height) when running on uneven surfaces, significant changes were observed in step variability of the same parameters while running on uneven surfaces.

The above changes in step parameter variability could be regarded as regulating factors in the maintenance of lateral stability while running. More specifically, humans tend to adjust step width in order to minimize a shift in lateral stability while walking on uneven surfaces and the same strategy has been proven to be present in running (Voloshina and Ferris, 2015). This strategy is more relevant to biomechanical adjustments due to incline variation and will be further explained in the following section.

It appears that trail runners are subject to numerous challenges stemming from ground surface variability which leads to greater energy demand and energy expenditure when compared to that of the smooth surfaces associated with RR. Uneven ground surfaces place a higher demand on the PCS in terms of facilitating various sensory inputs in a way that ensures safe progress over such terrain. This, together with an energy expenditure associated with subsequent biomechanical adjustments, leads one to consider the impact of increased physiological requirements on PC regulation on uneven ground services. Furthermore, gradient variability and the presence of obstacles form two key challenges that have the potential to disrupt and decrease the efficiency of PC facilitation.

Incline Variability

The geographical environment associated with trail running presents another challenge to those who choose to traverse the hills and mountains on off-road paths. Almost all authors who report on literature within the field of TR highlight the substantial variations of incline and decline as a noteworthy difference when comparing TR to that of RR, which is often associated with predominantly level running (LR) surfaces (Hoffman et al., 2010; Easthope et al., 2010; Degache et al., 2014; Malliaropoulos et al., 2015; Baiget et al., 2018; Svenningsen et al., 2019; Scheer et al., 2020). As the popularity of TR continues to increase, so too is the research into graded running within TR and how uphill (UR) and downhill running (DR) biomechanically and physiologically affect trail runners. For industry professionals within the field of TR, it is of the utmost importance to have a thorough understanding of the influence of graded running and its impact on the body in order to effectively guide/advise athletes in a way that will improve performance while decreasing the risks of overuse injuries (Degache et al., 2019). Vernillo et al. (2016) substantiate the importance of this, with specific regard to trail running (inclusive of all distances) by highlighting that to further understand the control of human locomotion, studying the physiological and biomechanical changes associated with running on different gradients can provide insight into how locomotive behaviour is regulated as a response to incline variability.

Changes in inclination mean that TR athletes are subject to undulating periods of UR as well as DR. Uphill running and DR lead to biomechanical adaptations that require the coordination of complex strategies in order to maintain running efficiency with TR (Vernillo et al., 2016; Willis et al., 2018; Lemire et al., 2020). However, regardless of the strategy, there are specific biomechanical and physiological adaptations to graded running that appear inevitable. Uphill running is primarily associated with concentric muscle contractions and has been shown to cause an increase in step frequency, longer ground contact time and thus extended time spent within the stance phase; requiring greater net mechanical work in order to increase the body's potential energy, thus requiring greater power output of hip and knee joints (Vernillo et al., 2016; Lemire et al., 2020). Furthermore, the velocity of movement during UR is considerably lower than during DR, however, requires a substantially greater metabolic cost in terms of energy output (Lemire et al., 2020).

Although UR requires greater overall mechanical work, the acute neuromuscular fatigue following UR is less than that of DR (Ehrstrom et al., 2017). This is due to the lower limbs being subjected to repetitive eccentric muscle contractions and increased ground reaction forces during DR compared to UR or LR (Biaget et al., 2017). The prolonged concentric and eccentric muscle actions that take place during uphill running (UR) and downhill running (DR) have been known to lead to large decreases in locomotive efficiency, characterized by reduced maximal voluntary contractions, decreases in electromyogram (EMG) activity as well as increases in muscle contraction time (Easthope et al., 2010). Fatigue during UR is typified by failures in excitation-contraction of related concentric muscles (Ehrstrom et al., 2017). However, eccentric actions during DR elicit greater fatigue than uphill running with a >15% decline in maximal voluntary contractions in plantar flexor and/or leg extensor muscles (Ehrstrom et al., 2017). Lemire et al. (2020) provide a further explanation into DR-induced fatigue could be primarily related to a combination of local muscle perturbations altering muscle contractibility and/or the lower-limb muscle complex falling under machinal loads that could lead to substantial muscle damage (Lemire et al., 2020).

The effect of acute neuromuscular fatigue on biomechanical and physiological factors associated with human locomotion (specifically TR) will be discussed later in this section and for the purpose of the current section, the focus will remain with that of UR and DR. Depending on the gradient and technicality of ground surfaces, DR sees an increase in movement velocity compared to UR and in turn leads to reduced ground contact time, increased flight time, reduced step frequency and a progressive shift from a mid-to-fore foot strike pattern to a rear-foot strike pattern as the angle of declination increases (Vernillo et al., 2016; Willis et al., 2018).

As one begins to comprehend the complexity of TR, a thought must be cast in the direction of the problem statement of this thesis. There appears to be an overwhelming responsibility placed upon the postural control system (PCS) to attend to the constant environmental disruptions where the primary task is maintaining upright stability. This becomes an increasingly more difficult task with prolonged activity inducing acute neuromuscular fatigue, affecting everything from locomotive efficiency to the overall PCS.

2.5 FATIGUE

Fatigue, in its multifaceted entirety, is remarkably complicated due to the wide variety of contributing factors as well as its definitive progression within literature over the past 10 years (Millet et al., 2011; Twomey et al., 2017).. Thus, this section will aim to thoroughly unpack all relevant aspects of fatigue before integrating the topic of fatigue with TR. Based on some of the earliest fatigue-focused literature, the term *fatigue* was explained as a single-layered entity, describes as the inability to maintain enough muscular force required to complete a certain task (Twomey et al., 2017). However, as scientific research into fatigue began to progress, we learn that the term *fatigue* is extremely complex and requires a far deeper understanding. A commonly accepted definition for the general term *fatigue* is put forth by Twomey et al. (2017, pg.97) to be, "…*any exercise-induced reduction in the ability of a muscle to generate force or power, reversible by rest"* thus highlighting, *"…a circumstance where less than the anticipated contractile response is obtained, which is sensitive to progressive changes in muscle contractile properties in that it incorporates a reduced force at low stimulation frequencies…"*

For the purpose of this thesis, it is important to note that the focus will be solely that of acute neuromuscular fatigue and will be defined with regard to the contributing factors as a whole. It is important to note that the magnitude and aetiology of fatigue is task-dependent (Millet et al., 2011a; Millet et al., 2011b). Furthermore, the task under consideration contains several critical task variables, all of which will influence the magnitude and aetiological classification. Such variables include: (1) the type of muscle group involved, (2) the muscle activation pattern, and (3) the type of muscle contraction. Additionally, the two primary factors holding an umbrella-like influence over TR is the intensity and duration of such activity (Millet et al., 2011a).

Acute neuromuscular fatigue is well documented in literature and has been defined in several ways, with the common factor stemming through the origin being *exercise-induced*, where exercise-induce fatigue is understood as:

In a study conducted by Millet et al. (2011a), where the purpose was to investigate the neuromuscular consequences associated with extreme-distance trail running, the study provides a basic description of neuromuscular fatigue to be, a decrease in maximal voluntary force of a muscle or muscle group brought on by initiated by exercise. Furthermore, it is highlighted that neuromuscular fatigue could involve processes related to all levels of motor neural pathways between the brain and muscle (Millet et al., 2011b). This definition is in accordance with several other studies regarding the explanation of neuromuscular fatigue (Byrne et al., 2004; Babault et al., 2006; Schmidt, 2014; Twomey et al., 2017).

Upon further analyses, the above definitions all highlight several key aspects relating to “motor pathways”, “biological levels” and the fact that there appears to be a decrease in the efficiency in regulatory functions as fatiguing activities progress. Neurologically, neuromuscular fatigue is broadly categorized as having a peripheral and central component (Twomey et al., 2017). Peripheral fatigue is identified as the primary source of the reduction in muscular force output at the level of the active muscle (Piallard, 2012; Schmidt, 2014). This type of fatigue focuses on the process that occurs at a level lower than the neuromuscular junction that subsequently leads to deficits in neurological stimulation which precedes skeletal muscular contractions (Millet et al., 2011b; Schmidt, 2014; Twomey et al., 2017). From the time an action potential arrives at the motor endplates to the time of actual muscle contraction, a series of processes must take place. However, each component involved in these processes are potentially susceptible to fatigue (Schmidt, 2014). Measured through either electrical or magnetic stimulation of muscle fibres, scientists have been able to record neural stimulations to evaluate fatigue at a neurological level, where a decrease in the amplitude of stimulation has been regarded as the gold standard marker of peripheral fatigue (Twomey et al., 2017).

Central fatigue, fatigue sited above the neuromuscular junction, is defined similarly throughout fatigue-focused literature to be a progressive decrease in muscular voluntary contractions during a bout prolonged of exercise. (Millet et al., 2011; Schmidt, 2014; (Twomey et al., 2017). In simple terms, central fatigue is dependent on the mediation of peripheral afferents (Millet et al., 2011). In this regard, central fatigue can be viewed as the inability of the central nervous system to recruit motor units at the rate needed to perform a task due to a decrease in tetanic frequency discharge as peripheral afferents become subject to fatigue (Millet et al., 2011; Twomey et al., 2017). The concluding outcome is thus a decrease in maximal voluntary contraction which will continue to decrease as the duration of the activity increases (Millet et al., 2011; Schmidt, 2014).

Central fatigue appears to be dependent on more than peripheral afferents, highlighting the multifaceted complexities of fatigue. Research has shown that central fatigue is influenced by two additional factors: (1) environmental conditions, and (2) mental fatigue

(Millet et al., 2011). Environmental conditions such as hyperthermia and hypothermia, have the potential to exacerbate central fatigue or perceived exertion (Ramos-Campo et al., 2016). Additionally, we learn that fatigue extends beyond that of physiological decrements in regulation systems, but reaches a psychological level as well (Twomey et al., 2017). Psychological perception of fatigue on activity cessation could hold significant value in terms of how “mental toughness” affects endurance-based activities, however, this is not the focus of this thesis and will thus not be discussed further.

As previously mentioned, the aetiology of fatigue is task-dependent. For the purpose of this thesis, the *task* refers to a TR time trial of 26km (+900m). The environmental characteristics associated with trail running could play a role in the magnitude of exercise-induced acute neuromuscular fatigue when one considers the critical task variables which depict the said magnitude including: (1) the muscle group involved (2) the muscle activation patterns (3) the type of muscle contraction, without disregarding the factors of duration and intensity (Paillard, 2012; Millet et al., 2011a; Degache et al., 2019). The following section will explore the potential influence TR may have to elicit general neuromuscular fatigue.

2.6 THE NATURE OF TRAIL RUNNING AND FATIGUE

There is little doubt that TR presents a physical challenge to those athletes who participate in the sport. The challenge can be summarized to revolve around the management of external factors such as the terrain and internal factors such as hydration and nutrition. TR races are often associated with long durations and therefore, continuous repetitive activations of the same muscle groups, muscle recruitment patterns and stress imposed on the body via repetitive ground impacts over an extended period of time. The prolonged repetition of concentric and eccentric muscle actions that takes place during downhill and uphill running have been known to lead to decreases in locomotive efficiency, characterized by reduced maximal voluntary contractions, decreases in electromyography (EMG) activity as well as increases in muscle contraction time (Easthope et al., 2010). Fatigue during uphill running is typified by failures in excitation-contraction of related concentric muscles (Ehrstrom et al., 2017). However, eccentric actions during downhill running elicit greater fatigue than uphill running with a greater than 15% decline in maximal voluntary contractions in plantar flexor and/or leg extensor muscles (Ehrstrom et al., 2017). Notably, results within the above study were drawn from short TR races and highlighted a general decline in mechanical and physiological parameters related to trail running performance.

Endurance-based efforts are known to elicit physical stress on the body that leads to thermal stress, decreases in body fat mass, inadequate fluid and electrolyte balance and decrements in the efficiency of the stretch-shortening cycle (Baiget et al., 2018). The consequences of such decrements and imbalances have been shown to influence neuromuscular performance in trail runners with substantial decreases in jump test variables (maximum and mean jump height) following prolonged trail races varying from 2.5 hours to 7 hours respectively (Baiget et al., 2018).

Several researchers have highlighted the relationship between maximal force generation capacity and decreased post-race locomotive efficiency (Millet et al., 2002, 2003; Place et al., 2004). A 24% decrease in force was found after a 30km race, a 28% decrease following a five-hour treadmill run, and a 30% decrease after a 65km ultra-marathon (Easthope et al., 2010). These findings are consistent in trail running whereby a 37% decrease in maximal voluntary force was observed at the end of a prolonged trail run (Gauche et al., 2006).

There is little doubt in concluding that the environmental characteristics associated with the task of TR play a role in depicting the aetiology as TR-induced acute neuromuscular fatigue. Trail running and TR events are demanding, and have technical challenges in the path of those who choose to participate in the sport. It is now apparent that TR requires the interpretation, organization and regulation of different inputs in order to effectively traverse off-road trails (Svenningsen, 2019). This process is managed by a system that works to not only maintain upright dynamic stability, but to also guide anticipatory movements to environmental disruptions in running and walking tasks in order to maintain locomotive efficiency (Paillard, 2012; Baiget et al., 2018). The following section will explore postural control as well as how the PCS finds its place within the sport of TR.

2.7 POSTURAL CONTROL

Postural Control and the Postural Control System

Throughout literature, there appears to be a degree of overlap with regard to defining the concept of PC due to almost identical definitions of balance (including dynamic and static balance). Before identifying the distinguishing factors between the two, the first part of this section will put forward how balance and PC have been defined within literature.

According to Cetin et al. (2008, pg.16), balance is defined as:

"…the ability to maintain equilibrium in a gravitational field by keeping the body mass centered over its base of support."

The above description is in accordance with Hrysomallis (2011, p.222) who defined balance as:

"… the process of maintaining the body's center of gravity vertically over the base of support and relies on rapid, continuous feedback from visual, vestibular and somatosensory structures…"

Furthermore, balance can be divided into static and dynamic balance, where static balance is defined as the ability to maintain a base of support with as little movement as possible (Hrysomallis, 2011) and dynamic balance is said to be,

"… the ability to perform a task while maintaining or regaining a stable position or the ability to maintain or regain balance on an unstable surface" (Hrysomallis, 2011, pg.222).

In terms of PC, various literature report on the term's definition. Paillard (2011, pg.163) provides a layered definition of PC which first states that:

"Postural control is a complex function that involves keeping the vertical projection of the center of gravity (COG) within the base of support." before adding that PC is, *"a permanent re-establishment process of balance."*

Thus, inferring that the ability of balance is regulated via the functional process of PC. In terms of identifying differentiating keywords, Degache et al. (2019, pg.2) provides an opening description of PC to be*, "… a complex function…"* which falls in accordance with that of Paillard (2011).

In the field of sports science, the word "complex" can mean many things, however, in this regard, PC is identified as being complex due to the multifaceted responsibility of facilitating sensory inputs in order to manage the organization of the body. Furthermore, there is a need to coordinate joint proprioception and dynamic movement in order to initiate postural corrections as and when disruptions occur (Degache et al., 2019). Balance is viewed as the *ability* to maintain the position of the body's COG vertically over the base of support while it is reliant on various sensory inputs while PC is the organizational *function* which is responsible for the permanent process of re-establishing balance (Hrysomallis, 2011; Paillard, 2012). This thesis makes several references to *postural sway* and for the purpose of academic clarity, this term will be used to describe the degree of movement away from the body's centre of mass in various directions including anteroposterior sway and mediolateral sway (Paillard, 2012).

The maintenance of dynamic equilibrium is dependent on input from three separate, yet complimentary sensory sources: visual, vestibular, proprioception and somatosensory. Furthermore, PC is reliant on voluntary muscle responses and reflexes in order to maintain posture in both dynamic and static instances. Interestingly enough, all of the variables contributing to PC are influenced negatively by fatigue, with Degache et al. (2017) concluding that any decrement in sensory input or muscular contractile ability due to fatigue will lead to a decreased ability to maintain optimal balance ability. Here one is able to gauge an understanding of the interest regarding this thesis and the hypothesized importance of PC in endurance-based, off-road running.

With the above in mind, it is clear that a complex degree of organisation must take place in order to facilitate sensory and environmental inputs into movement adjustments within a very short period of time. The PCS is responsible for the above-mentioned facilitation and plays a crucial role in the maintenance of postural stability (Paillard, 2012). The PCS has two main functions : (1) to build up posture using a mechanical anti-gravity function as well as ensuring balance is maintained, and (2) it serves as a frame of reference for the perception and action of movements in relation to the external world (Maisson, 1994). In this regard, body segments such as the head, trunk, arms and lower limbs play a reference role in relation to the external environment which are used by the PCS as input references to accurately calculate targeted movements in the form of adjustments to postural disturbances (Maisson, 1994; Paillard, 2012). For the purpose of practical application and understanding of the PCS, the following section will explore this organization system with specific reference TR and the TR environment.

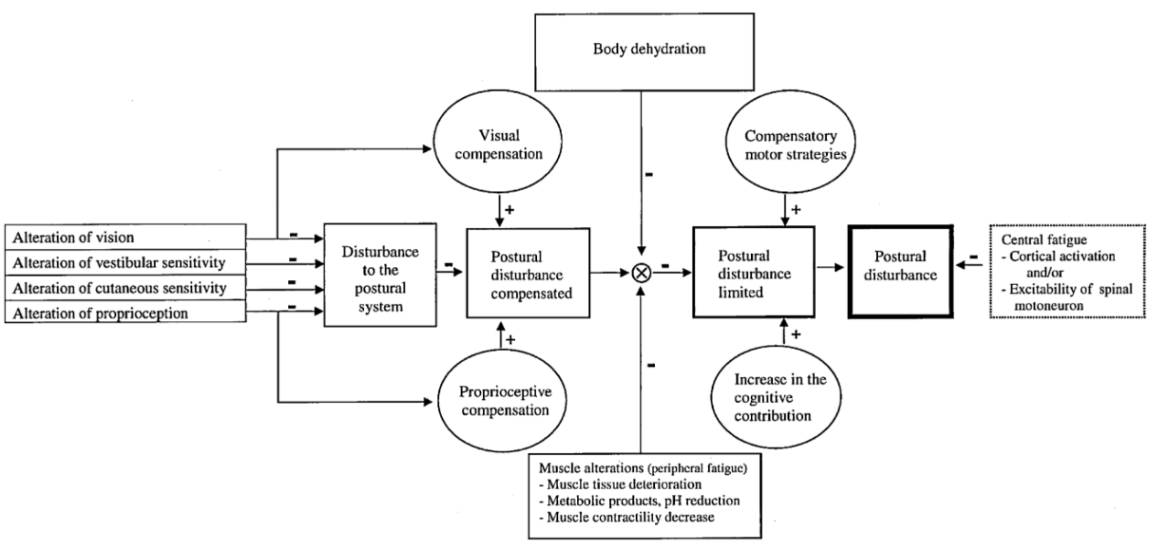


Figure 2.2 The process of the deterioration of postural control induced by general muscular exercise. Initially, postural alterations are compensated but, when certain physiological disturbances occur, the

compensatory effect no longer takes place (− indicates a disturbance; + indicates a compensation). With permission from Paillard (2011).

Regulating postural disturbances within trail running

Figure 2.2 above provides a graphical summary of the following section. The geographical locations in which TR takes place can vary, thus, presenting countless instances where natural obstacles cause disruptions in running gait and running velocity. There is a constant need for these obstacles to be identified and overcome in order for an athlete to safely and efficiently progress through the trail. Road running is well known to be associated with smooth terrains (asphalt) where possible terrain obstacles during RR races can be limited to a pavement step, or other runners (Hoffman et al., 2010). It is logical to assume that the PCS is under less stress during RR, excluding the influence of acute neuromuscular fatigue (distance specific), compared to a TR environment where terrain irregularities constantly disrupt running velocity and thus, running and walking gait spatiotemporal variables. It is understood that incline and ground surface variability place a greater demand on the biological functioning of the body and thus, a greater demand on the need to maintain a dynamic, upright stability equilibrium. Furthermore, it was found that any decrement in sensory input or muscular contractile ability due to fatigue will lead to a decreased ability to maintain optimal balance ability (Degache et al., 2017).

Central organization of the PCS begins via multisensory inputs from visual, vestibular and somatosensory feedback systems (Degache et al., 2019). These sensory inputs provide vital information to the PCS. For example, visual input could come in the form of observing a large rock in the path where a speed reduction and anticipatory movement adaptation could be necessary; a slip during initial contact of the foot on loose gravel could lead to a lateral tilt of the head and trunk, thus utilizing vestibular and joint proprioceptive input as to the orientation of these body segments; and finally, sensing an increase in temperature via somatosensory input could prompt a change in race strategy such as an adapted pacing strategy. As a collective, the various sensory inputs contribute to building up what is known as the body scheme (Massion, 1994; Paillard, 2011).

The body scheme is defined as an internal representation of the body (postural body scheme) that is not solely based on sensory inputs and incorporates body kinetics and kinematics together with proprioceptive orientation. (Massion, 1994). This internal representation is said to be the key to postural organization and is, *"…acquired by means of a learning process…"* (Paillard, 2011, pg.163). Guided via the two frames of reference (body segment orientation and over stability), this internally represented body scheme could be a major point of discussion should this thesis provide results showing superior balance ability among highly trained athletes. It begs the question of whether TR and time spent TR instils a separate, more stability-focused body scheme that is more tolerant of fatigue compared to those who do not participate in TR (i.e. predominantly road runners).

The nature of TR presents countless instances where an athlete will encounter a postural disturbance. A disturbance in posture thus needs to be interpreted in a way that sees compensation in movement adjustments where postural reactions overcome the disturbance and the PCS proceeds to interpret the next disruption. The end goal is to limit the magnitude of the disturbance on posture, where posture includes upright stability through balance ability, guided by proprioceptive inputs of changes in head, trunk and limb orientation where joint receptors in the lower limbs form the first point contact upon ground impact which is where the inputs originate (Paillard, 2011). Anticipatory postural reactions are the outcome of a successfully organized PCS where these reactions are understood to be, *"…elicited on the basis of sensory signals that indicate a disturbance of posture and/or equilibrium" – (Massion, 1994, pg.882),* that are known to precede the initial onset of a postural disturbance and thus minimize the magnitude of its potential influence. It is important to note that these reactions are initiated by voluntary movement of applicable joint segments during a time preceding a possible disturbance (Degache et al., 2019).

A practical application of this within TR could be the abducting of the arms to improve PC in preparation for a technical, single-track descent at a high velocity. The instinctive change in limb position acts as the voluntary skeletal movement in anticipation that the change in velocity and gradient will put the PCS under increased strain to facilitate the subsequent sensory inputs informing the body scheme of potentially high-risk scenarios (Dabbs and Chander, 2018). The inevitable flaw in the system is seen through the effect acute neuromuscular fatigue has on PC, measured via the degree of postural sway, where an increase in postural sway is identified as a decrease in balance ability which has been related to an increased risk of falls and related injuries (Dabbs and Chander, 2018).

