ANALYZING GAIT PARAMETERS IN TRAIL RUNNERS USING WIRELESS TRUNK ACCELEROMETRY DURING REAL-WORLD AND TREADMILL INCLINE RUNNING

by

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SUMMARY

Few studies have explored dynamic stability when running over complex or challenging surfaces, and no studies have investigated how trail terrain could affect components of dynamic stability. The aim of this study was to measure the acute changes in dynamic stability when running at incline, between treadmill and trail surfaces.

Twelve recreational trail runners (age 25.2 ± 2.6 years; mass 78.8 ± 5.9 kg; height 183.6 ± 7.1 cm) participated and completed all aspects of testing. They ran at 10 km.h^{-1} with an eight-degree incline, over both treadmill and trail surfaces. Each participant had a single Noraxon® myoMotion Research PRO inertial measurement unit (IMU) attached to their third lumbar vertebrae region, capable of collecting wireless acceleration data.

Linear acceleration data was captured up to 200 Hz and ± 16 *g* at the trunk region in three-dimensions, namely the vertical (VT), anterior-posterior (AP) and mediolateral (ML). Data was streamed to the Noraxon® myoRESEARCH software. Thereafter, the data was filtered using a zero-lag 4th order low-pass Butterworth filter with a cut-off frequency of 50 Hz. Filtered acceleration data was imported into MATLAB R2020a (Version 9.6), with a custom written code performing an autocorrelation procedure of each participant over both treadmill and trail surfaces. The autocorrelations provided information regarding the step and stride regularity, as well as the symmetry of the individual over the two terrains, based on the three-dimensional accelerations at the trunk. Furthermore, mean step and stride times, as well as their coefficients of variations (CV) were calculated from the filtered data.

Results were reported in the article (**Chapter Four**) and indicated that step and stride regularity was decreased ($p < 0.01$) in all three-dimensions when running over the more complex trail surface, compared to the steady treadmill surface. The AP and ML directions indicated a greater degree of diminution compared to the VT and is evident in the symmetry values. Symmetry decreased over the trail surface for both the AP ($z = -3.06$, $p < 0.01$) and ML ($p < 0.01$) directions, but not in the VT ($z = -1.65$, $p = 0.10$) direction. Additionally, there was no change in mean step ($p = 0.45$) and stride ($p =$

0.33) times, but a significant increase was observed for both step CV ($p < 0.01$) and stride CV ($p < 0.01$) when running on the trail surface.

The first null hypothesis was rejected, as the coefficients of variation for both step and stride times indicated a significant difference when comparing the treadmill and trail surfaces. The second null hypothesis was rejected, as the trail surface did indicate a general decrease in dynamic stability components compared to the treadmill. In conclusion the trail demonstrated a higher degree of step and stride variability, and low symmetry, primarily due to the inconsistent nature of the trail surface.

Future studies could investigate the role of cognition during trail running, by examining the decision-making process while traversing complex terrain such as the trail environment. Furthermore, future studies in the field of sports biomechanics could aim to incorporate a greater degree of software technology, such as adopting a more algorithmic approach to analysing data.

Keywords: Accelerometry; Dynamic Stability; Running Gait; Trail Running

OPSOMMING

Min studies het voorheen dinamiese stabiliteit ondersoek wanneer individue oor ingewikkelde of uitdagende oppervlaktes hardloop en geen studies het ondersoek ingestel na hoe die terrein van die voetslaanpad, komponente van dinamiese stabiliteit kan beïnvloed. Die doel van hierdie studie was om die akute veranderinge in dinamiese stabiliteit te meet wanneer individue teen 'n helling, op trapmeul en voetslaanpaaie hardloop.

Twaalf amateur voetslaanpad hardlopers (ouderdom 25.2 ± 2.6 jaar; massa 78.8 ± 5.9 kg; hoogte 183.6 ± 7.1 cm) het deelgeneem en alle aspekte van die toetsing voltooi. Hulle het met 'n helling van agt grade teen 10 km.h^{-1} gehardloop, oor beide trapmeul en voetslaanpad oppervlaktes. Elke deelnemer het 'n enkele Noraxon® myoMotion Research PRO – traagheidsmetingeenheid (IMU) gekoppel aan hul derde lumbale werwel gedra, wat draadlose versnellingsdata kon versamel.

Die IMU kon in drie dimensies lineêre versnellingsdata tot 200 Hz en ± 16 *g* opneem, naamlik die vertikale (VT), anteroposterior (AP) en mediolaterale (ML). Data is na die Noraxon® myoRESEARCH gestroom. Daarna is die data gefiltreer met behulp van 'n nul-lag 4de-orde laagdeurlaat Butterworth-filter met 'n afsnyfrekwensie van 50 Hz. Die gefiltreerde versnellingsdata is in MATLAB R2020a (Weergawe 9.6) ingevoer, met 'n self-geskrewe kode wat 'n outokorrelasie prosedure van elke deelnemer oor beide die trapmeul en voetslaanpad oppervlaktes uitvoer. Die outokorrelasies het inligting oor die tree en stap reëlmatigheid, sowel as die simmetrie van die individu oor die twee terreine gegee, gebaseer op die drie-dimensionele versnellings by die romp. Verdere berekeninge van die gemiddelde tree en stap tye, sowel as hul koëffisiënte van variasies (CV), was bereken uit die gefiltreerde data.

Resultate is in die artikel (**Hoofstuk Vier**) gerapporteer en het aangedui dat die reëlmatigheid van tree en stap in alle drie-afmetings ($p < 0.01$) verminder is wanneer die individue oor die meer ingewikkelde voetslaanpad hardloop, in vergelyking met die stabiele trapmeul oppervlakte. Die AP en ML rigtings van meting, het aangedui op 'n groter mate van afname in vergelyking met die VT en kan waargeneem word in die simmetriewaardes. Simmetrie het oor die voetslaanpad afgeneem vir beide die AP ($z = -3.06$, $p < 0.01$) en ML ($p < 0.01$) rigtings, maar nie in die VT ($z = -11.65$, $p = 0.10$) rigting nie. Boonop was daar geen verandering in die gemiddelde tree ($p = 0.45$) en die stap ($p = 0.33$) tye nie, maar 'n beduidende toename is waargeneem vir beide tree CV ($p < 0.01$) en stap CV ($p < 0.01$) tydens hardloop op die voetslaanpad oppervlakte.

Die eerste null hipotese is nie aanvaar nie, aangesien die koëffisiënte van variasies vir die stap tye en tree tye 'n beduidende verskil in die vergelykings tussen die trapmeul oppervlak en die voetslaanpad aandui. Die tweede null hipotese is nie aanvaar nie, aangesien die voetslaanpad se oppervlak wel 'n algemene afname in dinamiese stabiliteit toon, in vergelyking met die trapmeul. Ter afsluiting het die voetslaanpad 'n hoër mate van tree en stap veranderlikheid en 'n lae simmetrie getoon, hoofsaaklik as gevolg van die inkonsekwente aard van die spooroppervlak.

Toekomstige studies kan die rol van kognisie tydens voetslaanpad hardloop ondersoek, deur die besluitnemingsproses te ondersoek terwyl komplekse terrein, soos die spooromgewing, gekruis word. Verder kan toekomstige studies in die gebied van sportbiomeganika ten doel hê om 'n groter mate van sagtewaretegnologie te inkorporeer, soos om 'n meer algoritmiese benadering tot die ontleding van data te gebruik.

Sleutelwoorde: Versnellings faktore; Dinamiese stabiliteit; Loopgang; Voetslaanpad hardloop

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LIST OF ABBREVIATIONS AND ACRONYMS

%	:	Percentage
α	:	Significance level
β	:	Chance of a type 2 statistical error
a.u.	:	Arbitrary units
Ad1	:	First dominant period in the autocorrelation procedure
Ad2	:	Second dominant period in the autocorrelation procedure
AP	:	Anteroposterior
ASIS	:	Anterior superior iliac spine
BMI	:	Body Mass Index
CoM	:	Centre of Mass
cm	:	Centimetres
e.g.	:	exempli gratia (for example)
EEG	:	Electroencephalogram
EMG	:	Electromyography
et al.	:	et alia (“and others”)
g	:	Acceleration due to gravity (1 = 9.81 m/s^2)
Hz	:	Hertz
ITRA	:	International Trail Running Association
i.e.	:	id est (in other words)
ICF	:	Informed Consent Form
IMU	:	Inertial Measurement Unit

KE	:	Kinetic energy
$km.h^{-1}$	:	Kilometres per hour
km	:	Kilometres
LCD	:	Liquid crystal display
LDS	:	Local dynamic stability
m	:	Metre(s)
m/s	:	Metres per second (velocity)
m/s^2	:	Metres per second squared (acceleration)
MEMS	:	Microelectrochemical systems
ML	:	Mediolateral
mm	:	Millimetres
n	:	Sample size
PE	:	Potential energy
RMS	:	Root mean square
RR	:	Road running
SF	:	Stride frequency
SL	:	Stride length
™	:	Trade marked
TR	:	Trail running
TRD	:	Treadmill running
vs.	:	Versus
VT	:	Vertical

OVERVIEW

The thesis is presented in research article format. One research article (**Chapter four**) was prepared according to the guidelines of the Journal – *Journal of Sport Science* (**Appendix F**). Consequently, the referencing style used in Chapter Four will differ to that of the remaining chapters.

Chapter One: This chapter contains the introduction and problem statement as well as the aims of the study and the hypotheses. The Harvard method of referencing was used.

Chapter Two: The purpose of this chapter was to summarise the existing literature relating to trail running and the challenges runners face in real-world environments. Secondly, to provide insight into the inertial measurement units, and how they are used to capture data in real-world environments and how the data would be analysed afterwards. Again, the Harvard method of reference was used.

Chapter Three: This chapter explains the sample size, study design, ethics, methods of measurement, data analysis and statistical analysis. The Harvard method of reference was used.

Chapter Four: Research article titled - *Differences in dynamic stability between graded treadmill and real-world trail running.* This chapter was written according to the author guidelines of the *Journal of Sport Science* (**Appendix F**). The focus of the article was to investigate changes in dynamic stability when recreational trail runners ran at incline on a treadmill and real-world trail surface. The participants ran at an eight-degree incline on the treadmill and over a short trail section, while wearing a trunk mounted inertial measurement unit. Acceleration data from the inertial measurement unit was then used to determine three-dimensional trunk movements, which was then autocorrelated to determine the step and stride regularity. Gait symmetry was then calculated. Inclined trail running significantly decreases aspects of dynamic stability, compared to treadmill running.

Chapter Five: Conclusion. This chapter includes the conclusion of the study, practical applications of the results, limitations of the study, recommendations for research in a similar environment and suggestions for future research.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Running and walking are the most common forms of bipedal locomotion, each with their own distinct purpose and mechanics (Bramble & Lieberman, 2004). Bipedal locomotion is a compound activity which can be described as a series of controlled falls (O'Connor & Kuo, 2009), but is in fact a multifaceted repetition of complex co-ordinated movements with large amounts of sensory and mechanical organs assisting in the process (Rebula & Kuo, 2015). Although humans progress through different phases of locomotion during development, the goal is efficient locomotion through either running or walking.

The average person transitions from walking to running after walking becomes uncomfortable at approximately 2.3 - 2.5 m/s (Bramble & Lieberman, 2004). Running can be differentiated from walking, not only by the increased velocity and acceleration, but also by a flight phases that replaces the double stance phases in walking (Lohman III, *et al*., 2011). Running comprises of four phases, including: stance, early flight, swing, and late flight (Lohman III, *et al*., 2011). Running has a characteristic phase where the body is suspended in the air for a short period of time, with no more than one floor contact point during all phases of the movement cycle. Several other factors that differentiate running from walking include aspects such as; increased stride length (SL), increased stride frequency (SF), and greater force of muscular contractions (Chapman, 2013). These factors directly influence running kinetics and kinematics. Kinematics include aspects such as the displacement, velocity and acceleration of a body and can be defined as the study of a body in motion, whereas kinetics refers to the forces behind the movement of bodies, including factors such as impulse, work and power (Chapman, 2013).