To the best of our knowledge, there are few research publications that investigated the effect of fatigue on PC within trail running. These, however, focused on ultra-distance TR events and thus, no such investigation has been found to investigate the change in PC in a short TR and time-trial setting. Despite the lack of literature surrounding the focus of this thesis, the literature regarding TR and PC for longer distances presents sufficient groundwork for the investigation of the changes in PC for shorter TR distances. Nevertheless, it is noteworthy to highlight the key findings of these investigations to be able to provide sufficient understanding of the effect prolonged endurance TR events have on PC.

The most applicable publications are those conducted by Degache et al. (2014 and 2019), where the investigators investigated the alterations of PC throughout the world's toughest mountain ultra-marathon: the Tor des Geants. This mountain ultra-marathon is a 338.6 km race with a total of 30,914 m positive and negative elevation change (Degache et al., 2019). The study concluded the fact that the effectiveness of postural regulating mechanisms was impaired due to the impact of general muscular exercise on the musculoskeletal system (Degache et al., 2019). The authors describe the process of PCS deterioration to be multifaceted, including reasons revolving around metabolic activation, the type of muscle contractions, disturbances in sensory inputs and decrements in maximal voluntary muscle contractions (Degache et al., 2014; Degache et al., 2019). They observed a bi-phasic pattern of PC decrement insofar as PC variables significantly worsened in the first half of the race, but then returned almost to baseline values after the 200km mark. This bi-phasic pattern was attributed to compensatory strategies (e.g.

pacing strategies) that are said to have taken a primary position in the regulation of decrements in PC functioning.

These results forms the basis of the current thesis .There is no doubt that prolonged endurance events lead to significant decreases in PC due to severe acute neuromuscular fatigue, however, whether a short TR time trial (26km) will elicit significant changes in PC variables among a sample of highly trained trail runners is yet to be answered.

2.8 MEASURING POSTURAL CONTROL

The measurement and assessment of PC has evolved over time due to the availability of new technologies that provide more accurate measurements (Browne and O'Hare, 2001). Early research reports the use of observational tests where obvious variances in body sway were used to diagnose potential physiological disorders (Browne and O'Hare, 2001). The progression of PC assessments led to tests known as "simple field tests" where little to no equipment was needed, but valid and reliable results could be obtained (Panjan and Sarabon, 2010). More recent literature highlights the use of advanced equipment used to assess various aspects of PC such as Center of Pressure (COP) and sway (Millet et al., 2011a; Ramos-Campo et al., 2016; Svenningsen et al., 2019)

It is noteworthy to mention that PC is the umbrella term for the concept of maintaining stability where static and dynamic balance as well as proprioception fit under this umbrella. Thus, measurements of PC need to challenge all areas in which contribute to the PCS, meaning static and dynamic balance as well as proprioceptive ability should be tested via the manipulation of ground surfaces and conditions where visual feedback is prohibited (Browne and O'Hare, 2001; Svenningsen et al., 2019).

The measurement of postural control within literature is well documented (DiStefano et al., 2009; Hrysomallis, 2011; Ricotti, 2011; Svenningsen et al., 2019). However, there appears to be more literature available regarding PC in a clinical setting than that of athletic populations. Furthermore, the majority of existing literature is laboratory-based, where only a handful of researchers have attempted to measure PC in a field-based, real-world athletic population. This thesis set out to contribute towards this scarce body of literature (with specific regard to TR) in a way that was inexpensive and accessible to other researchers, coaches and athletes.

In terms of identifying which tests were best suited to measure PC in a sample of highly trained trail runners, there are several systemic literature reviews on this topic which provided guidance (DiStefano et al., 2009; Paillard, 2011; Svenningsen et al., 2019). A review by DiStefano et al. (2009) investigated specific academic questions relating to whether balance training might improve static and dynamic balance via the manipulation of ground surfaces. Of these articles, only three did not include test progression, where all others had some sort of change in visual feedback or ground surface manipulation. In terms of the nature of tests used, the respective methodologies varied from single limb stances to double limb stances where visual feedback was allowed and disallowed in the testing bouts as well as the ground surface altered (wobble boards, tilt board or foam mats) (DiStefano et al. (2009).

In addition to this, another systemic review was conducted on the methods of assessing balance ability and athletic performance in athletes of varying sports and competitive levels (Hrysomallis, 2011). Here, valuable information has been obtained regarding the type of balance assessed, the type of equipment used, the variables measured and the degree to which stance and eyesight are adjusted to effectively be able to measure PC. Whenever static balance was assessed, the use of equipment measuring sway and COP was incorporated to assess body movement around the centre of mass during different stances. Test timing for static balance tests was noted to be between twenty and sixty seconds per stance requirement and the protocols insisted on participants being barefoot for these tests (Hrysomallis, 2011).

Svenningsen et al. (2019) provide the most relevant insight into the potential measures used to assess dynamic stability in an outdoor setting. The authors provided a narrative review of how accelerometer measurements were quantified during tests that evaluated stability during dynamic locomotion. This thesis draws relevance from this systemic review based on the fact that a primary focus of discussion revolves around TR as an outdoor locomotive activity. Furthermore, this review provided additional insight into the scarce body of available literature pertaining to TR and dynamic stability. Several articles were relevant and deemed appropriate for the review of methods of measuring dynamic stability and TR (Svenningsen et al., 2019). It must be mentioned that this review evaluated methods of accelerometery use during locomotive activity (i.e. TR). This thesis only made use of an accelerometer during pre and post-testing due to the number of participants and limitations on available equipment in order to gain accurate measurements of static balance.

Postural control tests and measurements

Several standard tests exist for measuring and assessing different aspects of PC, each of which is common and popular in both sporting and clinical populations due to their multifaceted use, simplicity, cost-effectiveness and proven validity and reliability scores (Gribble et al., 2012). Measurements of PC vary in complexity, protocol, function and whether or not automated digital equipment is required or recommended (Panjan and Sarabon, 2010; Svenningsen et al., 2019). This section will explore how PC has been measured in literature thus far, highlighting a technological progression of digitalized equipment used to measure PC. PC is a complex ability, however, the tests and measurements of PC can be categorized into static and dynamic tests of balance ability.

Static balance tests

Modified Clinical Test of Sensory Interaction in Balance (MCTSIB) and Single Leg Modified Clinical test of Sensory Interaction in Balance (SLMCTSIB)

As previously mentioned in this chapter, the nature of TR poses many possible scenarios where postural disturbances can impede on sensory feedback. Therefore, inclusion of the MCTSIB is widely appropriate since the test requires individuals to maintain a static pose in different conditions which challenge the very sensory inputs that are so vital to PCS organization.

The MCTSIB test has been utilized to analyse static balance ability in populations varying from healthy elite athletes within several sporting codes to non-athletic elderly individuals (Hammami et al., 2014; Antoniadou et al., 2020). The MCTSIB protocol requires the use of a device that has the capability to measure variables of postural sway. The existing literature on the MCTSIB highlights two main types of devices commonly used to measure postural sway: firstly, the use of pressure platforms where COP platforms measure variations in pressure profiles to calculate aspects of postural sway and secondly, the use of wearable inertial measurement units (IMU) where tri-axial accelerometery identifies COM variability during testing (Hammami et al., 2014; Forza and Edmundson, 2019 and Antoniadou et al., 2020). Technological advances have led to the development of small IMUs to be strapped to the individual for use during static and dynamic testing instances, allowing researchers to obtain real-time information on movement variations in tests measuring anything from static balance to gait variables. This has allowed researchers to further their reach in terms of field-based testing in a way that is non-intrusive, affordable and easy to use.

A research study by Hammami et al. (2014) investigated static balance ability among different elite sporting codes where the purpose was focused around comparing static balance ability between elite sprinters, rugby players and jumpers with a secondary purpose of analysing the degree of visual dependence among these athletes. The study revealed that no significant difference in static balance performance was found between the sprinters and jumpers, however, there was a significant difference when these two sports were compared to that of the rugby players. The research study linked superior balance ability among rugby players to the fact that rugby is a contact sport where players are tasked with maintaining equilibrium while being tackled and influenced by their opposition. Furthermore, they describe the nature of rugby to have a high degree of visual dependence, but that the need to constantly pre-scan the immediate environment could be a contributing factor to superior balance ability via increased speed of sensory input organisation (Hammami et al., 2014).

In addition to this, the results of the above research study pose an important question of whether or not training status and sporting experience are primary contributing factors to superior balance performance. Furthermore, whether greater exposure to sport-specific environments is considered to be beneficial to superior balance ability due to repetitive and similar training experiences or if certain individuals have a more sensitive proprioceptive and vestibular system than others, regardless of training status. This topic of discussion will be outlined in detail within the research article in chapter four of this thesis. It is important to note that to the best of our knowledge, there is no available literature which compares the balance ability of trail runners to other sporting populations.

Dynamic balance tests

Star Excursion Balance Test (SEBT)

The SEBT is a simple yet effective functional screening tool that is used to assess single-limb dynamic stability, monitor the rehabilitation process following lower-limb injuries and identify athletic individuals who may be at risk of lower-limb injury (Filipa et al., 2010). This test requires the assembly of several neuromuscular characteristics such as lower limb coordination, flexibility and strength. Thus, the SEBT has been widely used by practitioners because it requires little equipment, is cost-effective, is mobile and holds strong validity and reliability among research conducted on athletic populations (Sabin et al., 2010; Gribble et al., 2012 and Keith et al., 2016).

The most recent literature regarding the use of the SEBT within athletic populations is courtesy of Stiffler et al. (2021), where different sporting codes were recruited for the purpose of determining whether or not dynamic stability performance differs between both sex and different sports. The study concluded that dynamic stability performance differs between men and women and found that ability varies between the different sporting codes. A key application consideration stated that due to the varying sport-specific movements and requirements, the process of injury identification should be interpreted within the context of the respective sport (Stiffler et al., 2021). Despite the fact that this study did not include a running population, it did include sports such as soccer, basketball and hockey which incorporate the basic gait requirements associated with running. Furthermore, this study provides justification for the use of a simple dynamic balance test within an athletic population while simultaneously highlighting its sensitivity in measuring lower-limb dynamic stability.

Trail running often requires postural adjustments that can occur on a single limb, where the adjustment motion sees manipulation of one's centre of mass around a single-stance support base in order to maintain an upright, dynamic equilibrium during locomotion incorporating a flight phase. Gribble et al. (2012) described dynamic PC as involving some level of an expected movement around a base of support. During TR, gait adaptations in the form of adjusted stride length and frequency are not always expected, however, the interpretation of off-road surfaces could allow for some level of anticipated postural adjustment around either a single or double-limb base of support. It is in this regard, that the use of a dynamic balance test such as the SEBT holds an appropriate level of use within this thesis.

The inertial measurement unit and accelerometer

The Inertial Measurement Unit (IMU)

The use of IMUs for research purposes dates back many years, where the use of such devices was primarily used for the orientation of automotive machinery as well as for aircraft navigation (Jarchi, et al., 2018). However, recent technological advancements have led to the progression of IMUs in a substantially larger field of use, including that of human biomechanics. Noteworthy advancements include that of microelectromechanical systems, which have drastically reduced the cost of these devices, their size, as well as where and when they can be used (Jarchi, D. et al., 2018). Found within IMUs, are several types of sensors which contribute to various measurements of movement and velocity of this movement. An accelerometer is one such sensor found within an IMU and can be understood as a sensor that calculates the acceleration of objects in motion along directional axes (Yang and Hsu, 2010). Different IMUs are capable of measuring motion along a different number of axes. When an accelerometer is able to measure one variable across three or more axes, then it is regarded as a tri-axial accelerometer and fulfils the accepted gold standard of motion measurement: 3D motion analysis (Yang and Hsu, 2010; Forza and Edmundson, 2019). Thus, certain IMUs are more applicable to what the respective research has set out to measure. This thesis set out to measure PC within an athletic sample of trail runners, therefore the decision of which IMU to use was simplified through the criteria of affordability, accessibility and accuracy of measurement.

The Gyko IMU (Microgate, Italy)

Developed by Microgate (Italy), the Gyko IMU has been developed to accurately obtain information regarding the kinematics of motion of any body segment as it performs a physical movement. This IMU contains a tri-axial accelerometer, gyroscope and magnetometer with the ability to record at up to 1KHz (Forza and Edmundson, 2019). Regarding the basis of Gyko data recording and measurement, complex software algorithms are used to describe the kinematics of the chosen body segment in motion. Furthermore, this software allows for immediate feedback on variables associated with PC as well as the quality of execution for a specific physical movement based on such variability.

The Gyko IMU (Microgate, Italy) is becoming more and more popular in research involving athletic populations due to its convenient size and accuracy of measurement (see Table 2.1 below). Literature by Forza and Edmundson (2019) identifies the use of the Gyko IMU on athletic sample groups including volleyball and rugby. In addition to this, Hatchett et al. (2018) provide valuable insight into the use of accelerometers in evaluating gait symmetry, PC and stride angle among a sample of runners. Furthermore, the Gyko IMU (Microgate, Italy) is documented to be effective in measuring jump height within athletics populations, where the device was used to measure maximal and mean jump heights for the countermovement jump test (CMJ) (Lesinski, Muehlbauer and Granacher, 2016; (Forza and Edmundson, 2019).

Table 2.1 Gyko Accelerometer Technical Data Sheet (Microgate, Italy). Source: *Gyko RePower User Manual Version 1.1.1.10*

Weight	46g, battery included
Dimensions	73 x 51 x 23mm
Operating temperature	0-45 degrees Celsius
Processing Unit	ARM 32 bit microprocessor
Sampling frequency	10Hz – 1KHz
Radio transmission	Bluetooth 4.0

Validity and Reliability

IMU and Accelerometer

As previously mentioned, the “gold standard” for measuring human movement is 3D motion capture (Cole et al., 2014). Certain data recording instruments are required to achieve this type of motion capture ability. Modern IMUs contain accelerometers which quantify human movement using accelerometery. Accelerometery can be described as the quantification of human movement through the evaluation of acceleration sequences during specific movement tasks (Kavanagh and Menz, 2008). These devices can generate large amounts of data which can be used to evaluate movement patterns such as gait cycles, as well as trunk movements for the evaluation of stability and postural sway (Jarchi et al., 2018). Several researchers have investigated the validity and reliability of IMUs and accelerometers, however, literature by Cole et al. (2014) appears to be the most appropriate in relation to this thesis. The researchers investigated the validity of a wireless accelerometer in measuring trunk accelerations over three different ground surfaces. Their sample consisted of young individuals as well as more mature individuals, who were tasked with walking on different surfaces at their pace of choice respectively

(Cole et al., 2014). The research study was able to draw two major conclusions from the results: firstly, that the IMU device can accurately measure trunk accelerations and secondly, that the IMU is an appropriate piece of equipment for measuring acceleration variables within healthy populations (Cole et al., 2014).

There appears to be a significant lack of literature available regarding the use of IMUs within a TR population for the purpose of measuring postural sway, however, there are several authors who have incorporated the use of IMUs for the purpose of testing sway variables in both young, athletic populations as well as the more mature populations (Jaworski et al., 2020). The most recent literature on this topic is courtesy of Jaworski et al. (2020), who examined a sample of twenty-nine healthy, individuals for the purpose of analysing absolute and relative reliability for several static postural stability variables using the Gyko IMU. The tests required participants to stand on one foot, with their eyes open and arms relaxed at their side for thirty seconds. The test and retest were of identical protocols, with the retest taking place one week after the baseline testing (Jaworski et al., 2020). This study concluded that there was moderate to good reliability on all static stability variables measured, with intraclass correlation coefficient (ICC) values ranging from 0.62 to 0.70 (Jaworski et al., 2020). Furthermore, in terms of the IMU device itself, the authors were able to conclude that the IMU device was both cost-effective, mobile, and highly reliable for measuring PC. Furthermore, it was stated that the IMU device can be a reliable alternative to stabilographic platforms (Jaworski et al., 2020).

Another recent study investigated whether the Gyko IMU could be an accurate and appropriate alternative to the widely accepted contact mat method (Forza and Edmundson, 2019). The study's sample consisted of ninety-six participants where fifteen of these participants were female athletes who participated in various sports such as gymnastics, fencing, volleyball and swimming. The remaining eighty-one participants were male athletes from different sporting backgrounds including rugby, soccer, water polo, handball, skiing and breakdancing (Forza and Edmundson, 2019). All participants were required to complete three jumps including a countermovement jump, squat jump and Abalakov jump. Jump height was measured by the Gyko system and the Chronojump

Contact Mat (Criterion device). The study found that when compared to the Chronojump Contact Mat, the Gyko IMU identified no significant systematic bias for mean jump height of all jumps (Forza and Edmundson, 2019). Thus, a conclusive finding was that the Gyko inertial sensor can be used interchangeably with the Chronojump Contact Mat and furthermore, that the Gyko IMU is sensitive in its measurements of jump height within an athletic population (Forza and Edmundson, 2019).

Further justification regarding the validity and reliability of the Gyko IMU (Microgate, Italy) within athletic populations is found in the research by authors, Hatchett et al. (2018). Their research analysed the effect of a curved, non-motorised treadmill, various gait variables as well as variables relating to imbalance or gait asymmetry. Postural control was measured via the Gyko IMU (Microgate, Italy) where its validity and reliability had been initially confirmed before their own statistical analysis further proved this point of use within an athletic population. For all variables measured, the degree of imbalance was statistically significant between trials comparing a standard treadmill with that of the curved treadmill where $p < 0.001$ and $p < 0.007$ respectively (Hatchett et al., 2018).

Star Excursion Balance Test

The SEBT is well documented in literature to be both a valid and reliable test of dynamic stability within athletic populations (Sabin et al., 2010; Gribble et al., 2012; Keith et al., 2016; Powden et al., 2019). Furthermore, there is evidence to suggest that poor balance ability can be a predicting factor of lower extremity injury. Research by Plisky et al. (2006) reported that in a sample of youthful boys and girls participating in basketball, those who displayed limb differences in the SEBT were 2.5 times more likely to develop a lower extremity injury during the basketball season. The SEBT is a popular test for examining dynamic PC since it requires very little equipment, is relatively cheap to execute and holds excellent validity and reliability scores for measuring dynamic PC (Sabin et al., 2016). Thus, the use of the SEBT runs parallel with the theme of this thesis insofar as highlighting a focus on the accessibility of accurate tests of PC.

In a study conducted by Olmsted et al. (2002), a sample of twenty individuals with chronic ankle instability and 20 uninjured individuals completed the SEBT as test of lower extremity stability for the purpose of identifying whether or not the SEBT was sensitive in detecting stability deficits in individuals with chronic ankle instability. Through group comparisons, the study was able to conclude that those with chronic ankle issues obtained significantly shorter reach distances than the uninjured group (78.6cm vs. 82.8cm; $p<0.05$). Thus, reiterating that the SEBT is a simple, inexpensive, and reliable test of dynamic stability.

Additionally, research completed by Gribble et al. (2012) in the form of a literature and systemic review, provided an in-depth summary of the existing literature that has used the SEBT either to assess dynamic stability or as an injury predictor. Below are extracts from the findings relating to studies using the SEBT to differentiate pathologic lesions regarding chronic ankle stability

Table 2.2 Review summary literature examining the ability of Star Excursion Balance Test to differentiate pathologic conditions: Ankle Instability

Authors	Main Comparison	N	Leg Length Normalized?	p-value	Effect size (95% CI)
Akbari et al., 2006	Injured limbs and uninjured limbs	30	No	0.03	0.19
Gribble et al., 2004	CAI-IS and CAI-US (ANT; MED; POST)	15	Yes	ANT=0.03 MED=0.02 POST=0.01	ANT=0.53 MED=0.39 POST=0.20
Hale et al., 2007	IS and US (POSTMED; POSTLAT; LAT)	29	Yes	POSTMED=0.47 POSTLAT=0.07 LAT=0.03	POSTMED=0.29 POSTLAT=0.38 LAT=0.44
Nakagawa and Hoffman, 2004	CAI and control	36	Yes	0.01	0.55

N: sample size; p: significance value; CI: confidence interval; CAI: chronic ankle instability; IS; injured side; US: uninjured side; ANT: anterior reach direction; MED: medial reach direction; POST: posterior reach direction; POSTMED: posteromedial reach direction; POSTLAT: posterolateral reach direction; LAT: lateral reach direction. (Source: Gribble et al., 2012).

2.9 SUMMARY

The theoretical context included in this chapter provides a comprehensive literature review of TR, PC and the possible impact acute neuromuscular fatigue could have on PC regulation. Trail running was defined in accordance with recent literature that highlights the need for universal terminology in the field of trail running research. The nature of trail running and the environment in which the sport takes place was thoroughly explained due to the influence factors such as uneven ground surfaces, distance, duration, elevation variation and the presence of obstacles may have on postural control regulatory mechanisms. Figure 2.2 provides an overview of the deterioration of postural control induced by general muscular exercise. In conditions of peripheral fatigue, certain compensatory strategies attend to postural disturbances to limit possible negative impacts. However, it has been explained that these compensatory strategies are rendered null and void in conditions of central fatigue. To date, it is unknown whether postural compensatory strategies are active in short-distance trail running events. A concept called the *body scheme* offers a theory that an internal representation of the body that is centred around body kinetics, kinematics and proprioceptive mechanisms could be developed through a learning process based on task experience. This theory positions the current thesis to explore whether greater exposure to sport-specific environments is considered to be beneficial to superior balance ability and compensatory strategies due to repetitive and similar training experiences. This chapter drew reference from existing research that investigated either fatigue and/or postural control in the sport of trail running. The methodologies of these studies provided a framework of reference for the current study. The following chapter explains the methodology used to carry out this study.

CHAPTER 3: METHODOLOGY

3.1 INTRODUCTION

Little is known about the postural control abilities within a sample of highly trained, male trail runners and what possible influence TR-induced fatigue may have on these abilities. This chapter will highlight the methods of undertaking required to explore the above grey areas within the sport of trail running (TR). This chapter will outline the chosen study design. Thereafter, the recruitment and sampling methods implemented for participant selection as well as the various inclusion and exclusion criteria of the study are detailed. Following this, the chapter will cover a study overview and ethical considerations before outlining the various testing procedures and equipment used during this study. Finally, a section on data analysis precedes that of the statistical analysis which subsequently concludes the chapter.

3.2 STUDY DESIGN

This study was an observational study design characterized as a cross-sectional, descriptive study where static balance, dynamic balance and jump performance were measured in both pre and post-fatigue stimulus (26km, +900m trail running time trial). Furthermore, this real-world observational study explored the effect of acute neuromuscular fatigue on postural control.

3.3 PARTICIPANTS

A total of fifteen participants volunteered to participate in this study and completed pre-testing. However, due to COVID-19 restrictions (one participant) and scheduling issues (one participant), only thirteen participants completed both pre and post-testing. All participants were male and highly trained (weekly running mileage >50km), meaning that >49% of their weekly running mileage takes place on natural, off-road surfaces (Schütte et al., 2016). A biostatistician was consulted and a post hoc analysis of the sample size was conducted. The biostatistician concluded that the sample size had sufficient power to detect 0.55 Cohen's D effect size. The post hoc analysis was calculated using STATA.

3.4 SAMPLING AND RECRUITMENT

Participants were sampled through a combination of purposive and snowball sampling methods. Several well-known highly trained trail runners were asked to assist in promoting the research study, while the primary researcher and study supervisor made use of personal connections within the Southern Cape trail running community for recruitment purposes. The study utilised an online recruitment strategy which was both active and passive in nature. Active online recruitment refers to directly contacting a person of interest via any online platform (Instagram, Facebook, WhatsApp etc.), whereas passive online recruitment would be sharing the advert for public viewing with the goal of the ideal candidates contacting the researcher (Gelinas et al., 2017). An information flyer (see Appendix A) was made available to the public and those meeting the advertised inclusion criteria were instructed to contact either the primary researcher or study supervisor of this study. The research study requirements were promoted on various social media platforms in order to recruit the minimum desired sample size (passive online recruitment). However, runners who were already known to fit the inclusion criteria were contacted directly via cell phone/social media platforms (active online recruitment). These individuals were encouraged to recommend other runners who might fit the inclusion/exclusion criteria.

All ethical considerations regarding online recruitment were identified and summarized to highlight researcher transparency and respect of prospective participants, their identity and private information. Before any information was collected, prospective participants completed and signed a written informed consent form (ICF) (see Appendix B). Participants were confirmed to be included in the study following a thorough examination of various relevant questions contained within a pre-testing questionnaire (see Appendix

C). This questionnaire was distributed after the participant had completed his ICF. After the questionnaire had been completed, those individuals who met the inclusion criteria were notified of the process to follow, including the proposed dates and details for pre-testing and the proposed dates and details for the time trial.

3.5 INCLUSION CRITERIA

Participants were included in the study if the following criteria were met: were male between the ages of 18 and 45; were highly trained trail runners (>50km/week where >49% of weekly training takes place on off-road trail surfaces); were injury free for 12 months prior to recruitment; signed and completed ICF prior to participation in testing.

3.6 EXCLUSION CRITERIA

Participants were excluded if they: failed the COVID-19 screenings prior to either testing session; completed their training either barefoot or in minimalist shoes; did not complete the pre-testing questionnaire; did not complete both pre and post-testing; did not complete the time trial on the marked route; if they currently had or have a history relating to any neurological conditions that could affect balance (disease/sensory loss/cognition, medications etc.).

3.7 STUDY OVERVIEW

The diagram below summarises the procedures followed throughout this research project. Please refer to this diagram as a reference for this section.

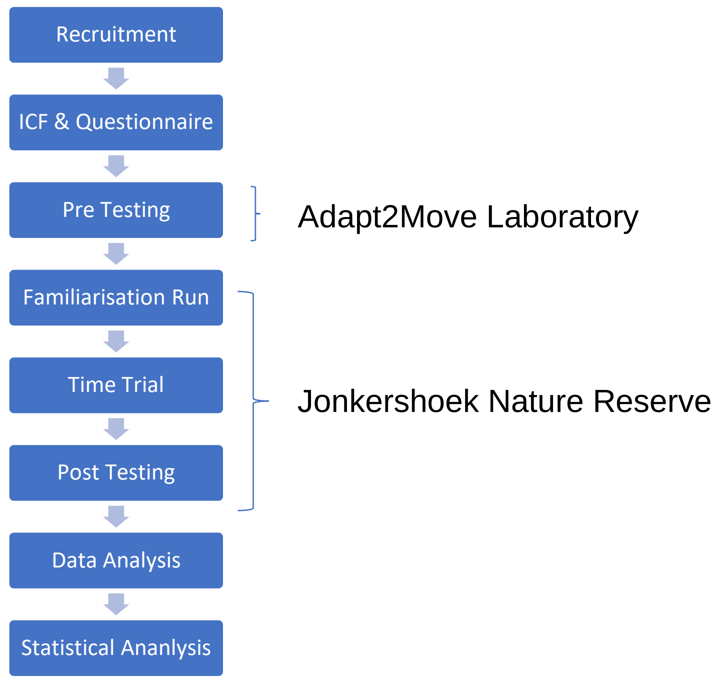


Figure 3.1 Flow diagram displaying procedural process for testing during this study (Compiled by Nicholas Price).

Following the circulation of the advertising material (flyer) on Facebook, Instagram and WhatsApp, interested individuals made contact with the researchers for further details on the research study. Those individuals who showed interest in the study (via the advertisement, personal contact, or word of mouth) were contacted via email with further information on the research study. Attached in the email was the original flyer (for snowball-type sampling), the ICF and the online questionnaire (in secure, editable PDF file format). The ICF was either signed digitally or in person prior to the commencement of the testing session. The purpose of the questionnaire was twofold: firstly, to obtain descriptive data on the sample and secondly, it was used as a screening tool for those individuals eligible to participate in the study. Following a thorough review of each questionnaire, participants meeting the inclusion criteria were allowed to participate in the research study.

Pre-testing took place at the Adapt2Move Laboratory (Lab) located at the Department of Exercise, Sport, and Lifestyle Medicine, Stellenbosch University. Participants were required to make only one visit to the Adapt2Move Lab where all pre-testing measurements took place. These tests and measurements included anthropometric measurements, two balance tests and one jump test. Each pre-testing session lasted thirty-five minutes per participant. All COVID-19 regulations were upheld throughout the sessions. Participants were screened prior to testing and sanitising practices were followed.

Participants were asked to arrive at pre-testing wearing comfortable, active clothing as well as the trail shoes in which they would run the time trial. Following this, participants were informed about the testing procedures, order of testing and asked if they had any initial questions. On completion, the anthropometric measurements were measured and recorded by the primary researcher with the assistance from either the secondary researcher or a research assistant within the first testing area: the anthropometric zone. All parties involved in testing were qualified Sport Scientists with levels of degrees ranging from Honours level qualifications to current PhD level researchers. Both the primary and secondary researchers had prior experience in the procedures for obtaining anthropometric data whereas the research assistants were only required for scribe purposes.

Following the anthropometric measurements, participants were introduced into the second test area: the balance zone. Here they were given detailed verbal explanations of each balance test, as well as provided with demonstrations regarding test procedure requirements. The participants were then given the opportunity to begin their familiarisation attempts for the various balance tests where a minimum of one and a maximum of three attempts were accepted. After it was clear that the individual had sufficient knowledge of what was required from them, an accelerometer device (Gyko, Microgate Italy) was attached via waist strap to the lower back of the participant. The primary researcher and study supervisor were trained with regard to the application of this device as well as the program management (RePower, Microgate, Italy) and execution via a laptop. Several equipment training sessions were carried out prior to official pre-testing to ensure maximum efficiency and correct device handling.

Despite all tests and measurements being non-fatiguing, the order of testing was based on least physically demanding tests to more physically demanding tests. Therefore in the balance zone, static balance tests were completed first, followed by the dynamic balance test. The static tests (Modified Clinical Test of Sensory Interaction in Balance and Single Leg Modified Clinical Test of Sensory Interaction in Balance) required the participants to stand freely on two feet for four separate conditions where conditions were adapted to change the ground surface as well as whether eyes were open or closed. The same was applicable for the single-leg trial that followed, where participants were instructed to complete the four conditions on their dominant leg. The dynamic balance test was measured via reach through a Star Excursion Balance Test. For all balance tests, participants were given a maximum of three trials to complete a successful trial of each test or condition. Any participant who failed to complete a balance pre-test after three trials was instructed to attempt and complete that test condition prior to the time trial on the date of post-testing. Following the completion of the balance tests, the Gyko accelerometer (Microgate, Italy) was removed, and the participant was guided over to the next test area.

The jump zone required participants to complete six jumps where three were maximal effort double leg, countermovement jumps and three were maximal effort single leg countermovement jumps performed on their dominant leg only. Each participant received a verbal explanation of what was required from them as well as a practical demonstration as guided by the test procedure protocols. Participants were then given time to familiarize themselves with the jump techniques. Following the successful completion of all six jumps, pre-testing was concluded and each participant was informed of the time trial date, their individual time trial start times and a proposed date for a familiarisation run. Two date options were provided, where participants were guided by the study supervisor along one lap of the time trial route. The purpose of the familiarisation run was to reduce the chances of anyone getting lost or taking a wrong turn during the actual time trial. Participants were informed to arrive on the morning of the time trial with only enough time to warm up prior to their start, as to avoid a large gathering and abide by social distancing regulations.

The time trial took place at the Jonkershoek Nature Reserve and the post testing at the entry gate to the Reserve within a small building that was cleared out for the purpose of this research study. All relevant permissions were obtained for the use of this building. Upon arrival, participants were sanitised, signed in and screened for symptoms of COVID-19. Before each departure, it was made clear that the runner was completely knowledgeable of the route, had a form of identification on their person as well as a cell phone for emergency preparations. Runners were sent off in ten-minute intervals with the first runner departing at 8:00 and the final runner departing at 10:00am. The time trial route consisted of two thirteen-kilometre loops which incorporated various numbers of undulating sections with the total elevation gain being approximately +482m per loop.

Upon finishing the time trial, participants were asked to provide a perceived exertion rating (via the Borg Scale) before drying themselves off and sanitizing their hands and entering the post-testing building. The order of testing mirrored that of pre-testing, however, only one anthropometric measurement (body mass) was measured within post-testing. Body mass was measured first, followed by the two static balance tests, then the dynamic balance test and finally the two jump tests. Following the successful completion of all test trials, participants were thanked for their time and effort and were allowed to depart from the post-testing site.

3.8 ETHICAL ASPECTS

This study was approved by the Stellenbosch University, Health Research Ethics Committee S20/10/292 . Furthermore, the study was carried out in accordance with the guidelines presented by the Declaration of Helsinki and was Protection of Personal Information (POPI) Act compliant. All participants were made aware that their participation in the research study was entirely voluntary and informed that they could withdraw from the study at any time. No invasive procedures or serious risks were involved in the study. All information was handled with strict confidentiality and stored on a password-protected computer. Complete anonymity was upheld throughout the research study, with each individual receiving a randomized participant identification number. All data was stored on a password protected laptop and a password protected hard drive. Only the primary researcher, study supervisor and study co-supervisor had access to this data. Only the primary researcher had knowledge of the personal information which correlated with the participant identification numbers. This knowledge was for participant-research communication only and all other parties involved in the study only had access the randomised participant identification numbers.

The top three finishers received a cash prize (first place: R1100; second place: R600 and third place: R300). Each participant received a complimentary beverage of choice at the finish line, as well as a complementary pair of running socks after completing the time trial. Furthermore, a lucky draw was held where one participant won a trail running t-shirt.

3.9 TESTING AND MEASUREMENTS

The purpose of this section is to describe the testing protocols that were used to obtain the desired data. The section will begin by explaining the methods for obtaining anthropometric data, followed by the balance and jump tests and finally the use of a competitive time trial as the fatigue stimulus. All data was recorded on hard-copy paper print outs before being logged into Microsoft Excel following the completion of all tests and measurements. Measurement equipment and methods were consistent pre and post testing.

TEST SITE LAYOUT

The anthropometric zone consisted of digital scale (Seca 813 Hamburg), stadiometer (Seca 711 Hamburg stadiometer), a tape measure and a large medical bed. Body mass and height were measured first, followed by that of anatomical and functional leg length on both the left and right lower limbs. The balance zone consisted of an area set aside for the MCTISB, Single Leg Modified Clinical Test of Sensory Interaction in Balance

(SLMCTISB) and SEBT. The star was made from four pieces of masking tape where each piece was 160cm long, intersecting at the middle, where each line was approximately 45 degrees. The MCTISB and SLMCTISB took place over the star of the SEBT to be able to use the lines as a stance point of reference or origin point. Additionally, for conditions of MCTISB and SLMCTISB requiring eyes to be open, there was a focal point of reference placed 1.2m away from the centre of the star on the wall immediately in front of the star at eye level for each participant. Two OptoGait bars (Microgait, Italy) were used as well as two digital cameras placed anteriorly and to the left of the jump area. For the sake of validity and reliability, all equipment used were marked off using masking tape to ensure that they were placed in exactly the same position for all test sessions. Post-testing took place within a building at the gate of Jonkershoek Nature Reserve which was cleared out (with permission) for the purpose of post-testing. Despite the obvious difference in space available, three test areas were arranged to utilise the space as best as possible. In order to streamline the post-testing process, the balance zone was split to allow the MCTISB and SLMCTISB and SEBT to be executed in their own zones. All protocol requirements for all tests were identical to that of pre-testing. The flooring differed between the testing venues. The flooring in the Adapt2Move Lab was solid linoleum gym flooring while the flooring in the post-test building was wooden.

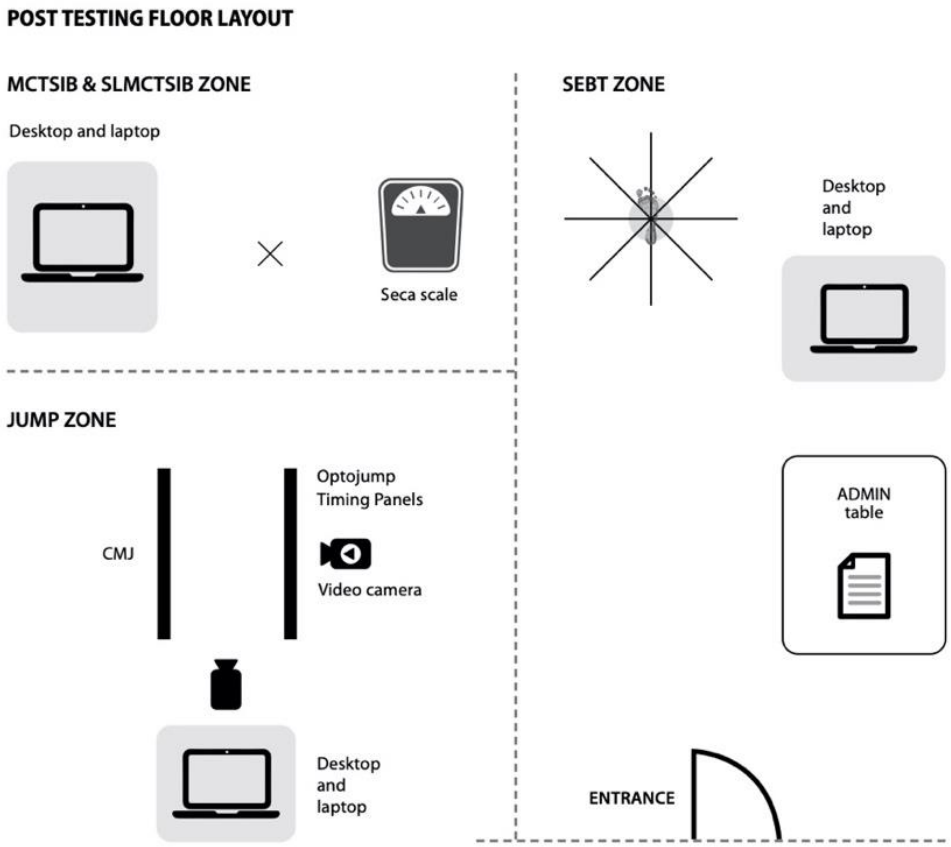


Figure 3.2 Pretesting floor layout. Location: Adapt2Move Lab, Department of Exercise, Sport, and Lifestyle Medicine, University of Stellenbosch. Compiled by Nicholas Price.

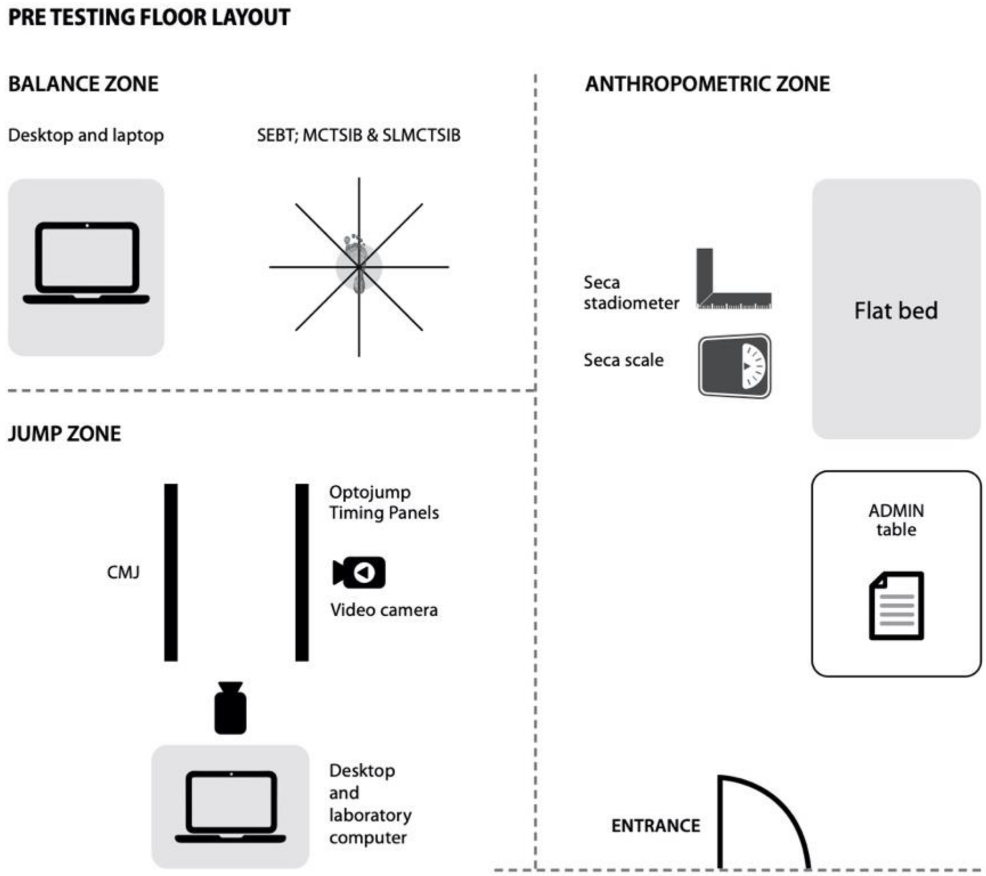


Figure 3.3 Post-testing floor layout. Location: Storage Building, Jonkershoek Nature Reserve, Stellenbosch. Compiled by Nicholas Price.

PRE-TESTING

Anthropometric Assessments (please note: COVID-19 face masks were required for all anthropometric measurements)

Body Height

Height was recorded using a calibrated stadiometer (Seca 711, Hamburg). Each participant was asked to remove their shoes and socks as well as any head gear and stand with their heels against the back of the standing platform. Participants were also required to ensure that their buttocks and upper back were in contact with the stadiometer shaft. The required head position was level with no upward or downward tilt allowed and relaxed shoulders. Participants were instructed to take a deep breath in prior to measurement. The researchers involved in these anthropometric measurements ensured that the correct body position was present before taking the height measurement. Height was measured in centimetres (cm), and measurement results were rounded off to the nearest 0.1 centimetre (Norton and Olds, 2001).

Body Mass

The body mass of each participant was measured in kilograms (kg) using the German Digital Scale (Seca 813, Hamburg) and was rounded off to the nearest 0.01kg. Participants were required to stand with their arms at the sides, look straight ahead and ensure an even distribution of weight on each leg.

Body Mass Index (BMI)

After having both height and mass recorded, BMI was calculated using the following formula via Microsoft Excel (Brener et al., 2003):

$$BMI = \frac{Weight\ (kg)}{Height^2\ (m^2)} = kg/m^2$$

Leg Length

Anatomical and functional leg lengths were measured using a measuring tape measure. Participants were asked to be barefoot and lie down on a platform bed that was present in the Adapt2Move Lab. Anatomical leg length was measured between the anterior superior iliac spine (ASIS), down the medial side of each leg, and the medial malleolus. Function leg length was measured between the navel and the medial malleolus of each leg, via the medial side of the legs. Due to the need to use anatomical leg length measurements to calculate normative values for the SEBT, functional leg lengths were discarded upon data analysis. Measurements were rounded off to the nearest 0.1 centimetre.

Static Balance Tests

Modified Clinical Test for Sensory Interaction in Balance (MCTSIB) and Single Leg Modified Clinical Test for Sensory Interaction in Balance (SLMCTSIB)

Following the completion of all anthropometric measurements, the participants were advised to remove their masks (to avoid the mask interfering with the field of sight during the tests) and guided to the balance zone, still barefoot, from the anthropometric measurements. Procedures for the MCTSIB were followed as per Hamammi et al. (2014) and Antoniadou et al. (2020). The four conditions included the following: Standing on a firm surface with eyes open (FO); standing on a firm surface with eyes closed (FC); standing on a compliant surface with eyes open (CO) and standing on a compliant surface with eyes closed (CC). Participants were advised that for each standing condition, they were required to stand still with their arms crossed over their chest. For conditions FO and CO, which involve visual feedback, participants looked straight ahead with no tilt of the chin. The other two conditions, FC and CC, eliminated visual feedback and thus the study supervisor stood within arm's distance of the participant in case of unforeseen falls (no such falls occurred).

Following a thorough explanation demonstration of each condition, a Gyko accelerometer (Microgate, Italy) was attached to the participant’s lower back (approximately at the site of the posterior super iliac spine). The accelerometer was attached using a Velcro-fastened Gyko device belt. The device was attached prior to any familiarisation attempts to ensure the participant was also familiar with what the belt felt like while performing the balance tests. The participants were then given the chance to begin familiarisation attempts as to ensure the correct technique was achievable for each condition. Once the researchers were satisfied that the participant had a sufficient understanding of the test requirements, the first condition was initiated via a verbal countdown. Each condition was exactly thirty seconds long, with a ten-second break in between the four conditions (Antoniadou et al., 2020).

Test trials were discarded if any of the following happened during the thirty seconds of condition observation: Any change of arm positioning; eyes opening during closed-eye conditions; any lifting of the heel or the toes; any readjustment of the feet in order to regain balance.

Following the MCTSIB, participants were allowed time to relax as the researcher explained the protocol of the SLMCTSIB. This protocol was identical to that of the MCTSIB but performed on the dominant leg only due to time constraints. Test trials were discarded under the same conditions as that of the MCTSIB with the addition of a scenario where the participant dropped their lifted foot at any time or if the participant showcased excessive abduction of the lifted limb. The primary and secondary researchers underwent training with regard to the identification of the degree of abduction that was deemed “excessive”. It is noteworthy that for the final condition of CC within the SLMCTSIB, no participant was able to complete the full thirty-second trial, therefore the time to failure was recorded for each participant for all three failed attempts.

Dynamic Balance Test

Star Excursion Balance Test

Remaining within the balance zone, the participant was instructed to stand to the side of the star, which had been set up prior to the arrival of the first participant and await further instruction.