Running has been a popular means of recreational exercise for many years, and millions of people worldwide participate in races every year (Hoffman, *et al*., 2010). As cities grow and expand, there are fewer opportunities to run in a natural environment, and many people have no choice but to run on asphalt roads or treadmills. An issue with running on concrete or asphalt roads, is the low compliance of the road surface. It has been shown that surfaces of high stiffness or low compliance induce higher ground reaction forces and anterior-posterior accelerations (Dolenec, *et al*., 2015; Schütte, *et al*., 2016), compared to surfaces of higher compliance. Therefore, running on concrete or asphalt surfaces result in higher levels of mechanical stress, compared to a natural surface.

Recently there has been an increase in the popularity of off-road social running events that take place in a natural environment (farms, forests and nature reserves), such as the Parkrun™ and the Myrun™, as well as a great increase in the popularity of trail running (TR) events (Hoffman, *et al*., 2010). TR has a characteristic difference from road running (RR) in that it has a larger amount of surface undulations with far more inclines and declines on a predominantly natural terrain or surface (Ehrstrom, *et al*., 2017). Changes in the surface dynamics and alternating gradients, have distinct effects on running characteristics, and could lead to altered mechanical forces on the lower extremities.

The surfaces on which athletes run play a role in the mechanics and economy of running (Tessutti, *et al*., 2010; Dolenec, *et al*., 2015; Voloshina & Ferris, 2015; Schütte, *et al*., 2016). In a real-world setting runners are required to constantly adapt their running patterns and techniques to adequately traverse complex terrains, such as natural environments as well as urban areas with constantly changing surface dynamics (Voloshina & Ferris, 2015). However, runners prefer a smooth movement of the centre of mass (CoM) that is characterized by an inverted pendular movement (Matthis & Fajen, 2013), even when running over uneven terrain. To achieve a smooth movement of the CoM, the runner needs to adjust running mechanics accordingly to maintain a set and controlled path of the CoM. During over-ground running, the presence of obstacles could alter spatio-temporal variables, and has an influence on the individuals CoM movement (Firminger, *et al*., 2018), compared to level terrain running. These adjustments will influence other spatio-temporal factors, including greater variations in SL, SF and muscle activities (Voloshina & Ferris, 2015). Furthermore, TR includes a greater quantity of graded running, which has been shown to influence the movement of the CoM (Dewolf, *et al*., 2005).

To evaluate the changes in human locomotion mechanics when obstacles are present, different studies have been conducted using either a modified treadmill with various step heights (Voloshina & Ferris, 2015), an LCD projector to display virtual obstacles (Matthis & Fajen, 2013) or by altering step heights on a track using force plates (Grimmer, *et al*., 2008). Previous studies have also investigated specific over-ground running conditions and the accompanied changes in running mechanics (Schütte, *et al.*, 2016; Firminger, *et al*., 2018; Orendurff, *et al*., 2018). Some of the more popular kinetics investigated during over-ground running include ground reaction forces, joint moments and motions, and the perpetuation of forces. However, few studies have used aspects of dynamic stability to indicate change in running kinematics during over-ground running (Svenningsen, *et al*., 2020). Dynamic stability is defined as the ability to maintain regularity, symmetry, variability and complexity of three-dimensional trunk accelerations during locomotion (Schütte, *et al*., 2018). Determining certain aspects of dynamic stability requires an in-depth analysis of the acceleration patterns recorded using an Inertial Measurement Unit (IMU). An IMU includes a variety of sensors including an accelerometer, gyroscope, and magnetometer. A single waist mounted IMU has the potential to provide a vast amount of information regarding running characteristics that can be derived from three-dimensional acceleration patterns (Jarchi, *et al*., 2018). These lightweight devices are ideal for studying real-world environments and the acute changes that occur when changing running surfaces.

RR and treadmill running (TRD) share several similarities, and the validity of a treadmill in simulating real-world over-ground running has recently been investigated (Firminger, *et al*., 2018). Firminger *et al*. (2018, pg.1) concluded that, "over-ground kinematics and ground reaction forces in graded running are reasonably replicated on a treadmill". In a study conducted by Oliveira *et al*. (2016, pg.14), electromyography (EMG) data indicated that both over-ground and TRD presented similar activations of motor modules and stated that, "muscle activation during running under different environmental constraints is predominantly similar". During a systematic review and meta-analysis of different studies that compared physiological, perceptual and performance measures between TRD and over-ground running, Miller *et al*. (2019) found oxygen uptake and heart rates of TRD and over-ground running to be very similar at submaximal pace. Therefore, it appears that TRD simulates over-ground running (both biomechanically and physiologically), relatively well at a submaximal pace. As such, a treadmill could be used to illustrate the changes in running mechanics when individuals run on different terrains and use the TRD as the base line for comparisons.

Although research has been done to compare uneven terrain and RR, many of them were conducted only in a laboratory setting, using either a modified treadmill (Voloshina & Ferris, 2015), alterations to track surfaces (Grimmer, *et al*., 2008) or even creating virtual obstacles (Matthis & Fajen, 2013). Furthermore, few studies have investigated the changes in dynamic stability during over-ground running (Svenningsen, *et al*., 2020) and no studies have used this to investigate TR (Svenningsen, *et al*., 2020). TR elicits changes in normal running gait because the athlete must adapt to the challenging natural terrain and altering surface conditions. Using a single waist mounted IMU, in-depth investigations into the alterations of gait characteristics could provide a further understanding of how TR affects time variables and aspects of dynamic stability.

1.2 PROBLEM STATEMENT AND SIGNIFICANCE OF STUDY

Over-ground running has been shown to elicit minor changes in normal running gait, compared to treadmill running. Very few studies have investigated aspects of dynamic stability during over-ground running, and no studies have done so for TR specifically. Even though TR has seen an exponential rise in participation rates, the academic contributions surrounding this relatively new competitive field of running appears to be lacking. An investigation into alterations of dynamic stability during TR could provide future recommendations regarding injury prevention and performance enhancement. This thesis should also contribute to the scarce literature surrounding both TR and dynamic stability during running.

1.3 RESEARCH QUESTION

Is there a difference in time variables and dynamic stability derived from three-dimensional trunk accelerations between incline treadmill and trail running amongst recreational trail runners?

1.4 AIM

The aim of this study was to investigate the acute changes in time variables and dynamic stability parameters, derived from three-dimensional trunk accelerations, between incline treadmill and trail running, in recreational trail runners.

1.5 OBJECTIVES

The objectives that guided this study was to measure and compare recreational trail runners during indoor treadmill and outdoor trail running, at an eight-degree incline (10 $km.h^{-1}$), based on:

1) time parameters by determining mean step and stride times, as well as their coefficients of variation
2) step regularity by means of calculating the *Ad1* peaks from autocorrelation procedures
3) stride regularity by means of calculating the *Ad2* peaks from autocorrelation procedures
4) gait symmetry by calculating the percentage difference between the *Ad1* and *Ad2* values

1.6 HYPOTHESES

Research hypothesis one: It was hypothesized that incline trail running will result in significantly lower time parameters (mean step and stride times, and coefficients of variation for both), compared to incline treadmill running, due to the complex terrain and different surface inconsistencies associated with trail running.

Null hypothesis (H_0): It was hypothesized that there would be no difference between incline trail and treadmill running for mean step and stride times, and the coefficients of variation.

Research hypothesis two: It was hypothesized that incline trail running will result in a significant decrease in dynamic stability variables (lower step and stride regularity and gait symmetry) in all three measured linear directions, compared to incline treadmill running, due to the complex terrain and different surface inconsistencies associated with trail running.

Null hypothesis (H_0): It was hypothesized that there would be no difference in dynamic stability variables (step and stride regularity, and gait symmetry) between incline treadmill and trail running.

1.7 VARIABLES

Table 1.1: Table of variables related to each hypothesis of the study.

Hypotheses	Dependent variables	Independent variables	Categorical variables	Control variables
1) Time parameters	Step time	Treadmill surface	Gender	Running speed
	Stride time	Trail surface	Age	Surface incline
	Step time coefficient of variation			Wind speeds
	Stride time coefficient of variation			Weather conditions
2) Dynamic stability	Step regularity			
	Stride regularity			
	Gait symmetry			

1.8 ASSUMPTIONS

Certain assumptions regarding the participating runners were made at the start and during the study. It was assumed that participants were motivated to take part in the study and that they would perform the running trials to the best of their ability. It was also assumed that participants were honest about the amount of trail running they participated in, to be classified as a "recreational trail runner". Finally, it was assumed that the participants refrained from consuming alcohol and caffeine within 24-hours, as well as not performing any exercise 48-hours prior to testing.

Regarding the data collection, it was assumed that the equipment produced reliable and valid data during the different testing days. The researchers would ensure that all equipment works properly, prior to the start of the testing protocol.

The researchers did their best to ensure similar circumstances during the testing days, to make sure all the testing happens in a similar way, data is recorded properly and that all participants have a similar experience.

CHAPTER 2

THEORETICAL CONTEXT

2.1 INTRODUCTION

Human locomotion has been described as a series of controlled falls, whereby the individual remains upright and transports the body forwards (O'Connor & Kuo, 2009). Moving the body from theoretical point A to B through running could be due to different reasons, but primarily for the purpose of moving faster than when walking, with the aim of covering a further distance or a similar distance at a faster pace (Chapman, 2013). Human running consists of several distinct features and events. A cyclical gait cycle can be described as "when one foot comes in contact with the ground and ends when the same foot contacts the ground again", as described by Novacheck (1998, pg.78). The gait cycle can be broken down into steps and strides and can be further characterised by four distinct phases. **Figure 2.1** represents a runner with a heel strike running pattern.

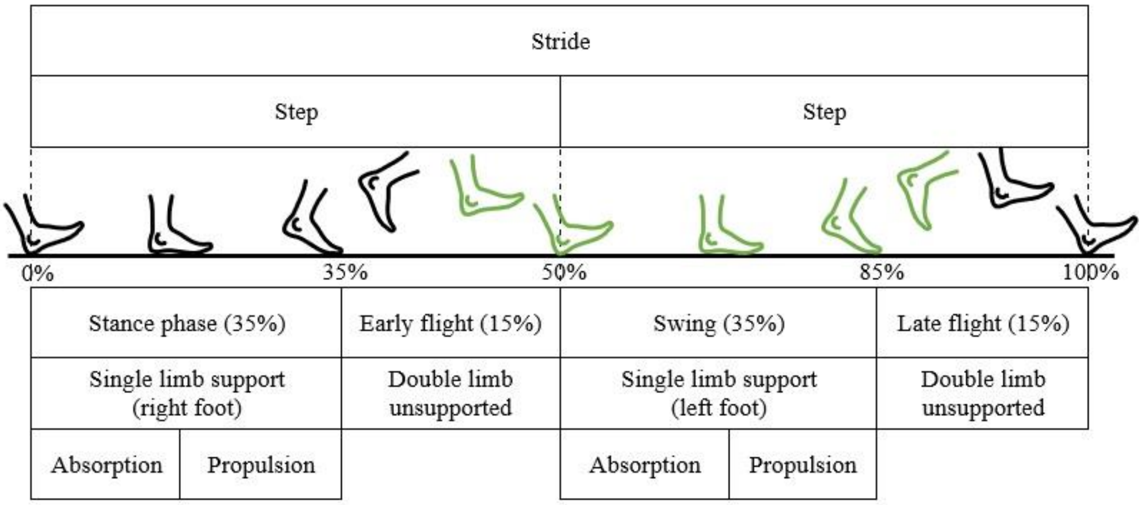

Figure 2.1: Illustration of the differences between steps and strides, and the stance and flight phases during a typical heel strike running gait. 0 – 100%, represents the percentage of the gait cycle. Note that the black and green feet, represent the right and left foot, respectively (compiled by Oloff CW Bergh, from Singleton, *et al*., 1992 and Lohman III *et al*., 2011).