Test procedures were carried out in accordance with Gribble et al. (2012). Participants were instructed to stand with their big toe on the anterior reach line with the mediolateral reach line intersecting the arch of their stance foot. Their hands were to be placed on their hips for the entirety of the reach test. Following a thorough verbal explanation and practical demonstration, participants began the familiarisation attempt. Within this familiarisation attempt, participants were told to practice reaching out maximally to each line where they were required to lightly place their big toe on the reach line and hold for one second. The participants were well informed of the conditions in which trials were to be discarded: if any double movement occurred during reach, where a double movement refers to an initial touch on the ground which is less than a maximal reach, followed immediately by a secondary attempt in the same to reach further in a respective direction; if their hands left the hips at any point; if the reach foot became weight bearing during any attempt and if the heel of the stance foot lifted or shifted from its original start position. The eight reach directions were attempted in the following order: anterior; medial anterior; medial; medial posterior; posterior; lateral posterior; lateral and lateral anterior (right foot stance; anti-clockwise). The same order of reach applied with a left foot stance, however, the direction of reach would be clockwise.

Once the participant expressed that they were ready, the test commenced on the non-dominant foot as to avoid any fatigue on the dominant foot following the SLMCTSIB. The research assistant was tasked with marking the point at which the toe made contact with the reach line. Reach distances were measured using a tape measure and rounded off to the nearest 0.1 centimetre. Different coloured chalk was used to mark the left and the right foot respectively and this was recorded on the hard-copy test sheet as to avoid confusion. Due to time constraints, only one successful attempt per leg was measured. Following the successful completion of both left and right foot trials, the participant was asked to put their shoes and socks back on and were then accompanied to the jump zone.

Jump Test

Counter Movement Jump Test (CMJ) and Single Leg Counter Movement Jump Test (SLCMJ)

Within the jump zone, participants were required to complete six jumps in total. These jumps were performed wearing the participants' trail shoes for CMJ as well as SLCMJ. There was a small line of tape placed within the centre of the Optojump bars as to equally align and re-align the feet before each jump. Before entering the jump zone, the primary research and/or study supervisor placed sticker markers at strategic anatomical points for the purpose of measuring knee valgus movement during landing. Please refer to

Figure 3.4 below. The purpose of these markers were to act as a reference for jump results based on video footage as well as to use the information regarding knee valgus motion during landing at a later stage. Due to time constraints, no video footage was analysed for this thesis.

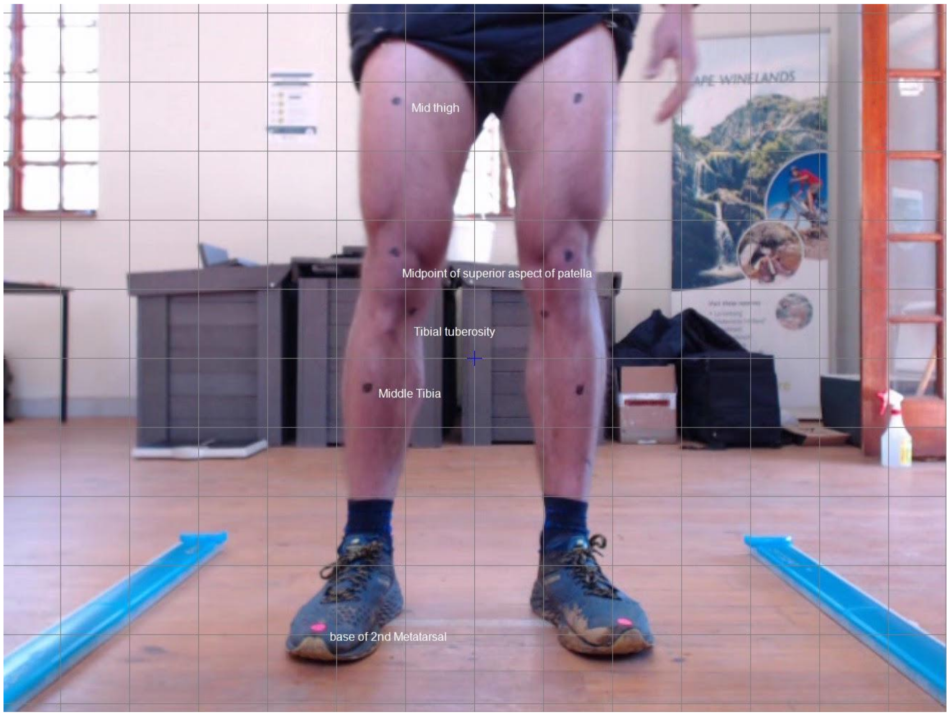


Figure 3.4 Anatomical landmarks identified and marked on the participant during jump tests Labels from top to bottom: Mid-thigh; midpoint of superior aspect of patella; Tibial tuberosity; middle Tibia and base of 2nd metatarsal. Compiled by Sarah Arnold.

A thorough verbal explanation and practical demonstration was provided by the primary researcher before allowing the participant to enter the jump zone and begin familiarisation attempts for both CMJ and SLCMJ. Their hands were to remain on the hips for the entirety of each jump, with feet hip-width apart and head facing forward without any tilt in the chin. Participants were advised that each jump would be a maximal effort jump where their cue was to “jump as high as you can”. Safety during landing was taken very seriously and the participants were instructed to land softly and in a controlled manner. The cue was to bend their knees on landing in order to absorb any excessive impact on contact with the ground. This was the instruction for both CMJ and SLCMJ jump trials. The three maximal effort CMJ trials were performed first, with a twenty-second break in between each trial. With regards to the CMJ, trials were considered invalid if the hands left the hips at any point and if the CMJ technique was not maintained throughout the jump. The trial exclusion considerations were the same for SLCMJ with the exception that participants needed to land unilaterally on the same leg from which they jumped. Following the completion of six successful jumps in total, participants were thanked for their time, informed of a proposed date for a familiarisation run as well as their start time and date of the time trial.

Familiarisation run

Please refer to Figure 3.5 below. Participants were required to complete a familiarisation run (FR) before the time trial. The purpose of the FR was to ensure that all participants had prior knowledge of the route thus allowing them to focus entirely on their race. Participants were contacted via either email or WhatsApp to arrange a time and date for this run. For convenience's sake, two FR dates were arranged to accommodate participants' respective schedules. The FR was led by the secondary researcher, who had extensive experience on these mountain trails (Jonkershoek Nature Reserve). Due to the time trial being two complete laps of one identified route, the FR guided the participants through one lap of the route. The identified route was a total of approximately thirteen kilometres and consisted of +482m elevation gain. The FR took place at least one week before the time trial and post-testing, as to avoid any unnecessary acute fatigue induced by the FR. All participants were provided with a GPX file of the route so that they could upload the route to their Global Positioning System (GPS) enabled watches. One participant was not able to attend either of the familiarisation runs, however, it was concluded by the primary and secondary researchers that his prior knowledge and experience of the Jonkershoek trails was sufficient as to deem his absence at the FR as acceptable. The participant completed the route on his own prior to the time trial and communicated with the study supervisor upon completion. The study supervisor verified via the participant's Strava profile that he completed the route correctly. Access into the Jonkershoek Nature Reserve for these FR was granted prior to the time, with all administrative matters seen to and at no cost to the participants. All COVID-19 safety regulations were exercised during the gathering of participants for the two familiarisation runs.

Fig 3.5 A map showing one lap of the time trial route including the distance (12.99km) and elevation gain (+482m) per lap. Image obtained via Strava Application. Image provided by Simon de Waal.

The trail run time trial

The COVID-19 regulations halted all formal races during this time and therefore this thesis attempted to create a race-like environment by selecting a competitive time trial (TT) as the fatigue stimulus. This took place at the Jonkershoek Nature Reserve. To achieve this, the TT mimicked a real race awards format where monetary rewards of decreasing value were arranged for the top three TT finishers with the three fastest times. Participants were asked to run this TT as if it were a race to further promote a competitive atmosphere. As previously mentioned, the TT route was two complete laps of one identified route. Participants were required to be self-sufficient during this time trial. The route was marked by the study supervisor three days prior to the TT, using arrow signage boards (with permission from the Reserve management) as to further eliminate route errors (see Figure 3.6). In case of an emergency, two experienced and qualified mountain safety officials with paramedic training were present on the route. The two mountain safety individuals conducted a precautionary “sweep” of the route after the final participant had completed the time trial.

Figure 3.6 Route markers used during the TT to ensure the correct route was followed by all participants.

Please refer to the Figure 3.7 below for information regarding the route profile for one lap. The route began with a gradual 5.4km single-track climb, where single track refers to a mountain path wide enough for one person. The route then entered a gradual 1.8km descent via a jeep track, where a jeep track refers to a mountain road wide enough for at least one vehicle. The jeep track then entered a steep climb for less than 1km before descending into a winding single track for 2.5km. The first lap concluded with a gradual descent back to the start line via jeep track where participants started the second lap. The entirety of the route was completed off-road either on single track (hiking trails) or jeep track (4x4 trails).

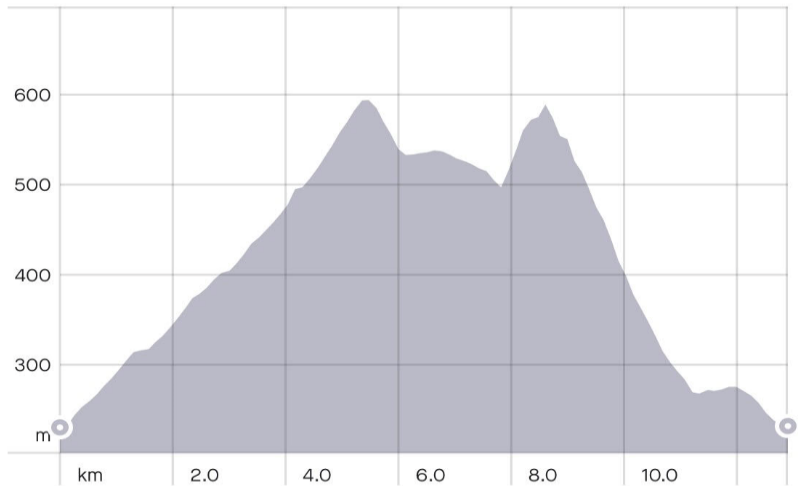


Figure 3.7 Time trial route profile (one lap) (Source: Strava Application). Provided by Simon de Waal.

The researchers and research assistants arrived one and half hours prior to testing to set up and test all equipment to be used on the day. Participants were responsible for their own travel arrangements to the testing site. Participants were advised to arrive at the TT start area with enough time to satisfy their individual warm-up needs before meeting the researchers at the TT start line. Here, the required emergency equipment was checked and confirmed before double-checking that each participant was confident in the route to be run. Once all parties were satisfied with what was required of the participants, they were informed as to how much time remained before they were able to begin the TT. For the purpose of avoiding a bottleneck situation following the TT, participants were sent off in ten-minute intervals. These start times were randomized based on ascending numeric value of participant identification numbers. The first participant began the TT at 8:00 am and the final participant departed at 10:30 am. The staggered starts and finishes were managed by the study co-supervisor. Following the final departure, the researchers and research assistants prepared for arrival of the first finisher to begin post testing. The average TT finishing time was two hours and nine minutes, with the winning time being approximately one hour and fifty-seven minutes.

POST TESTING

The post-testing was performed in the same order as pre-testing, however, only one anthropometric test (body mass) was measured following the time trial. This measurement took place within the first balance zone. Balance zone one consisted of the static balance tests (MCTSIB and SLMCTSIB) and was the first zone in which participants would enter following their TT completion. Balance zone two consisted of the dynamic balance test (SEBT) and was the second zone to be completed. Finally, participants entered the jump zone, where they completed six jumps in total (three CMJ and three SLCMJ on their dominant leg). Following the completion of all post-tests, participants were thanked for their participation, time and effort given for the research study. The average time to completion of post-testing was twenty-four minutes.

The researchers took note of the weather forecasts five days prior to the TT and post-testing. The following figures were recorded on July 11 2021 via https://www.accuweather.com/:

Table 3.1 Hourly weather report for day of time trial (July 11 2021).

Time	Temperature (°C)	Wind speed (m/s)	Humidity (%)
7am	6	2.3	76
8am	6	2.4	77
9am	8	2.5	73
10am	11	2.5	65

(°C): degrees celcius; m/s: meters per second; %: percentage; am: after maridian (Source: World-Weather-Info)

3.10 DATA COLLECTION METHODS AND ANALYSIS

This study gathered data relating to anthropometric measurements, standing leg reach, postural sway, jump height and flight time. The SEBT made use of a testing sheet, where the reach distance for each direction was recorded on this sheet before being transferred to Microsoft Excel (version 16.0.6742.2048). The data obtained from the remaining tests

(MCTSIB, SLMCTSIB, CMJ and SLCMJ) were all automatically uploaded onto digital software via the instruments used to obtain this data before being exported to '.csv' files compatible with Microsoft Excel. More specifically, the Gyko accelerometer (Micorgate, Italy) was used to measure postural sway via the inertial measurement unit (IMU) itself and the related data was viewed and recorded in real-time on the respective application (RePower, Microgate, Italy). The same is reported on the Optojump instrument (Microgate, Italy), where all data is viewed and recorded immediately via its own respective application (Optojump Next, Microgate, Italy).

The process of data analysis was made up of several steps in order to ensure a high level of accuracy and minimize the chance of errors. The data was visually inspected in order to identify any obvious red flags in the data sets. Any non-acceptable data was excluded from the study and all acceptable data was then filtered via visual inspection to obtain the desired variables to be analysed. Non-acceptable data included data sets of test trials where participants broke protocol requirements or data relating to equipment test trials. All data was exported and organised in Microsoft Excel and the data was then visually inspected and descriptive statistics were calculated.

MCTSIB and SLMCTSIB

In order to measure postural sway and frequencies related to postural sway, the Gyko accelerometer (Microgate, Italy) was used. This device is classified as an IMU which utilizes tri-axial accelerometery in order to measure various body and joint movements associated with sway and other accelerometer-based tests (Yang and Hsu, 2010; Forza and Edmundson, 2019). The Gyko accelerometer has been found to be both valid and reliable for measuring postural sway in athletic populations (Kavanagh and Menz, 2008; Cole et al., 2014; Jarchi et al., 2018; Forza and Edmundson, 2019; Jaworski et al., 2020). The data collected via the Gyko accelerometer (Microgate Italy) was automatically transferred via Bluetooth to a laptop where this data was filtered and exported to Microsoft Excel. The following variables were measured for tests MCTSIB and SLMCTSIB:

Table 3.2 The variables measured for tests MCTSIB and SLMCTSIB, their unit of measurement and definitions according to the GykoRePower User Manual (*GykoRePower User Manual Version 1.1.1.10).*

Variable	Unit Of Measurement	Definition
Mediolateral sway (Length ML)	Millimetres	The ML length is the total distance in the anteroposterior direction given as the sum of the absolute distances between two consecutive points in the ML direction
Anteroposterior sway (Length AP)	Millimetres	The AP length is the total distance in the anteroposterior direction given as the sum of the absolute distances between two consecutive points in the AP direction
Centroidal frequency of medial lateral sway	Hertz	This is the frequency at which the "spectral mass" in the ML direction is concentrated
Centroidal frequency of anterior posterior sway	Hertz	This is the frequency at which the "spectral mass" in the AP direction is concentrated

SEBT

The data relating to the SEBT required further calculations to convert the raw data into a comparable format. The raw data of reach distance (cm) was obtained via each reach line, however, due to variables such as height and leg length, the data required normalisation in order to be compared to the rest of the group. Relative scores (displayed as a percentage) based on individual anatomical leg lengths were equated to provide a comparable value of reach. The raw data was converted into normalised percentages using the following formula:

$$normalised\ score\ (\%)\ = \left(\frac{reach\ in\ cm}{anatomical\ leg\ length\ in\ cm}\right) \times\ 100$$

Variable	Unit of Measurement	Description
Reach	Centimetres	The distance obtained by the reach foot in each of the eight reach directions

Table 3.3 The variable measured for test SEBT and a description thereof.

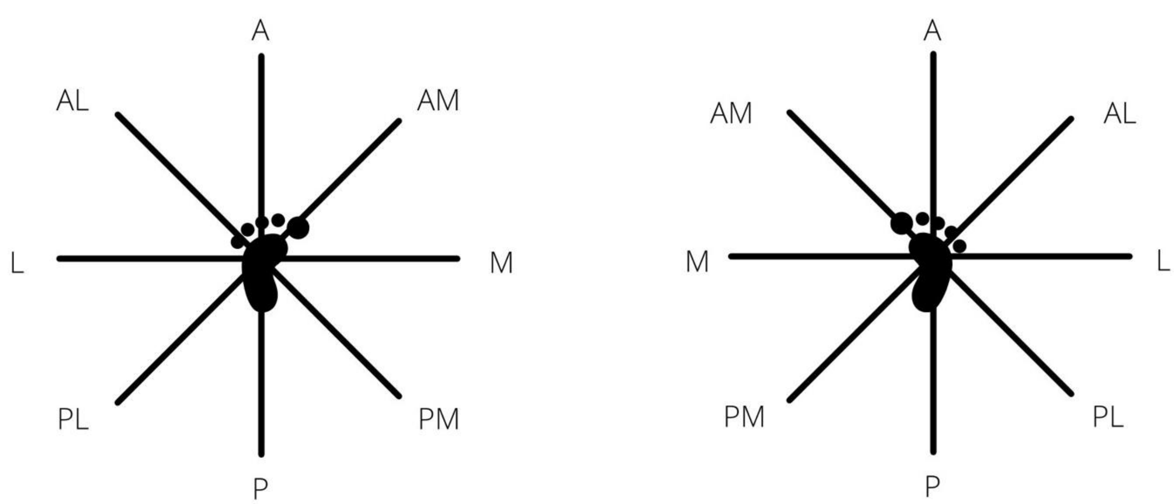


Figure 3.8 Reach directions for SEBT for left and right foot stance respectively. **A**=Anterior; **AM**=Anterior Medial; **M**=Medial; **PM**=Posterior Medial; **P**=Posterior; **PL**=Posterior Lateral; **L**=Lateral and **AL**=Anterior Lateral. Figure compiled by Nicholas Price.

CMJ and SLCMJ

The use of jump tests within a test battery associated with PC relates directly to that of fatigue. The following variables were measured for tests CMJ and SLCMJ.

Table 3.4 The variables measured for tests CMJ and SLCMJ and their descriptions (Gathercole et al, 2015; OptoJump Next User Manual Version 1.12.1).

Variable	Unit Of Measurement	Description
Maximum jump height	Centimetres	The highest jump trial recorded as a measure using velocity and flight time
Mean jump height	Centimetres	The combined jump height scores from jumps one, two and three divided by the number of jumps in total (three)
Maximum flight time	Seconds	The longest period spent in the air from jump take-off to landing
Mean flight time	Seconds	The combined flight time scores from jumps one, two and three divided by the number of jumps in total (three)

3.11 STATISTICAL ANALYSIS

Following data analysis, the statistical analysis of the variables of interest was conducted. All calculations of means, effect sizes and significance were conducted by the researchers. Following the completion of these calculations, a statistician from the Stellenbosch University Division of Epidemiology and Biostatistics, Faculty of Medicine and Health Sciences was consulted for further statistical guidance. Tests for normality were performed using the Shapiro-Wilk test to determine whether the data was normally distributed or skewed (Millet et al., 2011; Degache et al., 2014; Ramos Campo et al., 2016; Baiget et al., 2018 and Scheer et al., 2019). If the variable data sets were normally distributed, then a paired samples t-test was used to identify any significance differences between the selected dependent variables. However, a Wilcoxon signed-rank test was used under two conditions: firstly, when one normally distributed variable was tested in conjunction with a non-normally distributed variable and secondly when two non-normally distributed variables were compared together. The SPSS program allowed for automated calculation of effect size via Cohen's D value. The scale suggests that 0.0-0.019 represents a 'trivial' effect size, 0.20-0.50 a 'small' effect size, 0.5-0.79 a 'medium' effect size and 0.80 or great a 'large' effect size (Cohen, 1988). All statical analyses were performed using IBM SPSS Statistics 27.0 (SPSS Inc., Armonk, New York, US). The alpha value for all tests was $p<0.05$.

The same statistician mentioned above was consulted with to confirm that a sample size of thirteen participants (n=13) was sufficient for this research study. The outcome concluded that the sample size was able to detect a moderate effect size (0.55) with a statistical power of 0.80 and an alpha value of 0.95.

CHAPTER 4: RESEARCH ARTICLE

This chapter is written in article format. The article was written in accordance with the guidelines provided by Elsevier Gait & Posture Journal. Consequently, the font and referencing style for this chapter differs from that of the rest of this thesis in order to accommodate the preferred format Elsevier Gait & Posture Journal. There is intent to submit this article to Elsevier Gait & Posture Journal in 2023. The article-format chapter fulfils the requirements of the degree of Master's in Sport Science at University Stellenbosch

Postural control changes in highly trained trail runners following a short, competitive off-road time trial.

N Price[1], S Arnold[1], S de Waal[1]

[1]Department of Exercise, Sport, and Lifestyle Medicine, Stellenbosch University, Stellenbosch, Western Cape, South Africa

ABSTRACT

Trail running predominantly takes place on mountainous ground surfaces, requiring an individual to overcome countless postural disturbances. Despite the growing popularity of trail running, little research exists surrounding the influence race-induced fatigue may have on the postural control system. The purpose of this study was to document postural control ability within a group of highly trained trail runners and observe the change in various postural control variables in a real-world, pre-post setting. Thirteen highly trained trail runners completed five baseline tests (three balance tests and two jump tests) prior to a fatigue stimulus in the form of a competitive off-road time trial. The identical baseline test battery was repeated immediately after the time trial where dynamic and static postural control (tri-axial acceleration), proprioception (visual dependence) and jump height (via transmitting and receiving panels) was recorded. When comparing the pre-post results, it was found that the fatigue stimulus had several significant effects on postural sway in variables length mediolateral (LML) and length anteroposterior (LAP) for the Modified Clinical Test of Sensory Interaction in Balance (MCTSIB), uni-pedal countermovement jump (CMJ) results were significantly less despite no significant changes in bipedal CMJ results and dynamic stability remained primarily unchanged in the Star Excursion Balance Test (SEBT). These results show that a short, competitive, off-road time trial can significantly alter postural control variables in a cohort of highly trained trail runners. However, the results could suggest that trail experience and training status could contribute to superior compensatory strategies which serve to limit the impact of general fatigue on postural control regulation. These findings provide insight into the impact of trail running-induce general fatigue over short distances.

Keywords: Balance; Proprioception; Compensation strategies; Mountain running

1. Introduction

Recreational running and race participation have grown considerably over the last decade and continue to rise in popularity due to the accessibility thereof [1,2]. Similarly, different types of running and running events have begun to expand in popularity and variety [3–5]. Off-road running is considered a newer type of running with the governing organisation, the International Trail Running Association (ITRA), founded as recently as 2013 [5]. The sport comprises of different categories that vary in terms of classification and definition. The ITRA and World Athletics (WA) are responsible for regulating the rules and formal definitions of the off-road running disciplines [5]. Trail running (TR) is considered the largest and most popular category of off-road running [4] and is distinguishable from road running (RR) foremost by the environment and ground surfaces. Trail running takes place within natural environments (forests, parks and nature reserves etc.) where asphalt roads are mostly absent and dirt trails make up the majority of ground surfaces [1–5].

Due to a recent call for a universal language of description within off-road running, this article will follow description guidelines based on the latest TR literature by Scheer et al. (2020). For descriptive clarity, the TR time trial in this study met the following definition, “Trail running, the most popular discipline of off-road running, is defined as a foot race in a natural environment including mountains, deserts, forests, coastal areas, jungles/rainforests, grassy or arid plains over a variety of different terrains (eg. dirt road, forest trail, single track, beach sand, etc.) with minimal paved or asphalt roads, not exceeding 20–25 % of the total race course” [5].

When compared to RR, further differentiating characteristics of TR include the possibility of extensive race durations, large variance in vertical displacement and greater eccentric muscle contractions associated with this elevation change [6]. All factors considered, participation in TR and TR events (distance and duration dependent) put a considerable amount of stress on the body that inevitably leads to acute neuromuscular fatigue, subsequent decrements in muscular performance and impaired regulatory functioning of the postural control system (PCS) [2,4,6–8]

The PCS is responsible for facilitating sensory and environmental inputs in the shortest time possible in order to overcome postural disturbances and maintain an upright posture [7]. The geographical locations in which TR takes place present countless instances where natural obstacles cause disruptions in running gait and running velocity. Schutte (2016) reported that when comparing running on concrete to running on woodchips, dynamic stability is placed under significant stress due to alterations in stride length and step frequency. Furthermore, this literature alludes to the fact that the irregularity of woodchips as a ground surface can compromise dynamic stability as lower-limb muscles are forced to provide additional work at the point of ground contact, thus increasing the demand placed upon the PCS [4]. Disruptions must be continuously identified and overcome for an athlete to safely and efficiently progress along the trail. The PCS, however, is susceptible to acute neuromuscular fatigue through general muscular exercises, like running, which cause postural regulating mechanisms to perform sub-optimally [7,8]. The deterioration of the PCS is multifaceted and appears to be dependent on several factors such as the duration and intensity of exercise, vestibular and proprioceptive disturbances induced by running, as well as the type of muscle contraction in a setting comprised of large variances in vertical displacement [4,7,8]. These, together with the nature of TR, allow for logical inference of the importance placed upon postural control regulation for athletes that participate on off-road surfaces.

Most available literature that investigates the effect of muscular fatigue on the postural control of trail runners includes that of marathon and ultra-marathon distances. To the best of our knowledge, no literature has investigated the change in postural control variables during a competitive, short-distance (<42.2km) trail running route [4–6,9]. Therefore, the purpose of this study was to describe the change in postural control in a cohort of highly trained trail runners after a short-distance trail running time trial.

2. Methods:

2.1 Participants and Recruitment

Thirteen male, highly trained trail runners (training mileage >50km per week) aged 30.00 ± 5.58 years volunteered to participate in this study [5]. Participants were sampled via a combination of purposive and snowball sampling methods. The study utilised an online recruitment strategy, both active (direct communication) and passive (advertising made available to the public). Public advertising included an information flyer which briefly outlined the research study and stipulated the inclusion criteria. All participants were injury-free within twelve months before the study. Written informed consent was obtained from all participants before they participated in the research study. This study was approved by the University of Stellenbosch Health Research Ethics Committee (S20/10/292) and was conducted in accordance with the ethical principles and guidelines of the Declaration of Helsinki.

Fifteen participants completed the questionnaire and pre-testing, however, two participants did not complete the time trial or post-testing due to health-related issues unrelated to the current study. All data collected from these two participants were excluded from the analysis. One participant reported a history of a chronic condition (sports-induced asthma) where prescribed chronic medication was used to treat the condition via the use of an inhaler and nasal spray. The treated condition did not affect running or postural control ability.

2.2 Inclusion and Exclusion Criteria

Participants were included in the study if the following criteria were met: were male between the ages of 18 and 45; were highly trained trail runners (>50km/week where >49% of weekly training takes place on off-road trail surfaces); were injury free for twelve months prior to recruitment; signed and completed informed consent form prior to participation in testing. Participants were excluded if they failed the COVID-19 screenings prior to either testing session; had or have a history relating to any neurological conditions that could affect balance; completed their training either barefoot or in minimalist shoes; had any self-reported musculoskeletal injury within 12 months of the study.

2.3 Experimental Protocol

The experimental component of this study comprised of two phases including; 1) questionnaire and pre-testing, and 2) short trail running time trial and post-testing. Phase 1 comprised of running history questionnaire and non-fatiguing PCS test battery and phase 2 took place one week after phase 1.

2.3.1 Questionnaire

Limited profiling information is available for a sample of highly trained trail runners in South Africa. A questionnaire was developed to gather information on the following topics: general health-related questions, running-related questions and injury-related questions. After written consent was received, participants were given the choice of completing the questionnaire digitally (interactive pdf. document) or via hard copy. Questionnaires submitted digitally were securely stored in a password-protected cloud folder. Hard-copy questionnaires were submitted on the day of initial screening and pre-testing. All questionnaires were completed before any testing commenced.

2.3.2 Pre-testing:

The pre-testing consisted of three anthropometric measurements, three postural control tests and two jump tests. Each test was clearly explained and demonstrated before participants completed at least one familiarisation attempt per test and condition. Verbal instructions were used to communicate the test condition initiation and completion. An iPhone 12 was positioned anteriorly to video record all PCS tests for reviewing purposes.

The following anthropometric measurements were recorded during the initial screening: body height (cm) measured using a calibrated stadiometer (Seca 711, Hamburg); body mass (kg) measured using the German Digital Scale (Seca 813, Hamburg) and supine anatomical leg length (cm). Body Mass Index (kg/m^2) was calculated during data analysis.

Postural control tests followed the anthropometric measurements and were sequentially performed by each participant. A Gyko accelerometer (Microgate, Italy) was attached via a standardized Gyko belt to participants' lower back (approximately at the site of the posterior super iliac spine) for all postural control tests. The following tests were performed in the order listed below:

a. **Modified Clinical Test of Sensory Interaction of Balance (MCTSIB) and Single Leg Modified Clinical Test of Sensory Interaction of Balance (SL MCTSIB).** These tests required participants to hold stance conditions including firm surface eyes open (FO), firm surface eyes closed (FC), compliant surface eyes open (CO) and compliant surface eyes closed (CC). The SLMCTSIB was a modified, uni-pedal stance test of balance guided by procedures of prior research using the MCTSIB [10–13].

b. **Star Excursion Balance Test (SEBT).** Four strips of masking tape (1.6m long) placed at 45-degree angles were used to construct the "star" of eight reach directions. The test commenced on the non-dominant lower limb. Participants maintained a uni-pedal stance (non-dominant limb) while methodically completing maximal reaches (dominant limb) in eight separate directions. After successfully completing all eight reaches, participants could stand freely before repeating the test using the dominant limb as the stance limb and the non-dominant limb as the reaching limb. Chalk was used to mark ground contact points on each reach. Test procedures were carried out in accordance with the standards and methods outlined in previous research [14–16]

c. **Countermovement Jump Test (CMJ) and Single Leg Countermovement Jump Test (SLCMJ).** Participants were required to complete six maximal jumps in total (three countermovement jumps and three single-leg countermovement jumps on the dominant limb). OptoJump (Microgate, Bolzano, Italy) transmitting and receiving panels were placed parallel to one another to measure jump height and two Logitech web cameras (placed anteriorly and medially to participants) were used to record all jumps. Participants wore their trail running shoes for all jumps. A thorough verbal explanation and practical demonstration were provided before the participant began familiarisation efforts. Test procedure required participants to stand with feet shoulder-width apart with hands placed on hips for the entirety of the maximal-effort jump (pre-take off to post-landing). Safety upon landing was emphasized with an instruction to control the landing and absorb ground impact by bending the knees [17–19].

2.3.3 Familiarisation Run

To reduce the chance of participants taking a wrong turn during the time trial, all participants completed a familiarisation run that was privately arranged and took place at least one week before the time trial. To accommodate participant schedules, two familiarisation runs were arranged. Due to the TT route consisting of two loops of the same 13km route, only one loop was required. The familiarisation run was led by the secondary supervisor of the current study who had extensive knowledge and experience of the route.

2.3.4 Short, competitive, trail run time trial

To create a race-like environment, a competitive time trial (TT) was selected as a fatigue stimulus, which took place at the Jonkershoek Nature Reserve, Stellenbosch, South Africa. The route consisted of two laps of approximately thirteen kilometers (km) and 482m of elevation gain respectively. Thus, the total time trial effort equated to twenty-six km of distance and 964m of vertical elevation gain. The route was well-marked to clearly indicate any turns on the course. The TT mimicked an official trail race where cash prizes were awarded for the three fastest times. All participants were aware of this incentive and were asked to run the TT at their competitive race pace to further promote a competitive atmosphere.

On the day of the TT, participants were encouraged to arrive early enough to complete their individual pre-race preparations. The preparations were free of constraint, where the only requirement was to report to the start line at least five minutes before official start times. These start times were entirely randomized. Participants were sent off in ten-minute intervals where the first participant began the TT at approximately 8:00am and the final participant departed at 10:30am. Participant safety was the top priority during the TT. Two individuals with medical training and experience tending to emergency situations in mountainous areas were placed along the TT route to monitor the health and safety of all participants. The weather was carefully monitored prior to that TT and the following figures were recorded on the day of the TT: morning temperatures of 6°C with 1.9 $km.h^{-1}$ wind speed; afternoon temperature of 15°C and 2.9 $km.h^{-1}$ wind speed.

2.3.5 Post-testing:

The test and procedures for post-testing were identical to that of pre-testing. Due to the need for post-testing to take place as soon as possible following TT completion, multiple participants rotated between tests at a time. Therefore, the order of post-testing was not controlled but rather followed a rolling entry by order of finish. Due to time constraints, the SEBT was executed without the Gyko accelerometer (Microgate, Italy). The floor surface in the post-testing location (wooden) was different to that of the pre-testing location (hard surface).

3. Data and statistical analysis

All statistical analyses were performed using IBM SPSS Statistics 27.0 (SPSS Inc., Armonk, New York, US). Tests for normality were performed using the Shapiro-Wilk test [5,7,20–22]. For all normally distributed variables, a paired samples t-test was used to identify any differences in mean scores between pre and post-testing, alternatively, a Wilcoxon signed-rank test was used. Furthermore, a two-way repeated measure ANOVA or Friedman test was used to compare variables within tests which contained several different conditions, for normally and non-normally distributed data sets respectively. Cohen's d effect sizes were calculated to interpret the magnitude of effects between baseline and post-test results. The scale suggests that 0.0-0.019 represents a 'trivial' effect size, 0.20-0.50 a 'small' effect size, 0.5-0.79 a 'medium' effect size and 0.80 or great a 'large' effect size [23]. For all tests significance was set as $p<0.05$.

4. Results:

Descriptive and running-related data for all highly trained trail runners (n=13) was collected during the initial screening and are shown in Table 1 below.

Table 1

Descriptive and training-related data for thirteen highly trained trail runners who participated in a short, competitive, off-road time trial.

Descriptive variables	**Mean ± SD**
Age (years)	30.00 ± 5.58
Height (cm)	181.24 ± 4.42
Anatomical Leg Length (Left)	93.96 ± 3.76
Anatomical Leg Length (Right)	92.85 ± 3.75
Body Mass (kg)	76.40 ± 7.40
BMI (kg/m^2)	23.28 ± 1.81
Training frequency (days/week)	5.46 ± 0.78
Distance run on trail surface (km/week)	65.00 ± 6.45
Distance run on road surface (km/week)	23.80 ± 8.93
No. of years recreational trail running	6.77 ± 3.47
No. of years competitive trail running	5.62 ± 2.87

SD = Standard Deviation, BM I = Body Mass Index, cm = centimeter, kg = kilogram, n = total number of participants, No. = number

The questionnaire completed during the screening process also contained sections on training and injury. Ten participants incorporated strength training into their weekly training program (2.30 ± 1.06 days per week), seven incorporated balance-specific training (1.29 ± 0.49 days per week), one participant incorporated proprioceptive training (1 day per week) and eight participants reported making use of cross training in their weekly training program (2.25 ± 1.49 days per week). Examples of cross-training included cycling, CrossFit, yoga and swimming.

4.1 Short, competitive trail running time trial (TT)

The average time taken to complete the TT for the 13 participants was 2h 15min 53sec. The fastest recorded time was 1h 57min 33sec, while the slowest time recorded time was 2h 39min 33sec. Participants' rate of perceived exertion (RPE) was recorded immediately after completing the TT. The average RPE recorded was 9 out of a possible 10. The first two finishers began their post-testing immediately after TT completion. The average waiting time for participants completing the TT after the second finisher was fourteen minutes.

4.2 Static Balance

4.2.1 Modified Clinical Test of Sensory Interaction for Balance (MCTSIB)

The findings for static balance showed statistically significant changes ($p<0.05$) in mediolateral in stance conditions FO, FC and CC while anteroposterior sway showed significant increases ($p<0.05$) for stance conditions FO, and CO during the MCTSIB. No significant changes were observed for centroidal frequency. Statistically significant changes are shown in Table 2 below.

Table 2

Statistically significant differences for Gyko accelerometer-derived variables in the MCTSIB test between pre (non-fatigued) and post (fatigued) conditions for FO, FC, CO and CC.

MCTSIB								
Variable	**Stance Condition**							
	FO				**FC**			
	PRE	**POST**	**p.**	**d**	**PRE**	**POST**	**p.**	**d**
LML(mm)	0.11 ± 0.08	0.15 ± 0.07	0.01*	0.72	0.17 ± 0.10	1.33 ± 0.72	0.03*	0.60
LAP (mm)	0.21 ± 0.10	0.27 ± 0.10	0.01*	0.69				
	CO				**CC**			
LML (mm)					0.21 ± 0.13	0.26 ± 0.13	0.04*	0.58
LAP (mm)	0.24 ± 0.11	0.29 ± 0.12	0.01*	0.76				

MCTSIB = Modified Test of Sensory Interaction of Balance; LML = length mediolateral, LAP=length anteroposterior, FO = firm surface with eyes open, FC = firm surface with eyes closed, CO = compliant surface eyes open, CC = compliant surface eyes closed, mm = millimeter, p. = statistical value, d=effect size (0.20-0.50 ‘small’; 0.5-0.79 ‘medium’; >0.80 ‘large’), * = represents statistical significance ($p<0.05$).

4.2.2 *Single Leg Modified Clinical Test of Sensory Interaction for Balance (SLMCTSIB)*

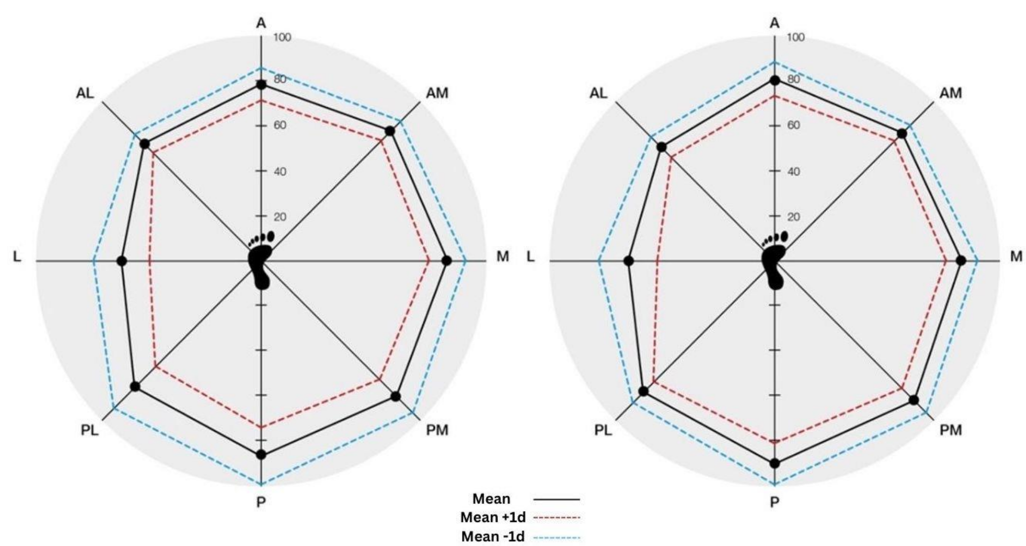
A significant difference in LML was observed when comparing baseline results (0.41 ± 0.19) with post-testing results (0.49 ± 0.18) during the stance condition FO ($p=0.03$, $d=0.61$). No other significant changes were observed for stance conditions FC, CO and CC. No participant was able to maintain a thirty-second unilateral stance for CC. Time-to-failure for each participant was recorded, where no statistically significant differences were observed.

4.3 Dynamic Balance

4.3.1 *Star Excursion Balance Test (SEBT)*

Figure 1 displays the mean reach distances per limb for this test. The results indicated that the majority of reach distances were not statistically significant following the TT. The only statistically significant difference in reach distance was observed for the anterior direction while standing on the right limb ($p<0.05$).

Fig. 1. *Diagram displaying mean reach distances(cm) during left leg stance as a relative percentage of anatomical leg length for pre and post-testing*.



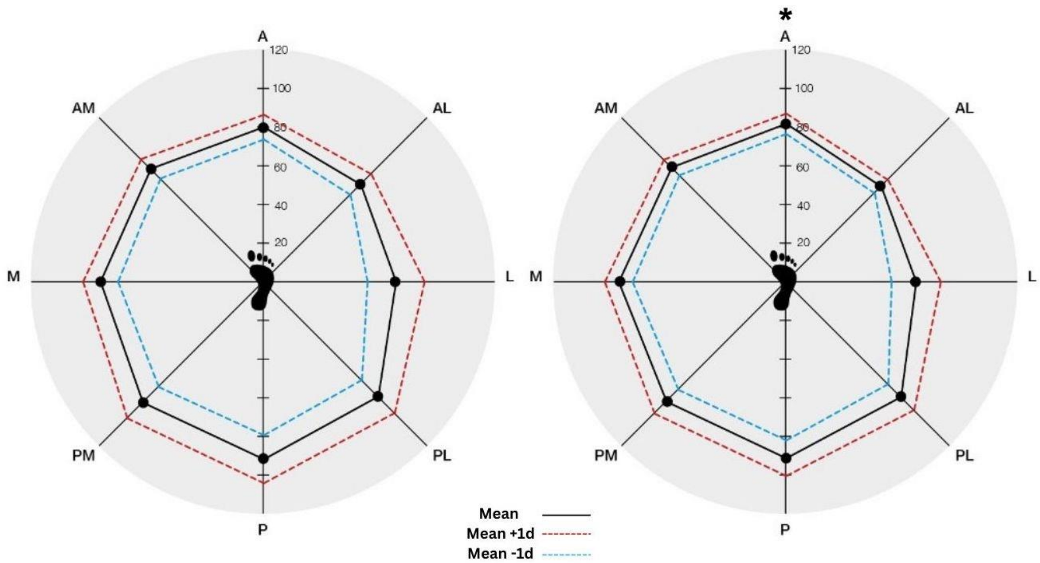
LEFT LEG STANCE
PRE

	Mean	Mean +1d	Mean -1d
Anterior [A]	78.4	71.2	85.6
Anterior Medial [AM]	81.6	75.5	87.7
Medial [M]	83.0	74.8	91.1
Posterior Medial [PM]	85.3	74.8	95.7
Posterior [P]	87.1	74.4	99.7
Posterior Lateral [PL]	79.7	66.6	92.9
Lateral [L]	62.2	49.7	74.6
Anterior Lateral [AL]	73.6	67.9	79.4

LEFT LEG STANCE
POST

	Mean	Mean +1d	Mean -1d
Anterior [A]	80.7	73.2	88.2
Anterior Medial [AM]	80.3	75.3	85.2
Medial [M]	83.4	76.4	90.4
Posterior Medial [PM]	88.1	80.4	95.7
Posterior [P]	90.6	81.4	99.7
Posterior Lateral [PL]	82.7	76.2	89.3
Lateral [L]	65.1	52.1	78.2
Anterior Lateral [AL]	71.3	64.9	77.7

Fig. 2. *Diagram displaying mean reach distances during a right leg stance (cm) as a relative percentage of anatomical leg length for pre and post-testing.*



RIGHT LEG STANCE
PRE

	—	----	----
Anterior [A]	80.3	86.7	73.9
Anterior Medial [AM]	83.0	90.1	75.9
Medial [M]	84.9	94.0	75.8
Posterior Medial [PM]	88.8	100.3	77.3
Posterior [P]	92.2	104.6	79.7
Posterior Lateral [PL]	84.2	96.3	72.1
Lateral [L]	68.7	83.5	53.9
Anterior Lateral [AL]	71.3	79.0	63.7

RIGHT LEG STANCE
POST

	—	----	----
Anterior [A]	82.2	87.5	76.9
Anterior Medial [AM]	84.2	89.9	78.5
Medial [M]	87.1	94.4	79.9
Posterior Medial [PM]	88.0	96.8	79.3
Posterior [P]	91.6	100.8	82.3
Posterior Lateral [PL]	84.5	94.1	75.0
Lateral [L]	67.6	80.4	54.8
Anterior Lateral [AL]	70.0	74.9	65.1

4.4 Jump Tests

4.4.1 Counter Movement Jump (CMJ)

During pre-testing the maximum jump height (cm) recorded was 29.88 ± 4.42 with no significant change in post-testing (p=0.38, d=0.25) . There were no significant changes in mean jump height (cm) during pre-testing (28.73 ± 4.13) when compared to post-testing (height) scores (p=0.30, d=0.30). The maximum flight time duration (s) recorded during pre-testing with no significant changes observed during post-testing (p=0.76, d=0.09). Similarly, no significant changes were found when comparing mean flight time duration for pre-testing (0.48 ± 0.04) and post-testing (p=0.39, d=0.25).

4.4.2 Single-Leg Counter Movement Jump (SLCMJ)

For SLCMJ there was a statistically significant difference between the pre and post-testing for all variables ($p<0.05$) with decreased performance in the post-test illustrated in Table 3 below.

Table 3

Statistically significant differences Optojump derived variables in the SLCMJ test between pre (non-fatigued) and post (fatigued) conditions.

Variable	PRE	POST	p.	d.
Maximum Jump Height (cm)	14.65 ± 2.70	13.17 ± 2.95	0.03*	0.62
Mean Jump Height (cm)	13.88 ± 2.50	12.36 ± 3.18	0.02*	0.63
Maximum Flight Time (s)	0.34 ± 0.03	0.33 ± 0.04	0.03*	0.69
Mean Flight Time (s)	0.34 ± 0.03	0.31 ± 0.04	0.03*	0.67

cm = centimeter, s = seconds, p. = statistical value, d=effect size (0.20-0.50 ‘small’; 0.5-0.79 ‘medium’; >0.80 ‘large’), * = represents statistical significance ($p<0.05$).