Refer to **Figure 2.1** during the description of the following paragraphs. Initial ground contact is immediately followed by the stance phase, which comprises approximately 35% of the entire running cycle (Lohman III, *et al*., 2011). Initial ground contact is also regarded as the starting point for a single step and stride (Singleton, *et al*., 1992). During the stance phase, the body is supported only by the initial support leg (right leg), which must perform two functions. Firstly, the leg has to absorb the downward momentum with the use of eccentric muscular contractions (DeVita, *et al*., 2008) and secondly propel the body forwards using concentric contractions. During the contractile phase the body is launched both horizontally and vertically (Novacheck, 1998) due to the subsequent extension of the hip, knee and ankle. Following the stance phase is a short section called the flight phase. The early flight phase encompasses around 15% of the entire running cycle (Lohman III, *et al*., 2011), and distinguishes running from walking. During this phase, the body is completely airborne with no ground contact point and the lower extremity muscles prepare for the subsequent absorption of forces during ground contact. The right leg now enters the swing phase.

Ground contact is made by the left foot while the right leg performs a "swing" function (Novacheck, 1998). The contact of the left foot is both the end of the step, and the start of the following step (Singleton, *et al*., 1992). During the swing phase the right foot does not touch the ground, but the entire body is supported by the left leg for the duration of the second stance phase. The swing phase comprises of similar events compared to the stance phase. The swing phase encompasses around 35% of the entire cycle, while the supporting leg has the same absorption and propulsion function in the stance phase (Lohman III, *et al*., 2011). Following the extension of the hip, knee and ankle, the final phase of the gait cycle begins after the left foot leaves the ground. The late flight phase occurs whereby both feet are in the air and there is no point of ground contact. Approximately 15% of the entire gait cycle consist of the late flight phase with similar actions to the early flight phase (Lohman III, *et al*., 2011). Finally, the right foot makes contact with the ground again, signalling the end of the first stride and the second step (Singleton, *et al*., 1992).

Understanding the specific sequences of the running gait cycle is necessary to further understand the underlying mechanisms and modalities that are affected and altered when running over different terrain. Firstly, this chapter will explore trail running (TR) and report on current research that include TR and dynamic stability. Secondly, the conditions that make TR unique will be explained. The chapter concludes with different methods for assessing changes in gait characteristics using accelerometry, and the reliability and validity of these methods.

2.2 TRAIL RUNNING

Human beings have been running over various types of terrain for thousands of years (Bramble & Lieberman, 2004). Upright bipedal running was a means of evolutionary survival for *Homo erectus*, but has since become a popular means of recreational exercise for modern humans (Bramble & Lieberman, 2004). Millions of people worldwide participate in running races annually (Hoffman, *et al*., 2010). Recently, there has been an increase in the popularity of off-road social running events that take place in natural environments (farms, forests and nature reserves), such as the Parkrun™ and the Myrun™, as well as a great increase in the popularity of TR events (Hoffman, *et al*., 2010). Ultra (>42.2km) TR, one of several formats of TR (Scheer, *et al*., 2018), has seen an exponential growth in participation over the past 40 years, potentially because of the greater attraction of these races compared to traditional road races (Hoffman, *et al*., 2010; Vernillo, *et al*., 2017). It is important to define TR in both practical and academic settings, to ensure that there are no discrepancies between research and application. The following section will discuss the definitions of TR in practical and academia terms.

2.2.1 **DEFINING TRAIL RUNNING**

According to the International Trail Running Association (ITRA), TR is defined as:

> "*A trail race is a* ***pedestrian competition*** *open to everyone, which takes place in a* ***natural environment****, with the minimum possible of paved roads (20% maximum). The course can range from a few kilometres for short distances all the way to 80 kilometres and beyond for ultra-trail races.*" - (ITRA Website, 2020)

Furthermore, the ITRA states that TR may occur in different environments, which makes each race unique. They add the following description of the race conditions to their definition of TR:

> "*Mountains or forests, countryside or desert, this* ***endurance race*** *takes place on naturally variable terrain, including very often significant climbs and descents, which result in* ***elevation gain and loss*** *between the start and finish line. The distance is not the only thing that matters! Together, the unique features of the terrain and the relationship between distance and elevation changes all work together to create the overall level of difficulty for a given race.*"- (ITRA Website, 2020)

Accurately defining a sport in both a practical and academic setting is important. In academia, several authors have described TR in their research, whereby **Table 2.1:** Description of TR according to literature since 2010. shows common expressions that relate to either the environment, different degrees of graded running, distances, or surface types.

Table 2.1: Description of TR according to literature since 2010.

Authors	Environment	Gradients	Duration/Distance	Surface
Easthope *et al.*, 2010	"mountain context"	"extensive vertical displacement (both uphill and downhill)"	Ultralong (> 5 hours)	-
Ehrström *et al.*, 2017	"mountain single track"	"including positive and negative elevations"	Short (< 42km) Ultralong (> 100km)	"rocky and root-covered paths"
Giandolini *et al.*, 2017	-	"large positive and negative elevations"	-	-
Vercruyssen *et al.*, 2017	"mountain single tracks"	"successive uphill and downhill"	-	"technical sections"
Vernillo *et al.*, 2017	-	"large positive/negative elevation changes"	-	"rough terrain"
Scheer *et al.*, 2018	"challenging environments"	"sections of uphill and downhill running"	-	"uneven tracks and surfaces"
Scheer *et al.*, 2020	"mountains, deserts, forests, coastal areas, jungles/rainforest"	"no restrictions"	"no restrictions"	"dirt track, forest trail, single track, beach sand"

TR has been described in numerous ways, with common aspects including a "mountain" environment (Easthope, *et al*., 2010; Ehrström, *et al*., 2017; Vercruyssen, *et al*., 2017), large "positive and negative elevations" (Easthope, *et al*., 2010; Ehrström, *et al*., 2017; Giandolini, *et al*., 2017; Vercruyssen, *et al*., 2017; Vernillo, *et al*., 2017; Scheer, *et al*., 2018), and challenging surface conditions (Ehrström, *et al*., 2017; Vercruyssen, *et al*., 2017; Vernillo, *et al*., 2017; Scheer, *et al*., 2018). The most recent academic definition of TR, based on ITRA and IAAF definitions is defined by Scheer *et al*. (2020, pg. 277) 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).

TR not only differs from traditional road running (RR) because of environmental changes and challenges, the regulations for participation also differs. During the TR race, large distances between both athletes and help (aid) stations require that the participant be self-sufficient with regards to "clothing, communications, food and drink" (Urbański, 2018, pg. 1238). This means that in the case of an emergency, participants are required to sustain themselves until emergency services can arrive. Because of the difficult natural terrain, the time that emergency services can reach an injured participant could vary dramatically. Therefore the ITRA requires participants to have several pieces of equipment with them (inspected prior to race participation) which includes; a whistle, emergency first aid blanket and an adequate supply of food and fluids (Urbański, 2018). Safety equipment, additional water and food all adds to the weight of the individual and could alter running mechanics accordingly.

Fundamentally TR differs from traditional RR through the incorporation of challenging underfoot surfaces and environmental conditions. The inclusion of undulating gradients coupled with challenging underfoot surface conditions affects various aspects of the typical running gait cycle.

2.3 TRAIL RUNNING CONDITIONS

Whether a runner is busy navigating the busy streets of the urban environment or the complexities of their TR race, they might find themselves having to conquer a steep incline which is common during TR (Ehrstrom, *et al*., 2017). Furthermore, natural environments might bring beauty and serenity to exercise, but it includes other challenges. The following sections will expand on the two primary differences between TR and traditional RR or TRD, namely the inclusion of greater amounts of inclines and complex uneven surfaces. Additionally, aspects related to dynamic stability and TR will be reflected upon in the following section.

2.3.1 **INCLINE RUNNING**

Differences that occur during incline running compared to level running are dependent on the angle of inclination (Vernillo, *et al*., 2017). Padulo *et al*. (2012) found that during inclined TRD (+ 2 and 7%) at 14 km.h^{-1} and 18 km.h^{-1}, there was an increase in stride frequency (SF) accompanied by a decrease in stride length (SL). An earlier study by Gottschall and Kram (2005) showed a significant increase in SF and decrease in SL when comparing uphill (+9°) to level running, with no differences in SF and SL at smaller inclines (+3° to 6°). Swanson and Caldwell (2000) demonstrated a significant increase in SF and time in stance phase at 16.2 km.h^{-1} over high incline (+ 16.7°), illustrating the importance of SF regulation during high inclined running. They also exemplified that the time spent in the stance phase was greatly increased during incline running and will influence the mean step and stride times (Swanson & Caldwell, 2000). A study by Willis *et al*. (2020) on elite trail runners indicated increased SF and ground contact time, and a decreased flight phase duration during graded (+12°) running, compared to level TRD. These alterations in SF, SL and time parameters of running will influence aspects of mechanical work, strain the physiological system, and alter the movements of the runner's centre of mass (CoM) (Willis, *et al*., 2020).

The mechanical work required to run downhill or uphill depends on the speed of movement and gradient of slope (Vernillo, *et al*., 2017). During uphill running the contractive or "active" work increases linearly as the gradient increases as described by Minetti *et al*. (1994), whereby the body needs to be propelled forward as well as raising the CoM to a greater height. The challenge that accompanies uphill running, is not only the momentary elevation of the CoM when going from flat to incline, but the continuous elevation of the CoM (Chapman, 2013). **Figure 2.2** demonstrates the affect that increasing height gain during inclined running has on the CoM.

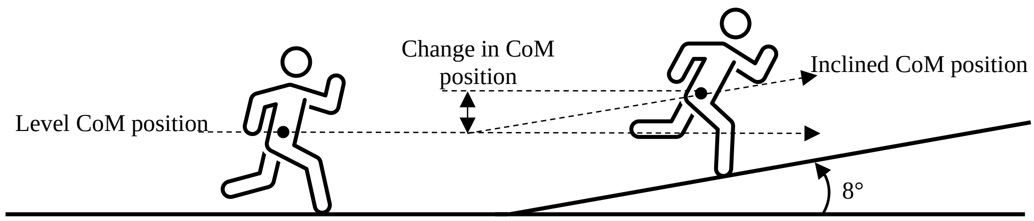

Figure 2.2: Changes in CoM (Centre of Mass) position when running at an incline compared to level. During level running average CoM position remains constant, whereas during inclined running the runner is required to consistently raise their CoM. (source: Oloff CW Bergh)

Elevating the CoM requires greater contributions of concentric muscle contractions of the leg extensors (Chapman, 2013). Furthermore, the physiological system is taxed more during incline running not only due to the higher energetic cost of concentric contractions (Minetti, *et al*., 1994), but the overall increased muscle output (Minetti, *et al*., 2002). This follows the basic rule of physics that, in a controlled system, kinetic energy is equal to potential energy (KE = PE), hence raising any mass above its original position to increase its PE, will require a greater amount of KE. Physiologically the body must adapt to these increased kinetic demands, which increases the overall metabolic cost of the run (Minetti, *et al*., 2002).

Alterations in SF, SL and the time spent during different phases of the gait cycle affects the acceleration patterns of the CoM. During level terrain running, the CoM follows a constant motion explained in the spring-mass model (Blickhan, 1989). However, the vertical aspects of this spring-mass movement diminish because the incline angle of running increases (Dewolf, *et al*., 2005). A decrease in excessive vertical oscillations of the CoM decreases the economic cost of running, but consistently raising the CoM leads to a linear increase in KE cost as the angle increases (Vernillo, *et* *al*., 2017). Thus, after a certain degree of incline, the decrease in the vertical oscillations of the CoM and lower metabolic cost is outweighed by the greater cost to elevate the CoM over the incline.

The alterations made during graded running challenge both the physiological and mechanical structures in the body (Willis, *et al*., 2020). Nevertheless, graded running might not be the only challenge to trail runners, because the environment and the surface on which they run might have additional influences.

2.3.2 **UNEVEN TERRAIN RUNNING**

Several factors relating to uneven terrain running affect a runner's locomotor abilities, namely; surface smoothness, surface density, and the presence of obstacles (Voloshina & Ferris, 2015). Primary alterations in gait parameters during uneven terrain running include spatio-temporal alterations to SF, SL and ground contact time (Warren, *et al*., 1986).