5. Discussion

Limited research pertaining to trail running-induced acute neuromuscular fatigue and postural control changes over any race distance is available. The purpose of the study was to investigate the change in postural control variables in a group of highly trained trail runners before and after a short (<42.2km) [5], offroad TT of 26.6km with 964m elevation gain. It was hypothesised that PC performance would deteriorate significantly across all test variables after the time trial. The main findings of this novel study included (i) significant increases in pre-post results for mediolateral and anteroposterior lengths for MCTSIB (ii) no significant pre-post difference for jump height and flight time for CMJ (iii) significant decrements in SLCMJ performance yet limited significant pre-post changes in any other unipedal tests including the SLMCTSIB and SEBT.

It is well understood that the aetiology of fatigue is dependent on several factors such as exercise type, intensity, duration, and neuromuscular conditions including muscle pattern activations and the type of muscular contractions [6,8,22]. These dependencies play a key role in comprehending the findings of this study. Due to the investigative nature of quantifying exercise-induced fatigue, pre-post measurements are common in test procedures. However, fatigue stimuli differ depending on whether the movement is generalised (involving the entire body) or localised (involving a specific muscle group) [8]. The short, competitive, off-road TT used as a fatigue stimulus in this study was approximately twenty-six km of distance with 964m of vertical elevation gain and with an average finishing time of 02:15:53 (hh:mm:ss). The results obtained from the current study lay sufficient grounds to consider (a) whether this TT was physically demanding enough to elicit measurable acute neuromuscular fatigue (b) whether training status and trail experience could be a mitigating factor of TR-induced acute neuromuscular fatigue.

This study evaluated various sources of proprioceptive information and postural sway in four static stance conditions. Albeit a valid and reliable test of static balance that is well documented in a clinical setting [24,25], limited literature exists where the MCTSIB coupled with triaxial accelerometery has been used for a pre-post exercise comparison on endurance runners. Thus, diluting the comparative instance among available literature. The current study found significant differences ($p<0.05$) in mediolateral sway (LML) post-TT in FO, FC and CC stance conditions. Furthermore, significant differences ($p<0.05$) in anteroposterior sway (LAP) were found post-TT in FO and CO stance conditions. Degache et al. (2018) investigated the time course of PC during an ultra-marathon trail race and found significant changes in LAP and LMP at the 50km mark. The current study found smaller increments of change, however, the TT route was almost half in distance and elevation compared to the route profile for the first 50km within the abovementioned study [7]. The changes in LAP could be explained by anatomical joint orientations when considering that LAP is under ankle control by plantar/dorsiflexors, inferring that PC is more stable in the frontal plane than the sagittal plane [7]. Previous literature has shown that fatigued ankle plantar flexors yield significant changes in LAP when compared to non-fatigued states [26]. Contrary to the hypothesis, this study did not find drastic differences in PC when comparing the impact of fatigue with eyes open and eyes closed. This is surprising due to the fact that when visual feedback is taken away, the ankle proprioceptive system should yield greater postural sway. The above finding could propose a correlation between training status and the standard of ankle proprioceptors. Furthermore, one should consider a point raised by Simoneau, Bégin and Teasdale

(2006) who suggest that increased cognition through task complexity could very well be a compensatory strategy to maintain and even improve balance ability in a fatigued state [27].

Dynamic stability was assessed using the SEBT and found significant changes in reach length post-TT for the anterior direction when standing on the right foot ($p<0.05$). No significant changes in reach length were found for any reach direction when standing on the left foot. Foot preferences were documented before pre-testing commences. Eleven out of the thirteen participants were right-footed. Therefore, the majority of participants' left foot could be classified as the stabilising limb (eg. the stabilising leg when kicking a ball), which could serve as a contributing factor to the lack of significant change found when performing the SEBT on the left foot. There appear to be conflicting findings in literature regarding the impact of fatigue on SEBT performance. The results of this study were partially in agreement with previous research by Zech et al. (2012) who, despite reporting degradations in postural control post fatigue, found no significant changes in mean SEBT reach distances. However, these results conflict with Gribble et al. (2012) and Sieb et al. (2013) who found reach distances to significantly decrease in a fatigued state. Differences in sample groups, fatigue stimuli and participants' athletic status are considered to be contributing factors towards the conflicting results.

Fatigue has been shown to lead to greater variability or noise in the afferent signal and thus, could negatively impact joint proprioception. However, in states of moderate fatigue, 1a afferents could be more sensitive to changes in neighbouring muscle fibre lengths and subsequently increase their firing rate [27]. Therefore, this increased sensitivity to change could aid the PCS in better identifying noise from other, possibly more important, proprioceptive input signals that contribute to maintaining a steady dynamic equilibrium. When one considers the above results coupled with training participant status and years spent trail running, it is worthwhile to consider that short trail running races could actually "switch on" the dynamic aspect of the PCS.

Neuromuscular performance was evaluated using the CMJ test. The current study found no significant changes for maximum and mean jump height as well as maximum and mean flight time when comparing baseline results to post-testing results. These findings are in agreement with Baiget et al. (2018) who found no changes in these CMJ variables in a study that investigated the effect of a 21.1km trail race on neuromuscular performance in a sample of recreational trail runners [22]. Despite discrepancies in distances (26km vs 21.1km), vertical displacement (964m vs 1940m) and participant training status (highly trained vs recreational), it appears that neuromuscular performance during trail races of less than 26km remains unaltered. Contrary to these findings, significant changes in CMJ performance were found following a 65km trail ultra-marathon ($p<0.05$) and a 166km trail ultra-marathon [20,28]. Obvious discrepancies are noted in route profile characteristics, however, these outcomes allow one to consider at what distance and level of elevation difficulty CMJ performance begins to decline for trail runners of varying training statuses.

Uni-pedal neuromuscular performance was also evaluated in this study using a modified, single-leg CMJ (SLCMJ). Significant pre-post differences were found for all SLCMJ variables. Maximum and mean jump height together with maximum and mean flight time significantly decreased in post-testing ($p<0.05$). Reductions in plantar flexor maximal contractions are present in literature [21] while other studies have confirmed fatigue in plantar and dorsiflexor muscles to be linked to increased unilateral postural sway (anteroposterior and mediolateral) [29]. The current study found only significant change in mediolateral sway for a unilateral stance condition despite all SLCMJ showing significant pre-post decrements. This lays sufficient grounds to consider whether certain postural compensation strategies and proprioceptive inputs play an active role to counteract or limit PC disturbances brought on by general neuromuscular fatigue.

Research shows that general muscular exercise impacts the sensitivity of different sensory receptors that make up the PCS [8]. Furthermore, it is proposed that disturbances in one sensory channel can be either entirely or partially compensated by another sensory channel. Disturbances in proprioceptive information have been noted to be more severe in impact-based locomotion than that of cycling, for example [8]. Running is associated with greater eccentric and concentric muscle contractions than walking, and thus places an exaggerated demand on the proprioceptive and mechanical processes which contribute to the maintenance of stability in motion [8]. However, certain compensatory strategies serve to limit the impact of general fatigue on postural control regulation. The findings of the current study appear to indicate the presence of peripheral fatigue at the level of the active muscle. Despite the physiological consequences at this level challenging the PCS and decreasing unilateral force production, the subsequent lack of significant change in proprioceptive test conditions where sensory inputs were challenged could indicate the presence of the compensatory mechanisms highlighted in previous literature [7, 9, 27] used to maintain adequate postural stability.

For ultra-marathon distance running events, pacing and nutritional intake strategies have been linked to limiting the extent of muscle damage and dehydration status, which in theory, could consolidate decrements in PC [7]. However, for shorter running events, such as the one simulated in this study, other compensatory strategies could be more appropriate in managing the effects of general neuromuscular fatigue on postural stability. When disturbances in proprioceptive sensitivity arise due to general fatigue, a greater contribution of cognitive resources can serve to limit any negative impeding effects on PC. Increased vigilance and attentional demand have been documented to plateau initial decrements in PC by increasing the frequency at which postural adjustments occur [7,8,27]. Paillard (2012) states that an increase in task vigilance the descending mechanism required to activate motor neurons of postural muscles better coordinates the integration of afferent feedback. Thus, improving the sensory detection capabilities needed to identify optimal balance demands via proprioceptive sensory sources. Furthermore, anticipatory strategies in the presence of foreseeable postural disturbances common in TR environments could contribute to reducing the magnitude of such disturbances by adjusting speed, stride lengths and approach.

It is plausible to assume that trail experience plays a part in the efficiency with which environmental disturbances are overcome. This is in agreement with what is known as the postural body scheme. Described as an internal representation of the body, the postural body scheme is said to be acquired by means of a learning process (i.e. trail running experience). The basis of this learning process stems more from body kinematics and kinetics and is not primarily based on sensory information [8]. Despite a small presence in literature, the concept of the postural body scheme presents a possible contributing factor to the results found in a sample of highly trained trail runners. It is important to note that this concept would serve as an addition to the broader PC equation where environmental learning and experience could see postural disturbances overcome more efficiently. Some literature suggests that the relationship between superior PC performance could be the result of repetitive and task-specific training experiences that result in improved motor responses [30]. Furthermore, it has been argued that experience (in this case training status) within an environment that elicits task-specific challenges could influence an individual's ability to better facilitate proprioceptive commands and visual feedback. With this in mind, training status, as categorised in literature [5], could be considered a dependency of TR-induced acute neuromuscular fatigue and considered in the aetiology of trail running-specific fatigue for future research concerning the influence of fatigue on PC. The results of the current study highlight that a short, competitive off-road time places a higher demand on PC regulation when compared to the demand required in a non-fatigued state.

6. Conclusion

There is sufficient evidence to suggest that whole-body exercises, like running, alter musculoskeletal performance and sensory proprioceptive inputs that ultimately degrade the effectiveness of the PCS to consolidate postural regulation [6–8,22]. The results of the current study suggest that a short, real-world, trail running time trial placed a greater demand on the PCS when compared to baseline test results. The findings of this study indicated significant changes in pre-post postural sway results for both LML and LAP for several stance conditions for the MCTSIB, thus substantiating the degradation of PC regulation. However, a lack of significant change for unilateral dynamic balance results could imply the initiation of postural compensatory strategies. A combination of training status, task experience and proprioceptive compensatory strategies appear to limit the magnitude that general neuromuscular fatigue had on PC regulation. It's possible that a greater contribution from cognitive resources such as increased awareness and attentional demand may have improved sensory detection capabilities needed to identify optimal balance demands via proprioceptive sensory sources.

Acknowledgements

The author would like to thank the Adapt2Move Laboratory regarding the use of testing equipment, Jonkershoek MTO for access to mountain trails for the TT and post-testing. Additionally, thanks are given to the Department of Exercise, Sport, and Lifestyle Medicine, University of Stellenbosch for their financial contributions to the study.

Conflict of Interest

There are no conflicts of interest to report.

References

[1] M. Fredericson, A.K. Misra, Epidemiology and Aetiology of Marathon Running Injuries, 2007.

[2] M.D. Hoffman, J.C. Ong, G. Wang, Historical analysis of participation in 161km ultramarathons in North America, International Journal of the History of Sport. 27 (2010) 1877–1891. https://doi.org/10.1080/09523367.2010.494385.

[3] N. Malliaropoulos, D. Mertyri, P. Tsaklis, Prevalence of Injury in Ultra Trail Running, Human Movement. 16 (2015) 52–59. https://doi.org/10.1515/humo-2015-0026.

[4] K.H. Schütte, J. Aeles, T.O. de Beéck, B.C. van der Zwaard, R. Venter, B. Vanwanseele, Surface effects on dynamic stability and loading during outdoor running using wireless trunk accelerometry, Gait Posture. 48 (2016) 220–225. https://doi.org/10.1016/j.gaitpost.2016.05.017.

[5] V. Scheer, P. Basset, N. Giovanelli, G. Vernillo, G.P. Millet, R.J.S. Costa, Defining Off-road Running: A Position Statement from the Ultra Sports Science Foundation, Int J Sports Med. 41 (2020) 275–284. https://doi.org/10.1055/a-1096-0980.

[6] C.S. Easthope, C. Hausswirth, J. Louis, R. Lepers, F. Vercruyssen, J. Brisswalter, Effects of a trail running competition on muscular performance and efficiency in well-trained young and master athletes, Eur J Appl Physiol. 110 (2010) 1107–1116. https://doi.org/10.1007/s00421-010-1597-1.

[7] F. Degache, J. van Zaen, L. Oehen, K. Guex, P. Trabucchi, G. Millet, Alterations in postural control during the world’s most challenging mountain ultra-marathon, PLoS One. 9 (2014). https://doi.org/10.1371/journal.pone.0084554.

[8] T. Paillard, Effects of general and local fatigue on postural control: A review, Neurosci Biobehav Rev. 36 (2012) 162–176. https://doi.org/10.1016/j.neubiorev.2011.05.009.

[9] S. Ehrström, M.P. Tartaruga, C.S. Easthope, J. Brisswalter, J.B. Morin, F. Vercruyssen, Short Trail Running Race: Beyond the Classic Model for Endurance Running Performance, Med Sci Sports Exerc. 50 (2018) 580–588. https://doi.org/10.1249/MSS.0000000000001467.

[10] R. Hammami, D.G. Behm, M. Chtara, A. ben Othman, A. Chaouachi, Comparison of static balance and the role of vision in elite athletes, J Hum Kinet. 41 (2014) 33–41. https://doi.org/10.2478/hukin-2014-0030.

[11] L. Freeman, G. Gera, F.B. Horak, M.T. Blackinton, M. Besch, L. King, Instrumented Test of Sensory Integration for Balance: A Validation Study, Journal of Geriatric Physical Therapy. 41 (2018) 77–84. https://doi.org/10.1519/JPT.0000000000000110.

[12] E. Antoniadou, X. Kalivioti, K. Stolakis, A. Koloniari, P. Megas, M. Tyllianakis, E. Panagiotopoulos, Reliability and validity of the mCTSIB dynamic platform test to assess balance in a population of older women living in the community, n.d. http://www.ismni.org.

[13] L. Freeman, G. Gera, F.B. Horak, M.T. Blackinton, M. Besch, L. King, Instrumented Test of Sensory Integration for Balance: A Validation Study, Journal of Geriatric Physical Therapy. 41 (2018) 77–84. https://doi.org/10.1519/JPT.0000000000000110.

[14] P.A. Gribble, J. Hertel, P. Plisky, Using the star excursion balance test to assess dynamic postural-control deficits and outcomes in lower extremity injury: A literature and systematic review, J Athl Train. 47 (2012) 339–357. https://doi.org/10.4085/1062-6050-47.3.08.

[15] M.J. Sabin, K.T. Ebersole, A.R. Martindale, J.W. Price, S.P. Broglio, Balance performance in male and female collegiate basketball athletes: influence of testing surface, n.d. https://journals.lww.com/nsca-jscr.

[16] T.R. Keith, T.A. Condon, A. Phillips, P.O. McKeon, D.L. King, Postural control strategies are dependent on reach direction in the star excursion balance test, International Journal of Athletic Therapy and Training. 21 (2016) 33–39. https://doi.org/10.1123/ijatt.2016-0004.

[17] L.K. Philpott, S.E. Forrester, K.A.J. van Lopik, S. Hayward, P.P. Conway, A.A. West, Countermovement jump performance in elite male and female sprinters and high jumpers, Proc Inst Mech Eng P J Sport Eng Technol. 235 (2021) 131–138. https://doi.org/10.1177/1754337120971436.

[18] C. Schwartz, B. Forthomme, J. Paulus, J.F. Kaux, O. Brüls, V. Denoël, J.L. Croisier, Reliability of unipodal and bipodal counter movement jump landings in a recreational male population, Eur J Sport Sci. 17 (2017) 1143–1152. https://doi.org/10.1080/17461391.2017.1353134.

[19] C.M.P. Meylan, K. Nosaka, J.P. Green, J.B. Cronin, Variability and influence of eccentric kinematics of unilateral vertical, horizontal, and lateral countermovement jump performance, n.d. www.nsca-jscr.org.

[20] D.J. Ramos-Campo, V. Ávila-Gandía, F. Alacid, F. Soto-Méndez, P.E. Alcaraz, F.J. López-Román, J.Á. Rubio-Arias, Muscle damage, physiological changes, and energy balance in ultra-

endurance mountain-event athletes, Applied Physiology, Nutrition and Metabolism. 41 (2016) 872–878. https://doi.org/10.1139/apnm-2016-0093.

[21] G.Y. Millet, K. Tomazin, S. Verges, C. Vincent, R. Bonnefoy, R.C. Boisson, L. Gergelé, L. Féasson, V. Martin, Neuromuscular consequences of an extreme mountain ultra-marathon, PLoS One. 6 (2011). https://doi.org/10.1371/journal.pone.0017059.

[22] E. Baiget, J. Peña, X. Borras, T. Caparrós, J.L. López, F. Marin, J. Coma, E. Comerma, Effects of a trail mountain race on neuromuscular performance and hydration status in trained runners, Journal of Sports Medicine and Physical Fitness. 58 (2018) 43–49. https://doi.org/10.23736/S0022-4707.16.06792-X.

[23] J. Cohen, Statistical power analysis for the behavioral sciences, L. Erlbaum Associates, 1988.

[24] E. Antoniadou, X. Kalivioti, K. Stolakis, A. Koloniari, P. Megas, M. Tyllianakis, E. Panagiotopoulos, Reliability and validity of the mCTSIB dynamic platform test to assess balance in a population of older women living in the community, n.d. http://www.ismni.org.

[25] L. Freeman, G. Gera, F.B. Horak, M.T. Blackinton, M. Besch, L. King, Instrumented Test of Sensory Integration for Balance: A Validation Study, Journal of Geriatric Physical Therapy. 41 (2018) 77–84. https://doi.org/10.1519/JPT.0000000000000110.

[26] P. Corbeil, J.S. Blouin, F. Bégin, V. Nougier, N. Teasdale, Perturbation of the postural control system induced by muscular fatigue, Gait Posture. 18 (2003) 92–100. https://doi.org/10.1016/S0966-6362(02)00198-4.

[27] M. Simoneau, F. Bégin, N. Teasdale, The effects of moderate fatigue on dynamic balance control and attentional demands, J Neuroeng Rehabil. 3 (2006). https://doi.org/10.1186/1743-0003-3-22.

[28] G. Millet, R. Lepers, G. Lattier, V. Martin, N. Babault, N. Ma• uletti, Influence of ultra-long-term fatigue on the oxygen cost of two types of locomotion, 2000.

[29] T.M. Lundin, J.W. Feuerbach, M.D. Grabiner, Effect of Plantar Flexor and Dorsiflexor Fatigue on Unilateral Postural Control, by Human Kinetics Publishers, Inc, 1993.

[30] R. Hammami, D.G. Behm, M. Chtara, A. ben Othman, A. Chaouachi, Comparison of static balance and the role of vision in elite athletes, J Hum Kinet. 41 (2014) 33–41. https://doi.org/10.2478/hukin-2014-0030.

CHAPTER 5: CONCLUSION

5.1 INTRODUCTION

The aim of the current research study was to measure the change in select postural control variables following a short, real-world, trail run time trail (26km; +900m) in a sample of highly trained trail runners. This chapter provides a conclusion to the current study based on the hypotheses stated in the first chapter. Additionally, the current chapter includes practical applications related to the findings of this study, study limitations as well as recommendations for future research. Due to the fact that this thesis document has been written in article format, the current chapter does not follow the structure associated with conventional discussion chapters. An in-depth discussion of the study's hypotheses is available in the research article in Chapter 4.

Hypothesis statement

It was hypothesised that postural control performance for the entire study sample would be significantly reduced across all test variables following the TT fatigue stimulus. As explained per test, this included increased postural sway lengths for LAP and LML (MCTSIB and SLMCTSIB); shorter reach distances (SEBT); decreased maximum and mean jump heights as well as decreased maximum and mean flight times (CMJ and SLCMJ).

The null hypothesis stated that there will be no significant difference in postural control performance in all tests (MCTISB, SLMCTSIB, SEBT, CMJ, SLCMJ) when comparing pre-and post-time trial performance results for the entire study sample.

The current study rejects the null hypothesis. The results of the current study indicated that a short, real-world trail run TT (26km, +900m) placed a high enough demand on the PCS to alter select PC variables, despite not all variables being significantly different following the fatigue stimulus. Statistically significant increases ($p<0.05$) in mediolateral sway were observed in stance conditions FO, FC and CC while anteroposterior sway showed significant increases ($p<0.05$) for stance conditions FO, and CO during the MCTSIB. Degache et al. (2019) found similar changes in mediolateral and anteroposterior sway at the 50km mark of an ultra-distance trail event. These changes could be due to significant muscle damage of the dorsi and plantar flexor muscles of the lower limbs. It is said that running generates a larger magnitude of damage for joint, muscle and tendon proprioception thus decreasing the efficiency of neural pathways to deliver sensory inputs needed to maintain an optimum equilibrium. Subsequently, PCS also decreases in efficiency as a greater demand is placed upon PC regulation in a fatigued state (Degache et al., 2019). However, the results of SLMCTSIB conflict with the above.

A statistically significant increase ($p<0.05$) in mediolateral sway was observed in the SLMCTSIB for the FO stance condition. However, no other variables for the SLMCTSIB were significantly altered following the TT ($p>0.05$). Regarding the SEBT, the only statistically significant difference in reach distance was observed for the anterior direction while standing on the right limb ($p<0.05$) with no other reach distances indicating significant changes during post-testing. A subsequent lack of change in PC control variables during a unilateral test indicates that some or other strategy may be initiated to counteract the challenges posed upon the PCS. Postural compensatory strategies have been documented in literature involving general activities of walking and running (Simoneau, Begin and Teasdale, 2006; Paillard, 2012). The most plausible strategy would be that of fatigue-induced increases in attentional demand that served to kickstart proprioceptive awareness by initiating a more sensitive and critical selection of proprioceptive sensory inputs. Furthermore, Paillard (2012) elaborates on an internal representation of the body in space called the body scheme. It is stated that the body scheme does not rely solely on sensory inputs and considers body kinetics and kinematics in terms of interpreting body orientation. It is important to note that the body scheme may be developed through a learning effect where task experience could further develop this internal representation. It may be possible for highly trained trail runners, who frequent uneven trails, could have a well-developed body scheme that contributes towards maintaining equilibrium.

A pre-post comparison of CMJ test results indicated no statistically significant difference in jump variables ($p>0.05$). For the SLCMJ test, however, significant decrements in all jump test variables (maximum and mean jump height; maximum and mean flight time) were observed ($p<0.05$). Significant decreases in bipedal jump test variables (maximum and mean jump height) following prolonged trail races varying from two and a half hours to seven hours have been reported in literature (Baiget et al., 2018). The current study had an average TT finishing time of two hours and nine minutes and observed no significant changes in CMJ jump test results post-TT. The lack of change in jump test variables for TR events less than 42.2km has also been documented (Ehrstrom et al., 2017). These authors made use of a 15km TR event in measuring the impact of TR-induced fatigue in a sample of highly trained trail runners and suggest that their chosen test distance may have been insufficient in detecting muscle damage and force reduction. Furthermore, it is mentioned that the training status and participation in general strength training may serve as contributing factors to the reasoning behind the lack of change in select jump variables. The results of this study are partially in agreement with these authors. Regarding the SLCMJ, previous studies have confirmed fatigue in plantar and dorsiflexor muscles to be linked to increased unilateral postural sway (anteroposterior and mediolateral) (Lundin et al., 1993; Millet et al., 2011). The current study found only a significant change in mediolateral sway for a unilateral stance condition despite all SLCMJ showing significant pre-post decrements. This lays sufficient grounds to consider whether certain postural compensation strategies and proprioceptive inputs play an active role to counteract or limit PC disturbances brought on by general neuromuscular fatigue.

5.1 PRACTICAL APPLICATIONS

In conclusion, a short, real-world, trail run TT (26km +900m) can negatively impact PC regulation in a sample of highly trained trail runners. Based on the premises that lead the rejection of the null hypothesis, the results appear to indicate that highly trained trail runners are well adapted to the rigours of short-distance, competitive TR. This lays grounds to suggest that through training status, task experience, and proprioceptive compensatory strategies, highly trained trail runners could have superior PC ability and be better equipped to limit the impact of general neuromuscular fatigue. Although it wasn't measured, it's possible that cognitive compensatory strategies may also play a role in reducing the impact of general neuromuscular fatigue on PC performance. The thesis could contribute to the limited literature on TR-induced acute neuromuscular fatigue and help further understand how this type of fatigue impacts PC.

These results have important practical implications for trail runners, regardless of training status. As the popularity of TR and TR events continues to grow, it is vital that both new and experienced trail runners understand the impact TR-induced acute neuromuscular fatigue can have on PC regulation. Understanding how and at what magnitude short-distance, competitive TR can impact the musculoskeletal system and PCS better prepare individuals for race preparation and events. As outlined in Chapter 2, TR takes place on uneven terrain which presents the need to overcome frequent disruptions in PC. It is important to understand that the system responsible for facilitating these disruptions, the PCS, is susceptible to general fatigue. Simply put, as fatigue increases, the ability of the PCS to efficiently tend to sensory inputs decreases. However, it appears that trail experience and training status could directly contribute to the development of an internal orientation that serves to limit the negative impacts of general fatigue on PC and improve proprioceptive awareness.

Individuals wanting to participate in the sport of TR should consider the following guidelines. First and foremost, TR challenges the PCS due to its unique demand of navigating undulating and uneven surfaces. Therefore, in order to adapt to these challenges and limit the subsequent impacts, it is recommended that training programmes incorporate field sessions that take place on uneven and undulating trails. It is advisable for beginners to consult with an industry professional regarding the frequency and duration of these sessions. Second, an increase in trail experience on uneven terrains could further develop the proprioceptive awareness and attentional awareness required to effectively overcome postural disturbances during TR. Within reason, trail runners of any training status should consider spending more time on technical, uneven terrain to improve dynamic stability. Third, intervention strategies to improve PC and proprioceptive ability could be a beneficial addition to the portion of general training programmes. Incorporating exercises where PC and proprioceptive sensory inputs are challenged in both a static and dynamic setting could serve to enhance stability and improve sensory selection to further develop an internal representation of the body in space.

5.2 STUDY LIMITATIONS

The current study successfully executed a real-world investigation. However, the nature of the study design presented several limitations that are worth mentioning.

The first limitation involved participant withdrawals. Two participants withdrew from this research study during the recruitment and pre-testing phases. One participant withdrew due to COVID-19 complications and the advised isolation period overlapped that of data collection. Another participant withdrew for personal reasons and thus, did not participate in the study. In addition, the COVID-19 pandemic enforced an eight-month delay for the current study by limiting non-essential human contact. Subsequently, physical interaction between researcher and supervisor was limited and the data collection timeline was delayed.

The second limitation was that due to variable timing between TT finishers, the order of post-testing was not able to mimic that of pre-testing. There was a need to begin post-testing as soon as possible after participants completed the TT, in order to limit any recovery in the PCS that may take place over time. Certain tests took longer to complete than others, therefore, the order of the post-testing battery was randomised based on station availability to ensure waiting time was kept as short as possible. Furthermore, the average waiting time after the second finisher was fourteen minutes, but waiting times varied between participants with some waiting longer than fourteen minutes.

The third limitation was that due to time constraints, the SLMCTSIB was only performed on the leg.

The final limitation was the difference in floor surface differed for pre and post-testing. Pre-testing took place in the Adapt2Move Laboratory where the flooring was solid, hard-flooring. The floor surface during post-testing was wooden, and thus, could have influenced jump test results.

5.3 FUTURE RESEARCH RECOMMENDATIONS

Limited research is available regarding the relationship between TR, fatigue and PC. The current study contributes toward expanding this area of research. Future studies could provide further contributions by replicating the current study (a) in a sample of recreational trail runners and (b) for TR race distances ranging between 27km and 42.2km.

Little is known about how TR-induced fatigue may impact PC in a sample of recreational trail runners. A sample group such as this might spend less time on uneven terrains and therefore, be less accustomed to the frequent postural disruptions associated with TR environments. Considering the impact the TT in the current study had on select PC variables in a sample of highly trained trailed runners, replicating the current study on a sample of recreational trail runners might provide insight into whether the magnitude of fatigue could be higher for less experienced trail runners. Whether or not this may be the case, the findings of a study such as this could contribute to a framework of literature which may guide future studies to explore other concepts relating to PC and fatigue within the sport of TR.

Current research surrounding the impact of TR-induced fatigue has primarily been investigated during formal trail races where distances exceed marathon distance (>42.2km) (Millet et al., 2011a; Ramos-Campo et al., 2016). Significant changes in decreases in CMJ jump heights were found in these studies which suggest that ultra-distance TR events could be detrimental to the musculoskeletal system. In terms of short-distance TR, one study has sought to investigate the impact of a 15km trail running route on muscular performance in a sample of highly trained trailer runners (Ehrstrom et al., 2017). The findings of this study are partially in alignment with that of the current study where no significant differences were found for pre-post CMJ results. To the best of our knowledge, only one other study has investigated the time-course change in PC variables during a TR event (ultra-marathon distance) (Degache et al., 2019). The results of this study indicated a significant decrease in PC variables at the 50km mark. However, the time-course of PC was classified as bi-phasic due to the plateau in PC decrements at 100km. It is noteworthy to mention that this event is classified as the *world's toughest mountain marathon*, therefore one should consider aetiologies of fatigue, such as distance and elevation, when comparing related studies. The current study appears to align with the beginning stages of a bi-phasic time-course theory due to significant differences in some PC variables post-TT. It is yet to be discovered whether distances between 27km and 42.2km may elicit similar fatigue-induced PC decrements where the results could substantiate or fit into a bi-phasic time-course theory of PC during TR. Such findings could further the understanding of TR-induced fatigue and the impact on PC over a wider variety of running distances.

REFERENCES

Abu-Faraj, Z.O., Harris, G.F., Smith, P.A. and Hassani, S., 2015. Human gait and clinical movement analysis. *Wiley Encyclopedia of Electrical and Electronics Engineering*, pp.1-34.

Akbari, M., Karimi, H., Farahini, H. and Faghihzadeh, S., 2006. Balance problems after unilateral lateral ankle sprains. *Journal of rehabilitation research and development*, *43*(7), pp.819-824.

Antoniadou, E., Kalivioti, X., Stolakis, K., Koloniari, A., Megas, P., Tyllianakis, M. and Panagiotopoulos, E., 2020. Reliability and validity of the mCTSIB dynamic platform test to assess balance in a population of older women living in the community. *Journal of musculoskeletal & neuronal interactions*, *20*(2), pp.185.

Baiget, E., Pena, J., Borràs, X., Caparros, T., López, J.L., Marin, F., Coma, J. and Comerma, E., 2016. Effects of a trail mountain race on neuromuscular performance and hydration status in trained runners. *The Journal of Sports Medicine and Physical Fitness*, *58*(1-2), pp.43-49.

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

Browne, J.E. and O'Hare, N.J., 2001. Review of the different methods for assessing standing balance. *Physiotherapy*, *87*(9), pp.489-495.

Byrne, C., Twist, C. and Eston, R., 2004. Neuromuscular function after exercise-induced muscle damage. *Sports medicine*, *34*(1), pp.49-69.

Cetin, N., Bayramoglu, M., Aytar, A., Surenkok, O. and Yemisci, O.U., 2008. Effects of lower-extremity and trunk muscle fatigue on balance. *The Open Sports Medicine Journal*, *2*(1).

Cohen, J., 1988. *Statistical power analysis for the behavioral sciences*. Routledge.

Cole, M.H., Van Den Hoorn, W., Kavanagh, J.K., Morrison, S., Hodges, P.W., Smeathers, J.E. and Kerr, G.K., 2014. Concurrent validity of accelerations measured using a tri-axial inertial measurement unit while walking on firm, compliant and uneven surfaces. *PloS one*, *9*(5), p.e98395.

Dabbs, N. and Chander, H., 2018. The Effects of Exercise Induced Muscle Damage on Knee Joint Torque and Balance Performance. *Sports*, 6(3), p.101.

Degache, F., Van Zaen, J., Oehen, L., Guex, K., Trabucchi, P. and Millet, G., 2014. Alterations in postural control during the world's most challenging mountain ultra-marathon. *PloS one*, *9*(1), p.e84554.

DiStefano, L.J., Clark, M.A. and Padua, D.A., 2009. Evidence supporting balance training in healthy individuals: a systemic review. *The Journal of Strength & Conditioning Research*, *23*(9), pp.2718-2731.

Dugan, S.A. and Bhat, K.P., 2005. Biomechanics and analysis of running gait. *Physical Medicine and Rehabilitation Clinics*, *16*(3), pp.603-621.

Easthope, C.S., Hausswirth, C., Louis, J., Lepers, R., Vercruyssen, F. and Brisswalter, J., 2010. Effects of a trail running competition on muscular performance and efficiency in well-trained young and master athletes. *European journal of applied physiology*, *110*(6), pp.1107-1116.

Ehrström, S., Tartaruga, M.P., Easthope, C.S., Brisswalter, J., Morin, J.B. and Vercruyssen, F., 2018. Short trail running race: beyond the classic model for endurance running performance. *Medicine and science in sports and exercise*, *50*(3), pp.580-588.

Filipa, A., Byrnes, R., Paterno, M.V., Myer, G.D. and Hewett, T.E., 2010. Neuromuscular training improves performance on the star excursion balance test in young female athletes. *Journal of orthopaedic & sports physical therapy*, *40*(9), pp.551-558.

Forza, J. and Edmundson, C.J., 2019. Comparison between Gyko inertial sensor and Chrono jump contact mat for the assessment of Squat Jump, Countermovement Jump and Abalakov Jump in amateur male volleyball players, amateur male rugby players and in high school students. *Journal of Multidisciplinary Engineering Science and Technology*, *6*, pp.9982-9988.

Fredericson, M. and Misra, A.K. (2007) "Epidemiology and Aetiology of marathon running injuries," *Sports Medicine*, 37(4), pp. 437–439. Available at: https://doi.org/10.2165/00007256-200737040-00043.

Gathercole, R.J., Stellingwerff, T. and Sporer, B.C., 2015. Effect of acute fatigue and training adaptation on countermovement jump performance in elite snowboard cross athletes. *The Journal of Strength & Conditioning Research*, *29*(1), pp.37-46.

Gelinas, L., Pierce, R., Winkler, S., Cohen, I.G., Lynch, H.F. and Bierer, B.E., 2017. Using social media as a research recruitment tool: ethical issues and recommendations. *The American Journal of Bioethics*, *17*(3), pp.3-14.

Giandolini, M., Horvais, N., Rossi, J., Millet, G.Y., Morin, J.B. and Samozino, P., 2017. Effects of the foot strike pattern on muscle activity and neuromuscular fatigue in downhill trail running. *Scandinavian Journal of Medicine & Science in Sports*, *27*(8), pp.809-819.

Gribble, P.A., Hertel, J. and Plisky, P., 2012. Using the Star Excursion Balance Test to assess dynamic postural-control deficits and outcomes in lower extremity injury: a literature and systematic review. *Journal of athletic training*, *47*(3), pp.339-357.

Grimmer, S., Ernst, M., Günther, M. & Blickhan, R., 2008. Running on uneven ground: leg adjustment to verticle steps and self-stability. *The Journal of Experimental Biology,* Volume 211, pp. 2989 - 3000.

Hale, S.A., Hertel, J. and Olmsted-Kramer, L.C., 2007. The effect of a 4-week comprehensive rehabilitation program on postural control and lower extremity function in individuals with chronic ankle instability. *Journal of orthopaedic & sports physical therapy*, *37*(6), pp.303-311.

Hammami, R., Behm, D.G., Chtara, M., Othman, A.B. and Chaouachi, A., 2014. Comparison of static balance and the role of vision in elite athletes. *Journal of human kinetics*, *41*, p.33.

Hatchett, A., Armstrong, K., Parr, B., Crews, M. and Tant, C., 2018. The effect of a curved non-motorized treadmill on running gait length, imbalance and stride angle. *Sports*, *6*(3), p.58.

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

Hrysomallis, C., 2011. Balance ability and athletic performance. *Sports medicine*, *41*(3), pp.221-232.

Jarchi, D., Pope, J., Lee, T.K., Tamjidi, L., Mirzaei, A. and Sanei, S., 2018. A review on accelerometry-based gait analysis and emerging clinical applications. *IEEE reviews in biomedical engineering*, *11*, pp.177-194.

Jaworski, J., Ambroży, T., Lech, G., Spieszny, M., Bujas, P., Żak, M. and Chwała, W., 2020. Absolute and relative reliability of several measures of static postural stability calculated using a GYKO inertial sensor system. *Acta Bioeng Biomech*, *22*, pp.1-14.

Kavanagh, J.J. and Menz, H.B., 2008. Accelerometry: a technique for quantifying movement patterns during walking. *Gait & posture*, *28*(1), pp.1-15.

Keith, T.R., Condon, T.A., Phillips, A., McKeon, P.O. and King, D.L., 2016. Postural control strategies are dependent on reach direction in the star excursion balance test. *International Journal of Athletic Therapy and Training*, *21*(6), pp.33-39.

Kharb, A., Saini, V., Jain, Y.K. and Dhiman, S., 2011. A review of gait cycle and its parameters. *IJCEM International Journal of Computational Engineering & Management*, *13*, pp.78-83.

Oh, B., Lee, K.J., Zaslawski, C., Yeung, A., Rosenthal, D., Larkey, L. and Back, M., 2017. Health and well-being benefits of spending time in forests: Systematic review. *Environmental health and preventive medicine*, *22*(1), pp.1-11.

Lemire, M., Hureau, T.J., Remetter, R., Geny, B., Kouassi, B.Y., Lonsdorfer, E., Isner-Horobeti, M.E., Favret, F. and Dufour, S.P., 2020. Trail runners cannot reach vo2max during a maximal incremental downhill test. *Med Sci Sports Exerc*, *52*(5), pp.1135-1143.

Lesinski, M., Hortobágyi, T., Muehlbauer, T., Gollhofer, A. and Granacher, U., 2015. Effects of balance training on balance performance in healthy older adults: a systematic review and meta-analysis. *Sports medicine*, *45*(12), pp.1721-1738.

Lohman III, E. B., Sackiriyas, K. S. B. & Swen, R. W., 2011. A comparison of the spatiotemporal parameters, kinematics, and biomechanics between shod, unshod, and minimally supported running as compared to walking. *Physical Therapy in Sport,* 12(4), pp. 151 - 163.

Lundin, T.M., Feuerbach, J.W. and Grabiner, M.D., 1993. Effect of plantar flexor and dorsiflexor fatigue on unilateral postural control. *Journal of Applied Biomechanics*, *9*(3), pp.191-201.

Malliaropoulos, N., Mertyri, D. and Tsaklis, P., 2015. Prevalence of injury in ultra trail running. *Human Movement*, *16*(2), pp.55-59.

Massion, J., 1992. Movement, posture and equilibrium: interaction and coordination. *Progress in neurobiology*, *38*(1), pp.35-56.

Millet, G.Y., 2011. Can neuromuscular fatigue explain running strategies and performance in ultra-marathons?. *Sports medicine*, *41*(6), pp.489-506.

Millet, G.Y., Tomazin, K., Verges, S., Vincent, C., Bonnefoy, R., Boisson, R.C., Gergelé, L., Féasson, L. and Martin, V., 2011. Neuromuscular consequences of an extreme mountain ultra-marathon. *PloS one*, *6*(2), p.e17059.

Nakagawa, L. and Hoffman, M., 2004. Performance in static, dynamic, and clinical tests of postural control in individuals with recurrent ankle sprains. *Journal of Sport Rehabilitation*, *13*(3).

Novacheck, T., 1998. The biomechanics of running. *Gait and Posture,* Volume 7, pp. 77 - 95.

Olmsted, L.C., Carcia, C.R., Hertel, J. and Shultz, S.J., 2002. Efficacy of the star excursion balance tests in detecting reach deficits in subjects with chronic ankle instability. *Journal of athletic training*, *37*(4), p.501.

Paillard, T., 2012. Effects of general and local fatigue on postural control: a review. *Neuroscience & Biobehavioral Reviews*, *36*(1), pp.162-176.

Panjan, A. and Sarabon, N., 2010. Review of methods for the evaluation of human body balance. *Sport Science Review*, *19*(5-6), p.131.

Place, N., Lepers, R., Deley, G.A.E.L.L.E. and Millet, G.Y., 2004. Time course of neuromuscular alterations during a prolonged running exercise. *Medicine and science in sports and exercise*, *36*, pp.1347-1356.

Plisky, P.J., Rauh, M.J., Kaminski, T.W. and Underwood, F.B., 2006. Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *Journal of orthopaedic & sports physical therapy*, *36*(12), pp.911-919.

Powden, C.J., Dodds, T.K. and Gabriel, E.H., 2019. The reliability of the star excursion balance test and lower quarter Y-balance test in healthy adults: a systematic review. *International journal of sports physical therapy*, *14*(5), p.683.

Ramos-Campo, D., Ávila-Gandía, V., Alacid, F., Soto-Méndez, F., Alcaraz, P., López-Román, F. And Rubio-Arias, J., 2016. Muscle Damage, Physiological Changes, And Energy Balance In Ultra-Endurance Mountain-Event Athletes. *Applied Physiology, Nutrition, And Metabolism*, 41(8), pp.872-878.

Ricotti, L., 2011. Static and dynamic balance in young athletes. *Journal of human sport and exercise*, *6*(4), pp.616-628.

Rothschild, C.E., 2012. Primitive running: a survey analysis of runners' interest, participation, and implementation. *The Journal of Strength & Conditioning Research*, *26*(8), pp.2021-2026.

Sabin, M.J., Ebersole, K.T., Martindale, A.R., Price, J.W. and Broglio, S.P., 2010. Balance performance in male and female collegiate basketball athletes: influence of testing surface. *The Journal of strength & conditioning research*, *24*(8), pp.2073-2078.

Scheer, V., 2019. Participation trends of ultra endurance events. *Sports medicine and arthroscopy review*, *27*(1), pp.3-7.

Scheer, V., Basset, P., Giovanelli, N., Vernillo, G., Millet, G.P. and Costa, R.J., 2020. Defining off-road running: a position statement from the Ultra Sports Science Foundation. *International journal of sports medicine*, *41*(05), pp.275-284.

Schütte, K. H. *et al*., 2016. Surface effects on dynamic stability and loading during outdoor running using wireless trunk accelerometry. *Gait & Posture,* Volume 48, pp. 220 - 225.

Schmidt, C.E., 2013. Reducing muscular fatigue in trail running: mechanisms and strategies (Doctoral dissertation, Université Nice Sophia Antipolis; University of Sydney).
.

Simoneau, M., Bégin, F. and Teasdale, N., 2006. The effects of moderate fatigue on dynamic balance control and attentional demands. *Journal of neuroengineering and rehabilitation*, *3*(1), pp.1-9.

Stiffler, M.R., Sanfilippo, J.L., Brooks, M.A. and Heiderscheit, B.C., 2015. Star Excursion Balance Test performance varies by sport in healthy division I collegiate athletes. *Journal of Orthopaedic & Sports Physical Therapy*, *45*(10), pp.772-780.

Svenningsen, F.P., Pavailler, S., Giandolini, M., Horvais, N. and Madeleine, P., 2020. A narrative review of potential measures of dynamic stability to be used during outdoor locomotion on different surfaces. *Sports biomechanics*, *19*(1), pp.120-140.

Twomey, R., Aboodarda, S.J., Kruger, R., Culos-Reed, S.N., Temesi, J. and Millet, G.Y., 2017. Neuromuscular fatigue during exercise: Methodological considerations, etiology and potential role in chronic fatigue. *Neurophysiologie Clinique/Clinical Neurophysiology*, *47*(2), pp.95-110.

Vernillo, G., Giandolini, M., Edwards, W. B., Morin, J. B., Samozino, P., Horvais, N., & Millet, G. Y. (2017). Biomechanics and Physiology of Uphill and Downhill Running. *Sports Medicine, 47*(4), 615–629.

Voloshina, A. S. & Ferris, D. P., 2015. Biomechanics and energetics of running on uneven terrain. *The Journal of Experimental Biology,* Volume 218, pp. 711 - 719.

Willis, S.J., Gellaerts, J., Mariani, B., Basset, P., Borrani, F. and Millet, G.P., 2019. Level versus uphill economy and mechanical responses in elite ultratrail runners. *International journal of sports physiology and performance*, *14*(7), pp.1001-1005.

APPENDICES

APPENDIX A: RECRUITMENT FLYER

APPENDIX B: INFORMED CONSENT FORM

TITLE OF RESEARCH PROJECT:

The change in postural control in highly trained trail runners following a short, competitive, off-road time trial	
DETAILS OF PRINCIPAL INVESTIGATOR (PI):	
Title, first name, surname: Mr, Nicholas Price	**Ethics reference number:** **19119**
Full postal address: **24 Prospect Hill Road Wynberg, 7800**	**PI Contact number:** 072 775 2761

We would like to invite you to take part in a research project. Please take some time to read the information presented here, which will explain the details of this project. Please ask the study staff any questions about any part of this project that you do not fully understand. It is very important that you are completely satisfied that you clearly understand what this research entails and how you could be involved. Also, your participation is **entirely voluntary** and you are free to decline to participate. In other words, you may choose to take part, or you may choose not to take part. Nothing bad will come of it if you say no: it will not affect you negatively in any way whatsoever. Refusal to participate will involve no penalty or loss of benefits or reduction in the level of care to which you are otherwise entitled. You are also free to withdraw from the study at any point, even if you do agree to take part initially.

The Health Research Ethics Committee at Stellenbosch University has approved this study**.** The study will be conducted according to the ethical guidelines and principles of the international Declaration of Helsinki, the South African Guidelines for Good Clinical Practice (2006), the Medical Research Council (MRC) Ethical Guidelines for Research (2002), and the Department of Health Ethics in Health Research: Principles, Processes and Studies (2015).

What is this research study all about?