Tessutti *et al*. (2010) investigated changes in plantar pressure distributions during natural grass and asphalt running at 12 km.h^{-1}, and found longer contact times when the runners ran on grass compared to asphalt. However, they did not investigate changes in SF or SL. Herbert-Losier *et al*. (2015) found shorter ground contact times when recreational runners ran over a forest pathway at 13.7 km.h^{-1}, compared to RR, and also indicated that SL was significantly shorter during the forest section. Contrarily, Schütte *et al*. (2016) did not find any alterations made to contact times when participants ran over three different surfaces (concrete, synthetic track, and woodchips). However, during the woodchip running there was a significant decrease in SF. These three articles are in contrast with one another, because they found different results for ground contact times and SF, even though they were all performed over uneven terrain. A possible explanation for the discrepancies is the presence of vertical obstacles during the forest run that was not present in the other two studies. The flight time and vertical impulse that is applied during the stance phase (Warren, *et al*., 1986) both influence the outcome of a subsequent step, hence the presence of vertical obstacles will lead to altered vertical movements of the CoM and further influence gait variables (Warren, *et al*., 1986).

The distance over which athletes ran could also have had an influence on the SF and SL, because they would only have a certain amount of space and visual perception of obstacles. Visual perception of a subsequent foot placement area is dependent on the distance that the individual can perceive (Matthis & Fajen, 2013). Alterations and adaptations that are made during each individual step in response to visual perception might not influence the mean outcome of these measurements but could result in large inter-step variability. A study by Voloshina and Ferris (2015) investigated the biomechanical and physiological changes that occur during uneven terrain running. The researchers added different size woodblocks to a treadmill belt (up to 2.5 cm), and had participants run at 8.3 km.h^{-1}. Although they found no differences in the mean SL, step height, or step period, they did find significant changes in the variability of all three variables during uneven terrain running. Unlike some previous studies, Voloshina and Ferris (2015) included the variability of each step parameter, indicating that mean step quantities might not change, but there were alterations made during each step individually. During studies of uneven terrain running, investigating both the mean and the coefficients of variation might yield more valuable results (Moe-Nilssen & Helbostad, 2004), because it will provide insight into each step regardless of its successor or predecessor. **Table 2.2** shows the importance of including aspects such as the CV for step parameters, because the mean values do not provide sufficient information regarding each step individually (Voloshina & Ferris, 2015).

Table 2.2: Step parameter data collected during level even and uneven terrain running at 2.3 m.s^{-1}, by Voloshina and Ferris (2015).

	Even surface		**Uneven surface**	
	Means (±SD)	Variability (±SD)	Means (±SD)	Variability (±SD)
Step width	0.055 (0.029)	0.022 (0.004)	0.059 (0.033)	0.028 (0.006)*
Step length	0.881 (0.051)	0.035 (0.009)	0.884 (0.044)	0.044 (0.011)*
Step height	-	0.004 (0.001)	-	0.009 (0.002)*
Step period (s)	0.729 (0.041)	0.010 (0.003)	0.731 (0.033)	0.013 (0.003)*

m.s^{-1} : meters per second, s: seconds, SD: standard deviation
* Indicates values that are significantly different ($p < 0.05$) between the even and uneven surfaces.

2.3.3 DYNAMIC STABILITY AND TRAIL RUNNING

A moving system without any internal feedback control mechanisms, could sustain stability to a certain extent, due to its movement and mechanical properties (Bruijn, *et al.,* 2013). When moving over complex terrain, "small perturbations may be controlled by passive dynamics without central nervous system involvement, and larger instabilities in the system are countered by active control, which requires sensing of perturbations, generating appropriate motor commands, and producing compensatory motions" (Mahaki, *et al*., 2019). There are three main systems within the human body that are crucial for maintaining and controlling human postural stability in both static and dynamic environments, namely the vestibular, visual, and proprioceptive systems (Marcolin, *et al.*, 2019). The primary aim of these systems (with regards to balance and stability) is to maintain the CoM over the base of support (Marcolin, *et al*., 2019) and lend itself to the secondary purpose of keeping the body upright when traversing complex terrain (Mahaki, *et al*., 2019). Methods of measuring stability during human locomotion differs (Bruijn, *et al*., 2013). Two different methods of calculating stability during human locomotion include the calculation of local dynamic stability (LDS) and dynamic stability.

LDS is defined as the "ability of the locomotor system to maintain continuous walking despite very small external or internal disturbances" (Josiński, *et al*., 2019) and is based on the calculation of the maximum Lyapunov exponent (Bruijn, *et al*., 2013). The Lyapunov exponent can be calculated from any source of kinematic data, allowing for the use of cheap and inexpensive IMU devices (Bruijn, *et al*., 2013). Calculation of the maximum Lyapunov exponent is dependent on the creation of a state space structure (Josiński, *et al*., 2019), which is a model based on "kinematic data obtained from a steady-state walking trial" (Bruijn, *et al*., 2013). A high maximum Lyapunov exponent indicates that even small perturbations can cause disruptions in the system, leading to low LDS (Josiński, *et al*., 2019), and vice versa. This method of evaluating stability could potentially be limited when smaller data sets are available, as this would decrease the statistical precision (Bruijn, *et al*., 2013). However, some research has suggested multiple sets of small data counts could still be of use (Sloot, *et al*., 2011). Only one research article has been found to describe the use of LDS in outdoor running, however it was only over synthetic track (Hoenig, et al., 2019).

Dynamic stability is defined as the ability to maintain variability, regularity, symmetry, and complexity of three-dimensional trunk accelerations during locomotion (Schütte, *et al*., 2016). Dynamic stability calculations and estimations are based on the integration of trunk accelerometer data and the use of an auto-correlation procedure (Moe-Nilssen & Helbostad, 2004) to produce specific peaks. These peaks indicate the correlation of each step and stride, with all other steps and strides within a data set (Moe-Nilssen, 1998b), and quantifies the deviation from perfect gait symmetry. Even though dynamic stability and LDS is relatively similar, as they both can be calculated from kinematic data and provide indications of changes in system stability, it would appear that the computational costs involved with calculating the dynamic stability, is lower than the LDS.

Dynamic stability is widely studied in relation to the fall risk of the elderly (Bizovska, *et al*., 2015), but there are almost no studies that explore dynamic stability during TR (Svenningsen, *et al*., 2020). A decrease in dynamic stability has a possible link to running related injuries, specifically when improper loads are redistributed through the kinetic chain (Schütte, 2018). Several authors have investigated the change in dynamic stability during walking on complex surfaces in the last twenty plus years, however running related studies with the use of accelerometry appear only relatively recently (see **Table 2.3**). The studies presented in **Table 2.3** investigated dynamic stability while running on uneven and complex terrain, however, woodchip trails are not often found during TR (Easthope, *et al*., 2014). However, such research does provide a framework to understand dynamic stability variables and their values, when running over uneven terrain, and these articles provide a relative comparison for future studies (Schütte *et al*., 2016; Boey *et al*., 2017).

Table 2.3: Studies that investigated the influence of irregular surfaces on dynamic stability during conventional walking and running.

Walking				Running			
Study	**Participants**	**Surfaces**	**Speeds**	**Study**	**Participants**	**Surfaces**	**Speeds**
Moe-Nilssen, 1998c	19 (4 males / 15 females)	Flat and uneven (rubber plates, underneath layers of rubber carpets)	Five speeds (very slow to almost running)	Schütte, *et al.*, 2016	28 (14 males / 14 females)	Concrete road, synthetic track, and woodchip trails	Self-selected
Menz, *et al.*, 2003	30 (11 males / 19 females)	Flat and uneven (wooden blocks underneath a foam layer, covered with turf)	Self-selected	Boey, *et al.*, 2017	35 (18 male / 17 female)	Concrete track, synthetic track, and woodchip trails	Self-selected and fixed 11 km.h^{-1}
Menant, *et al.*, 2011	6 (1 male / 5 females)	Flat and uneven (wooden blocks underneath a foam layer, covered with turf)	Self-selected				
Cole, *et al.*, 2014	12 (6 males / 6 females)	Firm, compliant and uneven (wooden blocks underneath a foam layer, covered with turf)	Self-selected				
Dixon, *et al.*, 2018	18 (10 males / 8 females)	Flat and uneven (irregular brick walkway)	Self-selected				

The study by Schütte *et al*. (2016), is referenced throughout this thesis, because it provides an excellent framework for studies related to trunk accelerometry, dynamic stability and outdoor running. The purpose of their study (Schütte *et al*., 2016), was to "investigate outdoor surface effects on dynamic stability and loading during running using tri-axial trunk accelerometry" (Schütte, *et al*., 2016, pg. 221). Participants (n = 28) ran over three different surfaces (concrete, synthetic track, and woodchip trails) at a self-selected pace. They ran over concrete (determining a self-selected pace), synthetic track and woodchip trails. The step and stride regularities provide information regarding the consistency of steps and strides, by means of the incorporation of an autocorrelation procedure (Moe-Nilssen & Helbostad, 2004). The authors found that during woodchip running, aspects of dynamic stability were challenged, because of the inconsistent nature and compression capabilities of the woodchips, compared to the concrete surface (Schütte, *et al*., 2016). Furthermore, they found a general decrease in mediolateral (ML) step and stride regularity over the woodchip trails, but not in the vertical (VT) or anterior-posterior(AP) directions (Schütte, *et al*., 2016). Step and stride regularities from Schütte *et al*. (2016) are reported in **Table 2.4**.

Table 2.4: Results related to step and stride regularities (means ±SD) during different surface conditions, from Schütte *et al*. (2016).

	Axis	Concrete	Synthetic track	Woodchip trail
Step regularity	VT	0.80 (0.09)	0.82 (0.08)	0.81 (0.08)
	ML	0.55 (0.13)	0.57 (0.12)	0.51 (0.12)
	AP	0.85 (0.12)	0.59 (0.13)	0.55 (0.11)
Stride regularity	VT	0.81 (0.09)	0.84 (0.06)	0.82 (0.08)
	ML	0.69 (0.12)	0.70 (0.09)	0.64 (0.10)
	AP	0.65 (0.12)	0.67 (0.13)	0.63 (0.12)

AP: anterior-posterior, ML: mediolateral, SD: standard deviation, VT: vertical

Similar to Schütte *et al.* (2016), Boey *et al*. (2017) also had participants run over concrete, synthetic track, and woodchip trails, whereby they incorporated a single accelerometer placed on the tibia, and measured vertical accelerations while participants ran at two different speeds (self-selected and 11 $km.h^{-1}$). The authors indicated a significant decrease in vertical accelerations during slower speeds on all surfaces, as well as running on the woodchips compared to the synthetic track and concrete (Boey, *et al*., 2017). Additionally, their results indicated lower vertical accelerations when running at a slower speed.

The studies by Schütte *et al*. (2016) and Boey *et al*. (2017), show the alterations that are made during uneven terrain running to accelerations at both the trunk (Schütte, *et al*., 2016) and the tibia (Boey, *et al*., 2017). However, settings such as woodchip trails do not often appear during TR (Svenningsen, *et al*., 2020) and the results might not be transferable to TR. Furthermore, to compare these results to TR would be problematic because TR includes greater inclinations and more complex environments with less dense substrates (compacted dirt tracks).

2.3.4 **SUMMARY**

Two primary factors differentiate TR from RR. Firstly, TR incorporates a larger amount of graded running, compared to traditional RR (Ehrstrom, *et al*., 2017). Inclined running alters running mechanics such as increasing SF (Swanson & Caldwell, 2000; Gottschall & Kram, 2005; Padulo, *et al*., 2012; Willis, *et al*., 2020) and ground contact times (Swanson & Caldwell, 2000; Willis, *et al*., 2020), and decreasing SL (Gottschall & Kram, 2005; Padulo, *et al*., 2012). Inclined running also requires greater mechanical work to continuously lift the CoM (Minetti, *et al*., 1994); Minetti, *et al*., 2002), leading to greater physiological strain on the athlete (Willis, *et al*., 2020). Secondly, TR is performed on complex and uneven terrain, which alters SF, SL, and ground contact times (Tessutti, *et al*., 2010; Herbert-Losier, *et al*., 2015; Schütte, *et al*., 2016). Even though uneven terrain running might not change the mean values of an athlete's SF, SL, or ground contact times, it is important to evaluate the variability within each of these variables.

Both inclined running and uneven terrain running influences the three-dimensional movements of the CoM, because of the alterations made to SF, SL, and ground contact times. Studies of dynamic stability could assist in quantifying the changes made to trunk accelerations during different terrain running (Moe-Nilssen & Helbostad, 2004; Schütte, *et al*., 2016; Svenningsen, *et al*., 2020). No studies have investigated changes in dynamic stability when athletes traverse TR terrain (Svenningsen, *et al*., 2020). Using dynamic stability as a method of quantifying the differences between TRD and TR, will provide a better understanding of how TR influences the running gait.

2.4 THE INERTIAL MEASUREMENT UNIT AND ACCELEROMETER

2.4.1 INERTIAL MEASUREMENT UNIT

Inertial measurement unit (IMU) sensors have been used by researchers since the early 1930's, to assist in aircraft navigation and other large machineries (Zhao & Wang, 2012). More recently, the IMU has been used in a wide variety of situations, because the low cost and small design makes it more accessible to different fields of research (Jarchi, *et al*., 2018). Manufacturing, robotics, navigation systems, augmented reality, medical rehabilitation and sports applications all benefit from IMU sensors (Ahmad, *et al*., 2013). There are different types of IMU sensors, each more applicable to a different environment or practice.

Determining what IMU to use, depends on the degrees of freedom that is required to align with the goals of the research in question, whereby degrees of freedom refer to the different measurable variables a system can measure (Ahmad, *et al*., 2013). If a sensor can measure one variable across a single axis, that sensor only has one degree of freedom, and is used for an extremely specific types of movement. If a sensor can measure a single variable over three different axes', then it has three degrees of freedom, and can be used to define and measure complex tri-axial movements. A combination of different sensors that can measure different variables across all three measurable axis's, implies that the IMU can achieve between two and nine degrees of freedom (Ahmad, *et al*., 2013), providing a wide variety of information. The most common sensors found within an IMU, include the gyroscope, magnetometer, and the accelerometer.

Godfrey *et al*. (2008, pg.1369) describes accelerometers as "devices that measure applied accelerations acting along a sensing axis which can be used to measure the rate and intensity of body movements in up to three planes", see **Figure 2.3**. Accelerometers were first used to evaluate human movement during the 1950s (Saunders, *et al*., 1953), however they were cumbersome and expensive.

Eventually, as science and the technology used in the scientific environment improved, the use of accelerometers arose again in the 1970s (Morris, 1973). Recently, the improvements in technology such as microelectromechanical systems (MEMS) have drastically reduced the cost and size of accelerometers (Culhane, *et al*., 2005). Due to the small size and low energy consumption of MEMS accelerometers, it can measure human activity constantly over several days or weeks (Godfrey, *et al*., 2008). This advance in technology lends its benefits to studies of biomechanical interests.

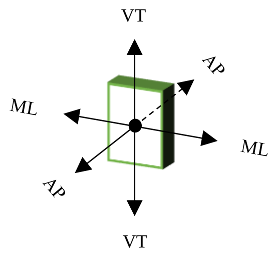

Figure 2.3: Demonstration of the three different directions of measurement that can be performed by a MEMS accelerometer. VT – vertical; AP – anterior-posterior; ML – mediolateral. (source: Oloff CW Bergh)

2.4.2 **ACCELEROMETRY**

Although many different techniques for assessing human movements exist, few are as simple and cost effective as the accelerometer (Godfrey, *et al*., 2008). This has given rise to the increased academic interest in accelerometry to measure human movement. Accelerometry could be defined as the use of accelerometers to quantify human movement (Morris, 1973; Kavanagh & Menz, 2008).

A single accelerometer can provide a wide range of information regarding specific running gait variables (Jarchi, *et al*., 2018). However, the basic information that is gathered is three directions of acceleration. These acceleration measurements create wavelets that can be differentiated from one-another, because each measurement direction experiences different accelerations in normal gait. Wavelets are defined as “a waveform of effectively limited duration that has an average value of zero and they come in many different shapes and sizes” (Godfrey, *et al*., 2008, pg. 1374). Wavelets that are produced during normal gait have a relatively symmetrical structure (see **Figure 2.4**), as each step is relatively similar to its predecessor (Moe-Nilssen & Helbostad, 2004).

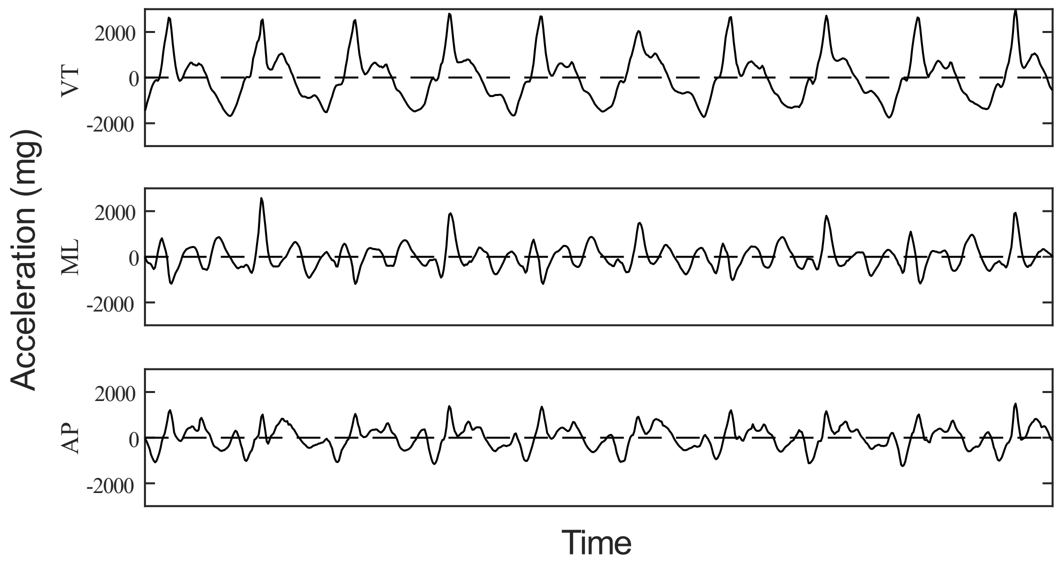

Figure 2.4: Illustration of accelerations measured at the third lumbar vertebrae during running (10 km.h^{-1}) on a inclined treadmill (eight-degrees). The *top, middle,* and *bottom* graphs show the vertical (VT), mediolateral (ML), and anterior-posterior (AP) accelerations wavelets, respectively. The dotted centre lines indicate the mean value over the entire graph. Through visual inspection, a repetitive pattern can be seen for all three directions, although ML is more difficult to differentiate. (source: Oloff CW Bergh).

Due to the cyclical nature of these wavelets (Moe-Nilssen & Helbostad, 2004), specific methods can be used to define certain key gait events. As early as 1991 researchers used uni-axial accelerometer and these wavelets to identify heel strikes (Evans, *et al*., 1991), and by 1999 other researchers were identifying more complex variables such as temporal parameters (Aminian, *et al*., 1999) and stride regularity and symmetry (Auvinet, *et al*., 1999). As technology improved over the years, an even greater amount of information regarding gait variables can be derived from acceleration wavelets. Jarchi *et al*. (2018) compiled an extensive list of variables summarized in **Table 2.5**, which describes a variety of gait phases and parameters that can be determined using accelerometry.

Table 2.5: The large amount of phases and variables, derived from acceleration data, which describe human gait (adapted from Jarchi *et al*. 2018).

Gait phases	Gait parameters
Initial contact	Acceleration amplitude variability
Loading response	Cadence
Mid stance	Cycle frequency
Terminal stance	Double support duration
Pre swing	Foot symmetry
Initial swing	Gait cycle time, irregularity, and variability
Mid swing	Harmonic ratio
Terminal swing	Inter-stride acceleration variability
	Lateral foot position
	Normalized speed
	Root mean square
	Stance duration
	Step asymmetry, duration, frequency, length, regularity, timing variability, width, and width variability
	Single support duration
	Stride duration, frequency, length, regularity, symmetry, and velocity
	Swing duration
	Walking distance, intensity, speed, time, velocity
	Walk ratio

Even though a wide range of variables can be extracted from accelerometer data, the use of accelerometry to investigate human gait provides a unique set of challenges. The two primary concerns when using accelerometers is the external noise captured within acceleration patterns and the static component of gravity (Godfrey, *et al*., 2008).

If an accelerometer moves independent of the body it is attached to (i.e. not properly fastened down), recordings of non-specific movements will reflect in the raw accelerometer data. These non-specific movements in the recordings are characterized as “noise”. Reducing the noise is critical for the purpose of reporting accurate acceleration signals (Wundersitz, *et al*., 2014). Noise reduction can be achieved using a frequency filter set to specific values, based on the activity performed.

Previous studies that have been conducted on similar surfaces and terrains to that of the trail environment, have advocated for the use of filtering at different values. Schütte *et al*. (2016) had their participants run over concrete, synthetic track, and woodchip trails, and used trunk accelerometry to determine changes in dynamic stability. During their study, the authors used a zero-lag 4^{th} order low-pass Butterworth filter with a cut-off frequency of 50 Hz. Firminger *et al*. (2018) used a similar filter, but the frequency was downscaled to 45 Hz, when participants ran on a treadmill and over-ground at inclines (+ 8°) and declines (- 8°). In the review article by Svenningsen *et al*. (2020), they indicated that the most common filtering methods used in studies that looked at surfaces that are similar to TR (both walking and running) was the zero-lag 4^{th} order low-pass Butterworth filter at 8 to 50 Hz, or zero-lag 2^{nd} order low-pass Butterworth filter at 10 to 60 Hz. However, the 2^{nd} order filters were more popular amongst walking studies (Svenningsen, *et al*., 2020).

Furthermore, components such as the static component of gravity and the arbitrary tilting of an accelerometer away from its sensing axis will further influence the measurements made by an accelerometer (Moe-Nilssen & Helbostad, 2004). During both level and incline running, the position and tilting of an accelerometer because of the curvature of the lumbar spine, is an important aspect to take into consideration when examining the direction of measurement (Moe-Nilssen, 1998b). Tilting an accelerometer away from the original sensing axes will result in an altered measurement of the static gravitational force (constant 1 *g* - gravity) and the dynamic force produced by the actual movement (Moe-Nilssen, 1998a). Correcting for this tilt away from the true horizontal-vertical coordinate system provides accurate results of the acceleration data. **Figure 2.5** illustrates the change in measurement direction when an accelerometer is rotated in a single direction. More complex calculations are required when an accelerometer is tilted in an arbitrary manner (whereby the direction and degree of tilt is unknown) and if all three directions of measurement are affected. Moe-Nilssen (1998a) provides a comprehensive guide on the procedural elements of manual trigonometrical corrections when an accelerometer is arbitrarily tilted.

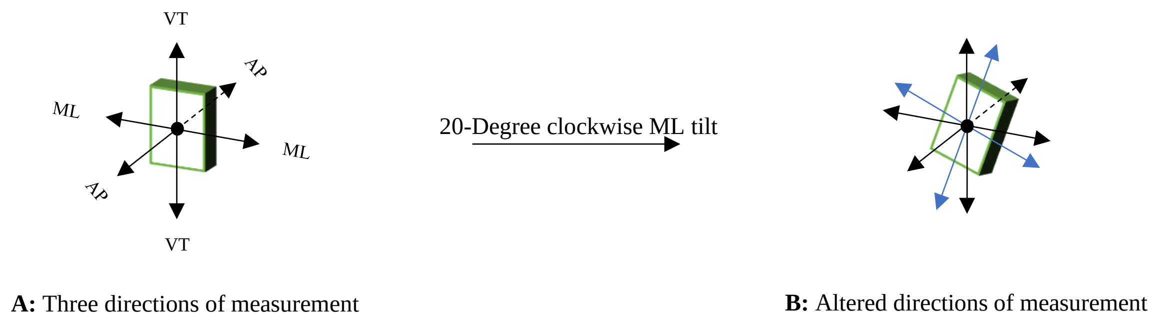

Figure 2.5: A demonstration of single directional rotation on the directions of measurement for an accelerometer. Object **A** illustrates the three normal directions of measurement (black arrows) when an accelerometer is in a standard position. Object **B** shows the shift of the measurement directions (the blue lines) from the true horizontal-vertical plane of measurement for the ML and VT directions, following a tilt of twenty-degrees in the ML direction. (source: Oloff CW Bergh).

2.4.3 VALIDITY AND RELIABILITY OF AN IMU

The *gold standard* for measuring human movement are 3D motion capture systems (Cole, *et al*., 2014). However, this method of measuring human movement is restricted to a small measurement area, difficulty in moving the system and the effect of ambient light in outdoor environments (Cole, *et al*., 2014). The question arises whether wireless measurement devices such as an IMU or an independent tri-axial accelerometer, would deliver valid and reliable results, compared to 3D motion capture systems. Several researchers have investigated the validity and reliability of wireless IMU devices and accelerometers.

Wundersitz *et al*. (2014) examined the ability of an accelerometer, inside an IMU, to accurately measure peak accelerations during walking (5.4 km.h^{-1}), jogging (11.8 km.h^{-1}) and running (female, 18 km.h^{-1}; males, 21.2 km.h^{-1}). Thirty-nine participants wore an integrated accelerometer capable of measuring at 100 Hz and a single-retroreflective marker at the same position, whereby a 12-camera motion system would determine movements of up to 200 Hz. The authors concluded that the filtered accelerometer data provided valid data, when the participants were walking and running (Wundersitz, *et al*., 2014). They did note that there was a decrease in accuracy when the participants were running, indicating that higher acceleration measurements tended to decrease the accuracy of the accelerometer compared to the motion capture system (Wundersitz, *et al*., 2014).

To investigate the effect of different trunk locations on the consistency of acceleration measurements, Rispens *et al*., (2014) included gait characteristics such as speed, stride time and frequency, step-stride regularity and gait symmetry (Rispens, *et al*., 2014). Twenty-one healthy adults participated in their study and placed three tri-axial accelerometers capable of data capture at 100 Hz, on the L2 vertebrae, L5 vertebrae and anterior superior iliac spine (ASIS). The authors found "good agreement" between all three measurement locations and stride time and frequency, gait speed and variability. However, for aspects of step-stride regularity and gait symmetry, there was no agreement between the L2 or L5 with the ASIS location (Rispens, *et al*., 2014). Hence, measurements whereby the device is placed within the L2 to L5 region of the lumbar spine would be ideal to produce valid and comparable acceleration data when investigating step-stride regularity and gait symmetry.

Cole *et al*. (2014) assessed the validity of trunk mounted accelerometers and their ability to measure accelerations during locomotion on "firm, compliant and uneven surfaces". An IMU was mounted on twelve younger and twelve older participants around the T12 vertebrae (12^{th} thoracic) and collected data at 100 Hz. An eleven-camera motion capture system was used to compare against the IMU data. All participants walked barefoot at self-selected paces over the three different surfaces, which were constructed from a variety of different wooden blocks under a layer of foam and artificial turf. The authors concluded that an IMU accurately measured trunk accelerations (Cole, *et al*., 2014). Furthermore, the authors concluded that IMU measurements, "are appropriate for research that evaluates healthy populations in complex environments" (Cole, *et al*., 2014, pg. 1). Similarly, Byun *et al*. (2016) indicated that using a single tri-axial accelerometer to investigate gait parameters, gait asymmetry and variability, would yield both valid and reliable results (Byun, *et al*., 2016).

2.4.4 **SUMMARY**

IMU and accelerometer devices are lightweight, easy-to-use, and relatively affordable (Godfrey, *et al*., 2008). Because of the lightweight and low energy consumption of accelerometers, they are frequently used in biomechanical studies. Accelerometry is defined as quantifying human movement, through the evaluation of acceleration patterns (Morris, 1973; Kavanagh & Menz, 2008). A large amount of gait related information can be obtained from three-dimensional trunk accelerations as described by Jarchi *et al*. (2018). When working with an accelerometer it is important to take into consideration the influence of noise (Wundersitz, et al., 2014) within the acceleration signal, the static component of gravity because of arbitrary tilting of an accelerometer away from its sensing axis and the trigonometrical corrections (Moe-Nilssen, 1998a; Moe-Nilssen & Helbostad, 2004; Schütte, *et al*., 2016).

Even though the IMU and accelerometer has been deemed both valid and reliable devices for recording three-dimensional accelerations during human locomotion, very few studies have used them to determine aspects of dynamic stability in outdoor settings (Schütte, *et al*., 2016; Svenningsen, *et al*., 2020). A study using either IMU or accelerometer devices during TR would assist in quantify the differences between TRD and TR, by illustrating how surfaces influence changes in trunk acceleration patterns.

2.5 CONCLUSION

TR differs from normal road running through the incorporation of complex and challenging terrain as well as a larger quantity of inclines and declines. Complex and uneven terrain running challenges aspects of dynamic stability, as shown when individuals ran over woodchip trails (Schütte, *et al*., 2016; Boey, *et al*., 2017). However, no studies have indicated changes in dynamic stability, while athletes run over TR terrain (Svenningsen, *et al*., 2020). Uneven terrain and incline running have both shown to alter step times, as well as the variability in step times (Voloshina & Ferris, 2015). Even though the use of accelerometry is deemed both valid and reliable in running studies, there is a lack of research exploring TR and dynamic stability.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

Through exploration of current literature regarding trail running (TR) in comparison to treadmill running (TRD), there is a clear need for the further examination of the acute kinematic and gait-parametric changes, with a key focus towards real-world environments and dynamic stability. In the following chapter there will be an overview provided of the study design, followed by the recruitment methods for participants, as well as their specific inclusion and exclusion criteria. Thereafter a description of the study outline and the timeline that guided the testing procedures follows, as well as explanations and details regarding the equipment used in the testing and measurements of participants. The statistical analysis of the data obtained closes off the chapter.

Throughout this section the term "research team" refers to three individuals. The primary researcher Oloff C.W. Bergh, and two other researchers (Matt Swart and Emily Robertson) who were also busy conducting their own research on the same sample group of trail runners, but with separate research questions. The researchers assisted each other during data collection, even though each researcher was interested in different variables. The mentioned researchers are part of a research team on the project uSTARRR (University Stellenbosch Trail and Road Running Research).

3.2 STUDY DESIGN

This study utilised a descriptive design whereby step regularity, stride regularity, gait symmetry and dynamic stability were determined in two separate running settings (TRD and TR) with no intervention. Additionally, this study design was observational in nature as the natural relationship between running surface (TR and TRD) and dynamic stability was observed without intervention.

3.3 PARTICIPANTS

A group of 13 male recreational trail runners were recruited, whereby recreational is defined as running 16 – 48 km per week (Orendurff, *et al*., 2018) with regular runs taking place on trail surfaces. An *a priori* power analysis with $\alpha = 0.05$, $\text{Power}_{(1-\beta)} = 0.98$ and effect size = 1.05 was used to determine sample size. Effect sizes were chosen based on data from a proof of concept study and data from Voloshina and Ferris (2015). Calculations were done using G*Power™ (3.1.9.2) statistical software, as it has been shown to be appropriate for use in the social, behavioural and biomedical sciences (Faul, *et al*., 2007). Twelve of the original thirteen participants completed all requirements to be included in the study. One participant appeared to have incorrect recorded data, due to two possible issues. Firstly, and most probably, was the incorrect attachment of the IMU that caused excessive noise and acceleration spikes within the participants data. Secondly, although less likely, the participant had a non-symmetrical gait that caused deviations from standard acceleration patterns. Following the study, a *post hoc* analysis was completed which indicated that 12 participant's data would influence the statistical power ($\text{Power}_{(1-\beta)}$) of the study from 0.98 (n = 13) to 0.95 (n = 12).

3.3.1 RECRUITMENT METHODS

A mixture of purposive, snowball and random sampling methods were proposed for the recruitment of participants. Purposive sampling is defined as a method of selecting individuals to partake in a study based on their previous knowledge or abilities surrounding a certain task or event (Etikan, *et al*., 2015). This method was used primarily due to two factors. Firstly, the distributing of a flyer (see **Appendix A**) through direct contact with a population of recreational trail runners. Secondly, the distribution of the flyer over social media (WhatsApp™, Facebook™, Instagram™), a TR website (www.rootedindirt.com) and specific notice boards (at Stellenbosch University, Department of Sport Science), provided the possibility of a wide range of individuals being reached and informed of the study. This technique of reaching individuals also aligned with a snowball and random sampling method. Individuals who contacted the researchers and met the inclusion and exclusion criteria of the study, made up the final study sample.

3.3.2 INCLUSION CRITERIA

To be included in the study the individuals needed to be a biological male between the age of 21 and 35 years old, run a minimum of 16 – 48 km per week (Orendurff, *et al.*, 2018), mostly over trail surfaces. They must have been willing to participate in two different tests (a TRD and TR test) that were non-invasive and purely observational. They also must have completed and signed the informed consent form (ICF) (see **Appendix B** or **C**) before any testing could commence.

3.3.3 EXCLUSION CRITERIA

Any individuals who had a current injury or currently recovering from a performance limiting injury within the last three six months prior to the study, was not allowed to partake. Furthermore, individuals with a gait impediment or severe deviation from conventional running gait, would be excluded. If the weather conditions during the testing day was deemed excessive (wind or rain), the participant could choose to not participate or complete their testing on a later date. If the data were affected by incorrect IMU placement or technical errors, the data would be excluded. If the participant did not run the correct route or could not complete the TR section, their data would also be excluded from the final sample pool.

3.4 STUDY OVERVIEW

Runners responding to the flyer and showing interest in participation were screened according to the inclusion criteria through a verbal discussion (telephone or in-person) with the researcher to determine if they were eligible to partake in the study. Participants were required to have a single visit to the Stellenbosch University, Department of Sport Science, and the CAF (Central Analytical Facilities) –

Neuromechanics Laboratory (further simply called "the lab"). They were asked to sign the ICF prior to any testing. The participants were given the form to read and then given a chance to ask any questions if they were not confident in all aspects of the agreement. If there were any complications with signing of the ICF, or rejection of any procedural elements, no testing was initiated.

Participants were asked to arrive in their regular running shoes as well as comfortable running attire. After the signing of the ICF, and prior to any other testing, anthropometric data from the participant was recorded by the researchers. The researchers were qualified Sport Scientists with Honours Degrees in High Performance Sport and have had previous experience in anthropometric measurements. Following anthropometric measurements, the application of the IMU's was completed. All researchers were well familiarized with application procedures of the testing equipment and completed the CAF-Neuromechanics workshop and training in July 2019.

The order of the two tests were randomized per participant. Outdoor running (TR) was conducted only when weather conditions were fair enough for outdoor running (see **Table 3.2**), otherwise the participant could decide not to partake in the study or come back at a later date. Participants were then informed regarding the specific procedure again and ran up to three attempts of the outdoor trail section. The course consisted of 30 m incline and 30 m decline, for a total of 60 m running distance. The measurements were recorded onto a mobile setup of the indoor testing equipment. All participants completed the outdoor testing within one hour, depending on equipment functionality. The participants were then taken inside to complete the treadmill protocol of the testing. The time of each bout was one minute, whereby 30 seconds was at 8 $km.h^{-1}$ and 30 seconds and 10 $km.h^{-1}$.

Although no payment for participation was provided, participants could request a free consultation session with the investigators where they had the chance to see their recorded data and have a professional conversation about their running technique and areas that might improve their training and performance.

3.5 ETHICS

This study was approved by the Stellenbosch University, Health Research Ethics Committee (N19/07/076)) (see **Appendix D**). The study was carried out in accordance with the Helsinki Declaration guidelines.

3.6 TESTS AND MEASUREMENTS

Throughout the duration of the study there was a set guideline of procedures and methods that were followed during data collection. **Table 3.1** shows the general processes that the researchers followed. The sections that follow will discuss the specific testing procedures and the methods that were followed.

Table 3.1: An over-view of procedural elements that guided that researchers through the data capture process.

Prior to arrival	Arrival		Indoor	Outdoor	Test Completion
	Anthropometrics	IMU Application			
Inform participants of all testing details Ensure environmental safety of the outdoor and indoor test areas Prepare necessary equipment, including outdoor setup items Check all equipment for functionality and if wireless devices are charger and clean Have ICF ready for participant to sign when they enter the lab	All measurements are to be performed in a similar manner and only if the participant signed the ICF Ask the participant if they may be touched to measure anthropometric values Measurements included age, height, mass, BMI, thigh circumference and calf circumference	Prepare all tape and straps, check IMU connectivity with the Noraxon software Ask the participant if they consent to taking of their shirt for the application of the IMUs' Apply tape over the IMU and secure the pelvis IMU with a neoprene belt The participant can put their shirt back on if they wish	Prepare the treadmill Ensure the speeds and angle of the treadmill is set correctly Allow sufficient time for the participant to warm-up and familiarize with the treadmill Always calibrate the IMU within the software after a run or attempt	During the indoor testing, the outdoor setup needs to be done Ensure the safety of equipment, participants, and researchers (and bystanders) Show the participant exactly where to run, turn and stand during calibration When done, bring all equipment inside	Thank the participant for their time and effort, escort them out of the building Clean up both inside the lab and outside Clean all equipment and charge if needed Pack everything back into the correct place Lock up the lab if needed, and thank the employees of the lab for their assistance

3.6.1 PRIOR TO PARTICIPANT ARRIVAL

The research team had to sign an indemnity form provided by the lab, to ensure that they acknowledge the rules and regulations of the facilities, and that they will abide to these rules without question. One week before the participant was to arrive for testing, a list of necessities for the day of testing was sent via WhatsApp™. This list included not only what the participants would need, but what they should refrain from doing prior to testing. It included aspects such as:

- Wear normal trail running shoes
- Please do not wear tights.
- Loose shorts are preferred
- No alcohol or caffeine 24-hours, prior to testing
- No strenuous training 48-hours, prior to testing
- A water bottle for hot days

The research team had to set up and prepare all equipment, to ensure a smooth transition from preparation to testing, and were thus required to be at the laboratory one hour prior to the participants arrival. Ensuring a clean and safe testing environment, checking that all wireless equipment were charged to full capacity, gathering all adhesive tapes, straps, scissors, and cables to prepare the participant, were all part of the researchers' duties. Additionally, researchers had to make sure that all equipment for outside testing was placed ready for the transition period from inside to outside, or if the testing had to occur outside first. The outside equipment included a gazebo, a camping chair, extension cords, a laboratory laptop, and a foldable table as well as the necessary receivers and wireless transmitters.

3.6.2 PARTICIPANT ARRIVAL

The participant arrived at the Department of Sport Science (Stellenbosch University) and was introduced to the research team. The individual was then provided with a printed copy of the ICF and given adequate time to read through the document with further time to ask any questions before signing. Upon signing, the individual was taken to the lab right next to the Department where they were prepared for testing.

3.6.3 ANTHROPOMETRICS

During the first few minutes after arrival, several anthropometric measurements were recorded. These included participant height, weight, BMI calculations, thigh and calf circumferences for the right leg, shoe size and leg length for both legs. These assessments were conducted by researchers who are qualified sport scientists and had previous experience in conducting these assessments.

The measurement of each participant's height was done using a set technique with the use of a calibrated stadiometer (Panamedic™). The participant stood with their backs against a wall without their shoes on. To ensure accurate measurements across all participants the head of each participant was placed in the Frankfort horizontal plane whereby the lower part of the eye socket is within the same horizontal plane as the Tragion of the ear. The participant was then asked to inhale as deep as possible, and the measurement was taken and recorded in Microsoft Excel (Version 16.0.6742.2048).

The participant's mass was measured in kilograms, using the digital scale provided by the lab. They stood on an OMRON™ (OMRON Healthcare Co., Ltd., Netherlands) scale without their shoes, with their feet at the appropriate locations and their arms next to their sides. The measurement was then recorded in the spreadsheet.

Body Mass Index (BMI) calculations used the standard formula:

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

These calculations were done automatically in Microsoft Excel after the height and mass for the participant was added to the Excel spreadsheet.

To measure the right thigh and calf circumferences the participant stood in a relaxed position, with feet approximately shoulder width and their arms hanging by their sides. Participants were not allowed to flex their lower-extremity muscles. The measurement for the thigh circumference was taken 15cm superior to the superior pole of the patella of each participant. This was done to ensure a similar measurement style and location for all the participants. The calf measurements were taken at the part with the most girth between the ankle and the knee joints. Two researchers recorded the measurement and ensured the tape did not slip and entered the recorded value in the Excel spreadsheet. These measurements were not used in this study but recorded for potential future studies.

3.6.4 INERTIAL MEASUREMENT UNITS

The IMU used during this study was a Noraxon myoMotion Research PRO IMU (Noraxon, USA). The device had a precise dimension of 52.2 x 37.8 x 18.1 mm and had a mass of 37 grams. There are several measurement devices imbedded in this IMU, including an accelerometer, gyroscope, and magnetometer. The accelerometer unit was able to measure linear accelerations of up to 200 Hz and up to ± 16 *g* force.

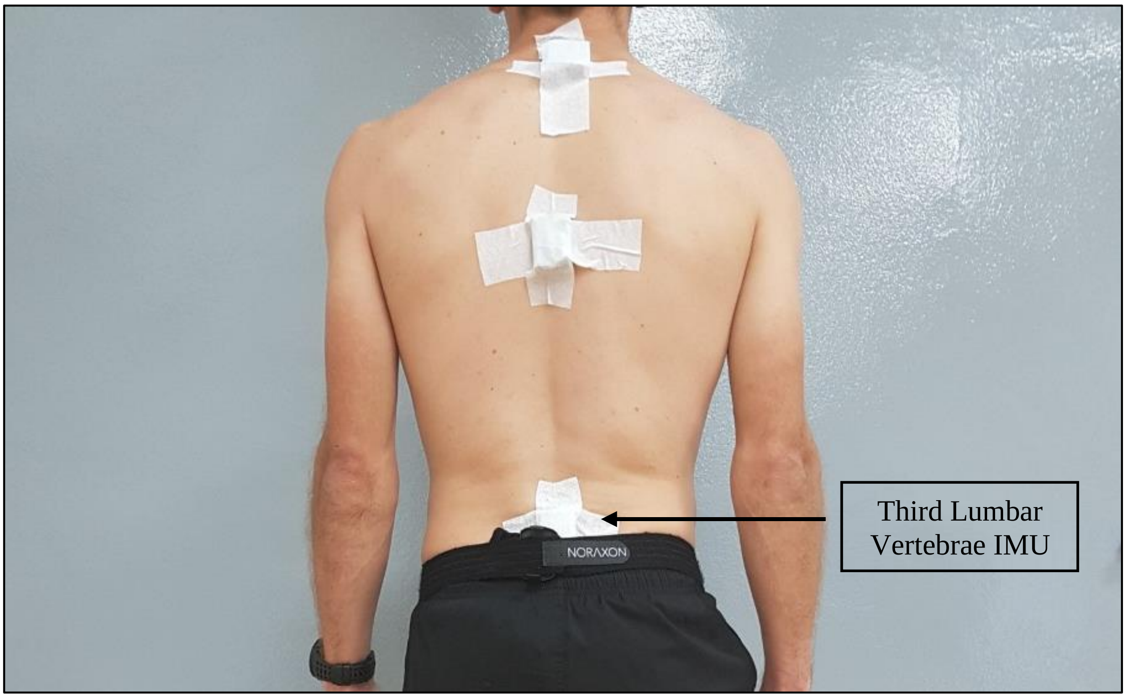

Figure 3.1: IMU's placed on the upper thoracic, middle thoracic and lumbar spine. (source: Oloff CW Bergh)

The specific location of the IMUs were chosen using the Neuromechanics Unit's guidelines and previous literature (Rispens, *et al*., 2014). This included placing the units on body landmarks and non-moving locations that are not affected by muscle contractions and subcutaneous tissue movements.

Although the primary focus of this study is the IMU located on the third lumbar vertebrae (**Figure 3.1**), several other units were also attached to the participants including: Upper thoracic, middle thoracic, left and right thighs, left and right shanks, and left and right feet. The data from these extra units are not reported on in the current study.

IMUs were secured using double sided tape and further adhesive tape on the foot and thoracic regions. For the pelvis, thigh, and shank regions a special strap (neoprene sleeve) and holder was used with non-slip rubber to ensure the proper placement and stability of the units. Streaming tests were also initially conducted to ensure the proper locations of the IMUs in relation to the Noraxon™ myoMETRICS Lab software (Noraxon, USA), prior to placing any units on the individuals. The IMU streaming test was done in the same recording, saved as, "Participant_(IDcode)_Streaming_Test". Data streaming from the IMU to the computer happened in the order as described by **Figure 3.2**.

The proper naming and labelling of data within the Noraxon® software is extremely important to show variables relating to the trial (such as speed and incline) and the actions performed after the testing was completed. All trials and tests were given a very precise name which was key to ensuring the correct data was collected. The names of all trials and conditions are very clearly stated in this chapter and served as guidelines for the researchers. After the streaming tests were done, the units were properly fastened to the participant with further adhesive tape and confirming the steadiness of the neoprene sleeves.

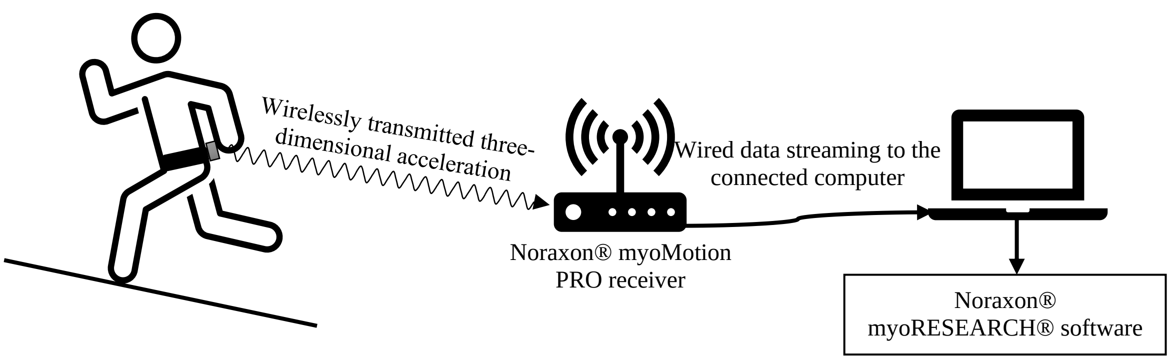

Figure 3.2: While the participant is running at an eight-degree incline (both indoors and outdoors), three-dimensional trunk acceleration data from the IMU is transmitted wirelessly to the Noraxon® myoMotion PRO receiver. The data is then streamed to the computer, and then into the Noraxon® myoRESEARCH® software for analysis. (source: Oloff CW Bergh)

After the fitting of all equipment, a “dynamic calibration” test had to be completed, to ensure the proper location of all IMUs with relation to the specifications of the Noraxon® software. The dynamic calibration included a variety of movements to ensure the IMUs were in the correct location, i.e. if the right shank was accidentally placed on the left shank of the participant, the software would indicate a criss-cross motion of the tibialis during normal forward walking. During the dynamic calibration, the participants were asked to perform actions such as hip flexion, knee flexion and extension, plantar- and dorsi-flexion of each foot and activities such as walking on the spot. The dynamic calibration was then saved as, “Participant_(IDcode)_Dynamic_Calibration”.

3.6.5 **INDOOR TESTING**

Figure 3.3: The treadmill at an eight-degree angle with the safety bar in front of the participant. (Source: Oloff CW Bergh)

The individuals were given detailed descriptions of the running processes that were to follow on the Bertec™ floor imbedded treadmill (**Figure 3.3**). The participant was recalibrated within the software, in case there was any shifting of the IMU between initial calibration and the beginning of the running trial(s). They were given one minute on the treadmill at a comfortable walking speed of 4.7 km.h^{-1} (Mazza, et al., 2009) and then one minute at a running speed (8 km.h^{-1}) as an initial familiarization period. After the participant reported to be familiar on the treadmill, they were checked for stability of the IMUs. All trials were completed in the participants normal trail running shoes. During all trials, a safety bar was installed in front of the participant to ensure safety and prevent falling, if the individual worried about falling or started to lose their balance. If the participant touched the safety bar, the trial would be deleted, and the participant would be given five minutes rest and a re-attempt. The participant had to run two different speeds during the incline run, set at 8 and 10 km.h^{-1} for 30 seconds each. The trial was then saved as, "Participant_(IDcode)_Indoor_Incline".

3.6.6 OUTDOOR TESTING

The outdoor setting was setup during the final part of the indoor testing, or early before the participant arrived, depending on the randomization. While the principal investigator was operating the treadmill, another researcher did the setup of a gazebo, portable table, extension cords, measured the distances and placed plastic cones at turning points, made sure the area was safe for testing (i.e. removed any large abnormal obstructions or safety hazards), informed any other individuals of the testing about to take place in the area and also chose allocated areas for calibration. **Figure 3.4** illustrates the testing setup outside.

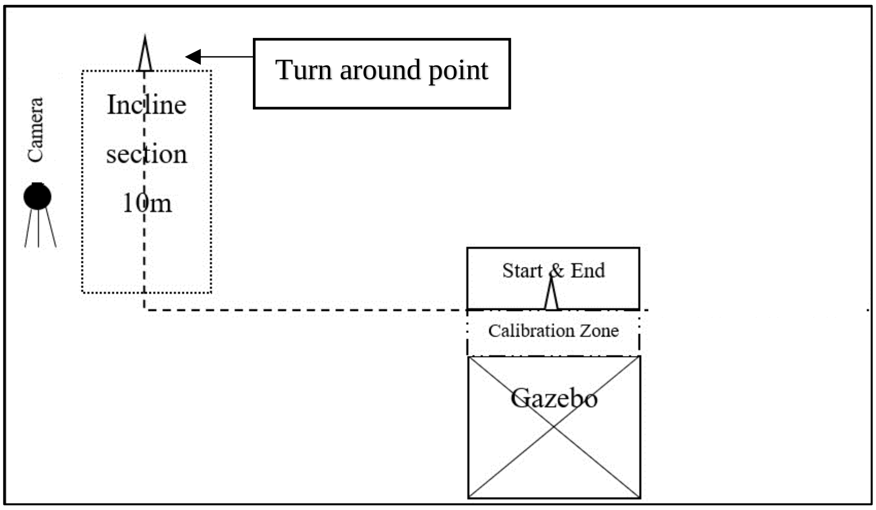

Figure 3.4: An illustrated reflection of what the testing area looked like during the outdoor testing sessions. The gazebo and calibration zone were on a flat grass field, while the running area (depicted by stripped line) was against an incline on a trail surface. Only 10 meters of the incline section was used for data analysis, however the entire running section was 60 meters in total.

The participant was led outside to the testing area by the principal investigator. During this time, the researcher group brought any other necessary equipment outside and began the final setup. While two researchers were setting up the equipment, the third took the participant through the course and showed the individual where to run, turn and where to stand upon finishing the section. **Figure 3.5** shows the uphill running section of the course. Even though the total running distance was 60 meters (30 up and 30 down), the only region that was used for data analysis was 10 meters of the incline section that was at +8°. This section was marked within the Noraxon® software using a specific start marker when the participant entered the straight 10m section after a slight curve and step (can be seen and identified within the y-axis acceleration) and a specific end marker (after the participant completed nine steps).

Once the participant had been well informed and familiarized with the different sections, the testing began. Before the participant started the trial, they were given a time estimate in which they needed to complete the course. They were instructed to regulate their running speed (not speeding up on the decline or slowing down on the inclines). The exact times they needed to take to complete the course was calculated prior to the start of testing. The participants had up to three attempts to run within one second from the calculated time of 21 seconds (average speed of 10 km.h^{-1} over the 60 m course).

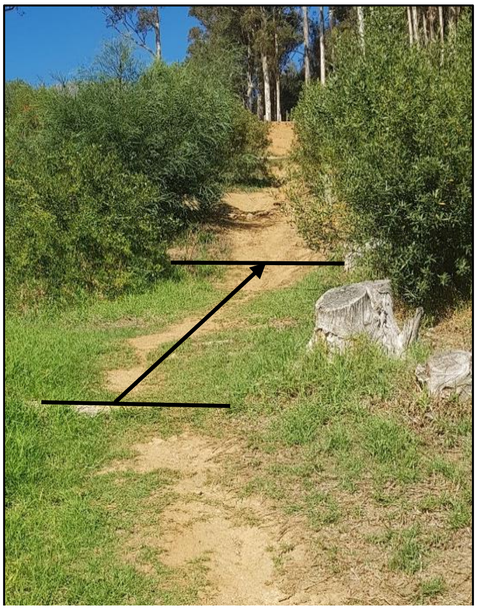

Figure 3.5: This image shows the 10-meter section of the incline run that was used for data analysis. Note that this picture was taken a few weeks after the start of the Covid-19 lockdown period, and the grass has grown over the usually compacted dirt pathway. (source: Oloff CW Bergh)

The participant had to stand for a quick re-calibration before the start of the trials and was conducted - in the same manner as the inside testing procedure. Once calibration was completed the participant stood at the starting position. A count down was given from three down to one, and then a loud “GO”. One researcher took time, the principal investigator managed the Noraxon® software (which also recorded time), while the third researcher managed the camera. The yelling of the word “GO” was also for the third researcher to know when to start the camera, so that data could be synchronized between video and IMU devices. When the participant reached the end, they were asked to stand close to the data receivers for data recovery (since they ran rather far away from the receiver, the on-board storage of the units had to be recovered). While the participant stood still for data recovery, additional information was loaded onto the Excel spreadsheet. This included the time for the trial and then the approximate speed calculated. If the participant ran too fast or too slow, the process was repeated.

3.6.7 **POST TESTING**

When the participants finished their attempts, they could return to the lab. The participant was then cleaned of all equipment and adhesive tapes were removed from the participant by one researcher, while the other two remained outside and cleaned up the testing area. The outside two researchers also ensured that all equipment and testing materials were returned to the lab, cleaned, and placed on charge for the next testing session. The participant was thanked for his time, effort and patience and was walked out by one of the researchers.

3.6.8 **CONSIDERATIONS**

Concerns were raised regarding the outdoor weather conditions during the testing. One day prior to testing, the researchers would examine the weather forecast and determine if testing would be able to commence. If there was rain or harsh winds, that would inhibit the participant or influence the wireless technology, the participant would be notified that testing would be moved to the next possible date. Wind speeds of over 25 $km.h^{-1}$ were deemed as too harsh for testing as well as any rain that would potentially cause the dirt track to become slippery or muddy. During each day of the study, the researchers recorded the current weather in Stellenbosch, using the Stellenbosch University, Faculty of Engineering weather recordings. **Table 3.2** shows the weather details for the participants when they ran on the treadmill (indoor) and the outdoor trail section. The fastest wind speed recorded was 16.3 km.h^{-1}, well below the cut-off value. The testing days were fair weathered, with no precipitation.

Table 3.2: Weather details during testing days.

	Indoors	Outdoors		
	Temperature (°C)	Temperature (°C)	Wind Speed (km.h^{-1})	Humidity (%)
Mean	23.9	23.3	8.6	50
Minimum	23.0	18.3	2.7	43
Maximum	24.0	28.7	16.3	63

3.7 DATA ANALYSIS

This study gathered a large amount of data that needed to be handled in a specific manner in order to conform to the goal of the study. Information was stored on the labs laptops and was then handed over to the researchers. The researchers had access to the Noraxon® myoRESEARCH software and could conduct data handling procedures. Initially the data was visually inspected to ensure that it could be used for processing. Three main aspects of data processing occurred, namely, data filtering, trigonometrical corrections, and the autocorrelation procedures. The data handling and analysis are presented in the following section. **Figure 3.6** shows the procedural elements of the data handling process.

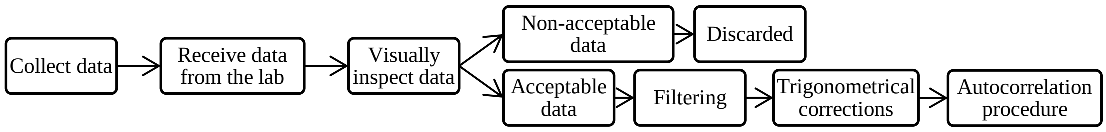

Figure 3.6: A visual representation of the process that followed data collection, and how data was processed.

3.7.1 DATA FILTERING

During the current study, a zero-lag 4th order Butterworth filter with a cut-off frequency of 50 Hz was implemented based on the partial agreement between running surfaces of previous studies (Schütte, *et al.*, 2016; Schütte, *et al.*, 2018). Filtering of the data was handled within the Noraxon® software.

3.7.2 TRIGONOMETRICAL CORRECTIONS

No manual correction of the accelerometer data was required during this study, due to the use of the Noraxon® IMU and specialized software. **Figure 3.7** shows the alterations made by the Noraxon® software to the acceleration measurements of the pelvis IMU during a short 10 km.h^{-1} run on at +8° incline on a treadmill. The Noraxon® software provides information regarding both the tilted measurements as well as the corrected measurements based on the angle of the IMU.

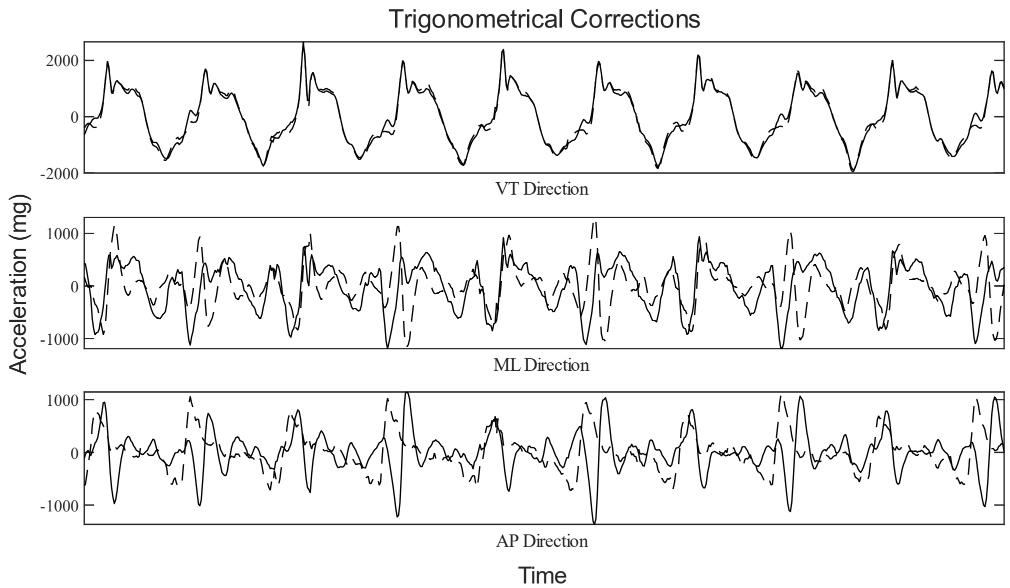

Figure 3.7: Acceleration pattern adjusted to fit the normal horizontal-vertical coordinate system, following trigonometrical corrections. The solid black and dashed black lines represent the true accelerations and the measured accelerations, respectively. (mg = micro "*g*" whereby; 1 *g* = 9.82m/s^2). (source Oloff CW Bergh)
AP: anteroposterior, ML: mediolateral, VT: vertical

3.7.3 AUTOCORRELATION PROCEDURES

Determining the length of data to use for the data analysis was based on two factors. Firstly, the limited amount of space in the outdoor section and secondly, the methods of measurement in previous research. The distance for data analysis on the outdoor trail was set at 10 m, because this section was the most accurate representation of a compacted dirt TR environment at an eight-degree incline. Only the middle portion of the running event was used during the evaluation of acceleration patterns (Svenningsen, *et al.*, 2020), equating to nine steps per participant over both the treadmill and trail surfaces. The researchers wanted to not only compare momentary acceleration values, but over-all values, and a method to evaluate the general adaptations to steps and strides.