This Masters research project will be conducted at the Department of Sport Science at the University of Stellenbosch. All testing will be conduct at the department within a private scientific laboratory while the fatigue stimulus time trial run will take place on a popular, public and clearly marked mountain route within the Jonkershoek Nature Reserve

The study aims to highlight the importance of postural control when influenced by fatigue. The findings of this study could lead to the recommended inclusion of balance training into training programs of highly trained trail running athletes. We will be testing postural control both before and after the time trial in order to obtain the relative results and examine the impact of fatigue on postural control.

You will be required to complete a questionnaire (10-15 mins) that will give us athlete information as well as help sample participants that fall under the criteria needed to partake in the study. If you tick all the right boxes, then you will be invited to participate in the research project. The pre-time trial testing (30 mins) will consist of basic bodily measures including height, and weight as well as various balance and jump tests. You will also be invited to complete a familiarization session on the time trial route as part of the pre-time trial testing. Following the familiarization sessions and pre-time trial testing, the you will be informed the date of the time trial and prompted to refrain from vigorous exercise and alcohol consumption for at least 24 hours before time trail. The time trial may last between 2 to 3 hours depending on yourself as well as weather conditions. Within 20mins after time trial completion, the post testing will commence (30 mins). We will be using the following measurement tools: Gyko Accelerometer (measuring balance); Optojump System (measuring how high you jump) and 2D video analysis (to assess the movement in your knees when you land after the jump tests).

Any and all data collected by the primary and secondary researchers of the study will be completely confidential, anonymous and only accessible to the primary and secondary researchers. This information will be stored on a password-protected laptop, as well as password-protect cloud storage for back up purposes. During any filming, no faces will be shown in these videos as only the lower limbs will be filmed. Individual participant codes will be allocated to each participant in order to maintain confidentiality and rights to privacy. All data collected during this research study will be stored for a maximum period of 5 years and any data shared with external parties such as statisticians or technical equipment experts will be anonymized in order to protect your identity.

Please note that the researchers will cover all costs involved with any research-related injuries that may occur during either testing or the time trial itself.

Please note that all testing procedures will be conducted under the official healthy and safety guidelines in line with the Covid-19 pandemic.

Why do we invite you to participate?

We invite you to participate should you reach all the participation inclusion criteria (which includes being a male, highly trained trail runner with an average weekly training milage of between 75km-90km). By participating in the study you will be aiding the progression of scientific research within the field of trial running and postural control.

What will your responsibilities be?

Your responsibilities will be to have efficient and open communication with all official correspondents involved in the study (primary and secondary researchers); arrive on time to all agreed upon meetings; be open and honest about any illness/injuries before/during/after the study and give your all during the maximal effort time trial.

Refrain from vigorous exercise and alcohol consumption for at least 24 hours before time trail. You must be self-sufficient during the time trial (carrying own water, space blanket, whistle, food and emergency provisions). You must adhere to all COVID-19 safety guidelines (wearing a mask and maintaining a social distance of at least 1.5m as far as possible (mask not required during the time trial due to it being classified as vigorous activity and you will be running alone). You will be required to sanitize your hands with provided alcohol based sanitizer before meeting with researchers or entering testing facilities. You will be required to complete a COVID-19 health check prior to all testing session. In addition, if you have any symptoms of COVID-19, you will not be allowed to participate until a period of 14 days has passed and you are no longer experiencing any COVID-19 symptoms.

Will you benefit from taking part in this research?

Yes. Following the research data collection, you will receive a comprehensive report outlining your balance ability, knee stability and areas which need improvement. Beyond this, your participation in the study may benefit the entire trail running community in terms of the potential importance of postural control within the sport.

Are there any risks involved in your taking part in this research?

The risks included within the study align with the risks involved in any trail running event (well familiar with highly trained trail runners) as well we the unlikely risk of harm due to balance assessments. Risk of injury and death; loss of valuable items and exposure to possible environment extremes (weather dependent).

Several steps have been implemented in order to limit/prevent any COVID-19 related risks, however, the risks include:

- Becoming infected by a researcher or fellow research participant that might be asymptomatic/symptomatic during a research-related visit.

- Potential exposure to risk during travel to or from these sites for the purpose of participating in the research.
- Being infected due to handling objects contaminated by the virus at a study site.
- Potential for being more severely affected by COVID-19 if over the age of 60 and/or having a comorbidity or an illness causing an immunocompromised health status.
- Spreading the virus from the research site into the home or community.
- Being fined or arrested for not adhering to appropriate lockdown alert level restrictions e.g. not wearing masks, travelling without appropriate permits, etc.

If you do not agree to take part, what alternatives do you have?

If you do not agree to take part, you will be excluded from the study. Should you wish to have your postural control and knee control assessed, you can make an appointment at any sports related institute within Stellenbosch (eg. Stellenbosch Biokinetics Centre; Stellenbosch Academy of Sport).

Who will have access to your medical records?

We do not require access to your medical records, however, we will require you to report any running related injuries that you have sustained in the past 6 to 12 months.

Even though it is unlikely, what will happen if you get injured somehow because you took part in this research study?

There is an inherent risk associated with time trial running and as such, the following measures have been put in place to compensate you in case of injury/loss/or death during this research project:

- This research project is covered by comprehensive insurance issued by Marsh Proprietary Limited including Primary General Liability, Umbrella Liability and Professional Indemnity Insurance to the value of >R150 000 000.
- It is important to note that:
    - By agreeing to participate in this study, you agree that there is a risk that the time trial or balance assessments may cause you harm. If it does, the sponsor will reimburse you for your medical expenses without you having to prove that the researchers were at fault.
    - You may still claim for emotional pain and suffering if you choose to. In this event, you will have to prove that the researcher was negligent and did not take all reasonable and foreseeable steps to prevent the injury or emotional trauma. This will be a separate legal matter.

- Stellenbosch University will provide comprehensive no-fault insurance and will pay for any medical costs that came about because participants took part in the research (either because the participant used the medicine in this study, or took part in another way). The participant will not need to prove that the sponsor was at fault.

Will you be paid to take part in this study and are there any costs involved?

There will be no cost of participation in the study. All participants be included in a random draw for various prizes for completing the research study requirements. The top 3 participants in the time trial will receive cash prizes (R1100; R600; R300 respectfully). We have targeted athletes within the Cape and Cape Winelands area in an effort to minimize any time or monetary inconvenience or expenses. We will arrange a time and day for testing purposes that suits both the participant and the researchers.

Is there anything else that you should know or do?

- You can phone the Health Research Ethics Committee at 021 938 9677/9819 if there still is something that your study doctor has not explained to you, or if you have a complaint.
- You will receive a copy of this information and consent form for you to keep safe.

Permission to have all anonymous data shared with journals:

Please carefully read the statements below (or have them read to you) and think about your choice. No matter what you decide, it will not affect whether you can be in the research study, or your routine health care

When this study is finished, we would like to publish results of the study in journals. Most journals require us to share your anonymous data with them before they publish the results. Therefore, we would like to obtain your permission to have your anonymous data shared with journals.

Permission for sharing samples and/or information with other investigators:

Please carefully read the statements below (or have them read to you) and think about your choice. No matter what you decide, it will not affect whether you can be in the research study, or your routine health care.

In order to do the research we have discussed, we must collect and store information about your training background/history, time-trial performance data, postural control data and basic demographic information. We will do some of the tests right away. Other tests may be done in the future, like collecting your Strava data in training leading up to the time trial or analysing your pacing on the day thereof. Once we have done the research that we are planning for this research project, we would like to store your sample and/or information. Other investigators from the Department of Sport Science, Stellenbosch University can ask to use these samples in future research. To protect your privacy, we will replace your name with a unique study number. We will only use this code for your sample and information about you. We will do our best to keep the code private. It is however always possible that someone could find out about your name but this is very unlikely to happen. Therefore, we would like to ask for your permission to share your samples and information with other investigators.

Tick the Option you choose for anonymous data sharing with journals:

I agree to have my anonymous data shared with journals during publication of results of this study

Signature_

OR

I do not agree to have my anonymous data shared with journals during publication of results of this study

Signature____________

Tick the Option you choose for sharing samples and/or information with other investigators:

I do not want my sample and/or information to be shared with other investigators

Signature______________

OR

My sample and/or information may be shared with other investigators for further analysis and future research in a field related to performance amongst trail runners

Signature___

Declaration by participant

By signing below, I …………………… agree to take part in a research study entitled (**The change in postural control following a competitive short trail run time trial in highly trained trail runners**).

I declare that:

- I have read this information and consent form, or it was read to me, and it is written in a language in which I am fluent and with which I am comfortable.
- I have had a chance to ask questions and I am satisfied that all my questions have been answered.
- I understand that taking part in this study is **voluntary,** and I have not been pressurised to take part.
- I may choose to leave the study at any time and nothing bad will come of it – I will not be penalised or prejudiced in any way.

- I may be asked to leave the study before it has finished, if the study doctor or researcher feels it is in my best interests, or if I do not follow the study plan that we have agreed on.

Signed at (*place*) ....……………. on (*date*) ……….. 2021.

....

Signature of participant **Signature of witness**

Declaration by investigator

I *(name)* ……………………………………….……… declare that:

- I explained the information in this document in a simple and clear manner to …………………………………..
- I encouraged him/her to ask questions and took enough time to answer them.
- I am satisfied that he/she completely understands all aspects of the research, as discussed above.
- I did/did not use an interpreter. (*If an interpreter is used then the interpreter must sign the declaration below.)*

Signed at (*place*) ....…........……………. on (*date*) …………....……….. 2021.

....

Signature of investigator **Signature of witness**

APPENDIX C: QUESTIONNAIRE

MASTERS RESEARCH QUESTIONNAIRE

The change in postural control following a competitive, short trail run time trial, in highly trained trail runners

To the best of our knowledge, this masters study is the first study to examine **the change in postural control in highly trained trail runners, following a competitive, short trail run time trial** specifically. Postural control holds critical importance in a sport where the running surface is constantly changing and largely uneven. The purpose of this questionnaire is to gather information of athletes participating in this Masters project 2020 for the sole purpose of scientific expansion of the sport of trail running.

The questions will range from "general" to "running specific" and lastly "injury history". The format of the questionnaire is option-selection based, including short answers where applicable. All data collected will be strictly confidential and only accessible to the two researchers below:

PRIMARY RESEARCHER
Nicholas Price
nicpricess@gmail.com
072 775 2761

PRIMARY SUPERVISOR
Simon de Waal
simondw@sun.ac.za
083 260 2324

UNIVERSITEIT STELLENBOSCH UNIVERSITY
University of Stellenbosch
Faculty of Medicine and Health Science
Sport Science Department

THE EFFECT OF A COMPETITIVE SHORT TRAIL RUN TIME TRIAL ON POSTURAL CONTROL IN HIGHLY TRAINED TRAIL RUNNERS

GENERAL

Name and surname									
Contact details									
Mobile									
Telephone									
Email									
Date of birth (dd/mm/yyyy)		D	D	M	M	Y	Y	Y	Y
Sex		M		F		O			
Weight (kg)									
Height (cm)									
Nationality									
History of chronic medical conditions? (if yes, please state)						Yes		No	
Are you currently taking any prescribed medication? (if yes, please state)						Yes		No	
Do you have a history of any acute/chronic condition or injury affecting your central nervous system and/or balance? (if yes, please state)						Yes		No	

RUNNING SPECIFIC

How many years have you been running with the goal being to improve fitness/contribute to a healthy lifestyle? (round off to the nearest whole number)						YEARS	
How many years have you been trail running? (round off to the nearest whole number)							
How many years have you been participating in formal road or trail races?							
Do you complete greater than 49% of your total weekly running volume off-road? (if not, please specify which surfaces make up the bulk of your training: eg. road, grass, track, etc)							
YES		NO		ROAD		GRASS		TRACK
On average, in which category do you usually finish during formal trail races?							
TOP 100		100—500		500—1000		1000—1500	
Which road running shoe brand are you currently running in?							
Which trail running shoe brand are you currently running in?							
Roughly how many kilometers have you done in your current road and trail running shoes?						ROAD	KM
						TRAIL	KM
Do you currently make use of any orthotics within your trail and/or road running shoes? Are they prescribed?							
YES & PRESCRIBED		YES & NOT PRESCRIBED		NO			
Do you participate in ultra-distance trail races? (if yes, for how many years have you been participating in ultra-distance trail races?)							
		YES		YEARS		NO	
How many days per week do you train running specifically?						DAYS	
How many kilometers per week are you running on road and trail? (average to nearest whole number)						ROAD	KM
						TRAIL	KM
How many trail races are you running per year? (estimated to whole number)							
How many of these races are ultra-distance trail races?							
Do you currently incorporate strength specific training in your weekly program? (if yes, please specify how many days per week)							
		YES		DAYS		NO	
Do you currently incorporate balance specific training in your weekly program (if yes, please specify how many days per week)							
		YES		DAYS		NO	
Do you currently incorporate any proprioception specific training in your weekly program? (if yes, please specify how many days per week)							
		YES		DAYS		NO	
Other than strength, balance or proprioception specific training, do you incorporate any other form of cross training in your weekly program? (if yes, please specific what the training is and how many days per week you incorporate this training)							
TRAINING				YES		NO	

INJURY HISTORY

Are you currently suffering from any injuries? (if yes, please specify)		YES		NO		
Have you obtained an injury in the last 12 months? (if yes, please specify)		YES		NO		
Of these injuries, did you make use of a medical professional in its diagnosis?		YES		NO		
Post injury diagnosis, what time period was suggested for recovery? (ie. No running and requiring rehabilitation)						
To the best of your knowledge, be it training or race, when did the injury occur in training/race duration? (beginning/middle/end)						
	BEGINNING		MIDDLE		END	x
Do you make use of recovery methods eg. Sports massage, EMS, cryotherapy? (if yes, please specify)		YES		NO		

APPENDIX D: ETHICS APPROVAL LETTER

Stellenbosch
UNIVERSITY
IYUNIVESITHI
UNIVERSITEIT

forward together
sonke siya phambili
saam vorentoe

Approval Letter
Progress Report

06/06/2022

Project ID: 19119

Ethics Reference No: S20/10/292

Project Title: Effect of fatigue on postural control in trail runners

Dear Mr N Price

We refer to your request for an extension/annual renewal of ethics approval dated 01/06/2022 12:28.

The Health Research Ethics Committee reviewed and approved the annual progress report through an expedited review process.

The approval of this project is extended for a further year.

Approval date: 06 June 2022

Expiry date: 05 June 2023

While reviewing the progress report, it was noted that the following stipulations listed by HREC were not addressed in the response dated 29/06/2021. Kindly address the following stipulations:

1. Please upload signed investigator declaration forms for Hadia White and Donna Jullien.
2. In the informed consent form (ICF) (on HREC template) – please delete the instructional paragraph in italics at the top of the document.
3. In the ICF section where participants need to sign, please update the year to 2021.
4. The paragraph asking consent for data/sample sharing with other investigators (beyond this MSc) and internationally is not in line with what has been described regarding data sharing in the Infonetica application form. In addition, instructional text (in block brackets) has been left in the paragraph and should be removed or replaced with applicable information. Please revise this section so that participants understand exactly why and with whom data will be shared.

While reviewing the progress report, it was noted that the following stipulations listed by HREC were not addressed in the response dated 29/06/2021. Kindly address the following stipulations:

1. Please upload signed investigator declaration forms for Hadia White and Donna Jullien.
2. In the informed consent form (ICF) (on HREC template) – please delete the instructional paragraph in italics at the top of the document.
3. In the ICF section where participants need to sign, please update the year to 2021.
4. The paragraph asking consent for data/sample sharing with other investigators (beyond this MSc) and internationally is not in line with what has been described regarding data sharing in the Infonetica application form. In addition, instructional text (in block brackets) has been left in the paragraph and should be removed or replaced with applicable information. Please revise this section so that participants understand exactly why and with whom data will be shared.

Kindly be reminded to submit progress reports two (2) months before expiry date.

Where to submit any documentation

Kindly note that the HREC uses an electronic ethics review management system, *Infonetica*, to manage ethics applications and ethics review process. To submit any documentation to HREC, please click on the following link: https://applyethics.sun.ac.za.

Please remember to use your Project Id 19119 and ethics reference number S20/10/292 on any documents or correspondence with the HREC concerning your research protocol.

Please note that for studies involving the use of questionnaires, the final copy should be uploaded on Infonetica.

Yours sincerely,

Ms Brightness Nxumalo
Coordinator: Health Research Ethics Committee 2

APPENDIX E: PERMISSION FOR USE OF FIGURE 2.1

Lohman III, Everett (LLU) <elohman@llu.edu> Thu, 4 Nov 2021, 16:50

to me, SJ,, SL,

Nicholas Price

Thank you for your interest in our masterclass article and the image.

I am so pleased that you found it useful.

Yes, absolutely, you have my personal permission to use the image in your thesis. I cannot speak for PT in Sport Journal though.

Wishing you the best in your thesis.

I would love to hear about your novel findings from your thesis.

Sincerely,

Everett

Everett Lohman, III, D.Sc., P.T., OCS — *Associate Dean for Graduate Academic Affairs*
Assistant Dean for Research Affairs
Program Director, Post-professional Physical Therapy Programs
Director, Orthoscience Research Laboratory
Director, Motion Capture Research Laboratory
Professor
Pronouns (He/Him/His)

APPENDIX F: PERMISSION FOR USE OF FIGURE 2.2

Nicholas Price <nicpricess@gmail.com>
to thierry.paillard, SJ,, SL,

Thu, 4 Nov 2021, 10:43

Good morning,

I am a Masters student from the University of Stellenbosch, South Africa. My thesis looks into the change in postural control following an off-road time trial in a sample of highly trained trail runners (pre-post measurements). As part of my literature review, I unpack the postural control system and found great value in your article. Within your article, there is a useful graphic, **figure 2 on page 166,** that I would like to request permission to use for my thesis please. I have cited the related article below:

Paillard, T., 2012. Effects of general and local fatigue on postural control: A review. *Neuroscience & Biobehavioral Reviews*, 36(1), pp.162-176.

Thank you in advance

Kind regards,

--
Nicholas Price
MSc Sport Science
072 775 2761

Thierry Paillard <thierry.paillard@univ-pau.fr>
to me, SJ,, SL,

Thu, 4 Nov 2021, 10:49

Dear Mr,

No problem if you cite it
It is a pleasure
King regards
Thierry Paillard

APPENDIX G: TESTING SHEET

PT#: 33336

N. Price Trail Running MSC 2021

TESTING

DATE:

PARTICIPANT NUMBER:

HEIGHT:

COVID-19 sign in: Yes | No

MASS:

ICF & questionnaire completed? Yes | No

TT Start Time: 10:10

TEST 1: MTCISB

TEST CHECK LIST

Gyko + belt
30s test
Hands crossed at chest
Barefoot
Knees unlocked

KEY WORD DESCRIPTIONS

Balance test
4 components
Feet hip width apart
Eyes open - tape
Knees unlocked

Double Leg Trial

1.1 Firm surface eyes open (FO)

Successful trial Yes | No

Notes:

Repeated trials:

1.2 Firm surface eyes closed (FC)

Successful trial Yes | No

Notes:

Repeated trials:

1.3 Compliant surface eyes open (CO)

Successful trial Yes | No

Notes:

Repeated trials:

1.4 Compliant surface eyes closed (CC)

Successful trial Yes | No

Notes:

Repeated trials & TOF:

PT#: 33336

TEST 1: MTCISB

TEST CHECK LIST

Gyko + belt
30s test
Hands crossed at chest
Barefoot
Knees unlocked

KEY WORD DESCRIPTIONS

Balance test
4 components
Feet hip width apart
Eyes open - tape
Knees unlocked

DOMINANT SINGLE LEG TRIAL | R | L |

1.1 Firm surface eyes open (FO)

Successful trial | Yes | No |

Notes:

Repeated trials & TOF:

1.2 Firm surface eyes closed (FC)

Successful trial | Yes | No |

Notes:

Repeated trials & TOF:

1.3 Compliant surface eyes open (CO)

Successful trial | Yes | No |

Notes:

Repeated trials & TOF:

1.4 Compliant surface eyes closed (CC)

Successful trial | Yes | No |

Notes:

Repeated trials & TOF:

PT#: 33336

TEST 2: SEBT

NON DOMINANT LEG FIRST

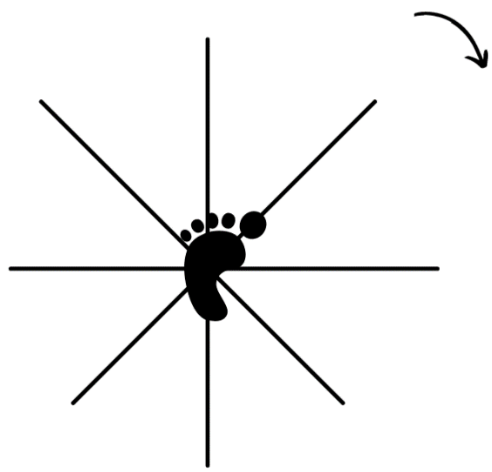
LEFT FOOT STANCE

TEST CHECK LIST

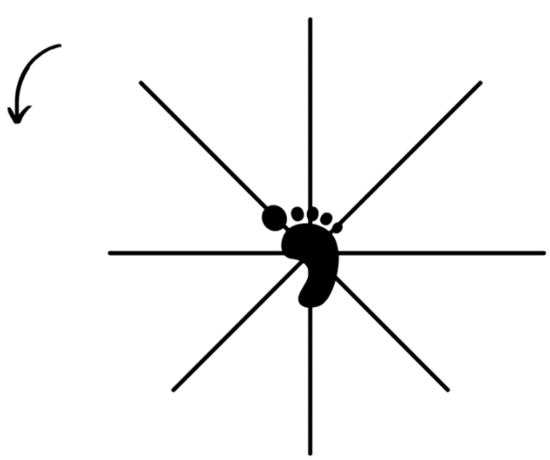
Gyko + belt
65s test
Hands on hips
Barefoot
Non dominant first
Big toe on center line
Mid-foot over intersection

KEY WORD DESCRIPTIONS

Balance test
Two trials (R+L)
Hands on hips
Slide to reach - don't lean
Back to start position each reach



RIGHT FOOT STANCE



PT#: 33336

TEST 3: CMJ_

Double Leg Trial

TEST CHECK LIST

Beams on
Cameras set and saved
Shoes on
Hands on hips
Uncheck test when selecting new

KEY WORD DESCRIPTIONS

Jump test for height
Quick down, quick up
Hands on hips
Soft, safe landing

Jump 1:

Successful trial | Yes | No |

Notes:

Jump 2:

Successful trial | Yes | No |

Notes:

Jump 3:

Successful trial | Yes | No |

Notes:

Dominant Single Leg Trial

TEST CHECK LIST

Beams on
Cameras set and saved
Shoes on
Hands on hips
Uncheck test when selecting new

KEY WORD DESCRIPTIONS

Jump test for height
Quick down, quick up
Hands on hips
Soft, safe landing
Keep lifted leg still when jumping

Jump 1:

Successful trial | Yes | No |

Notes:

Jump 2:

Successful trial | Yes | No |

Notes:

Jump 3:

Successful trial | Yes | No |

Notes: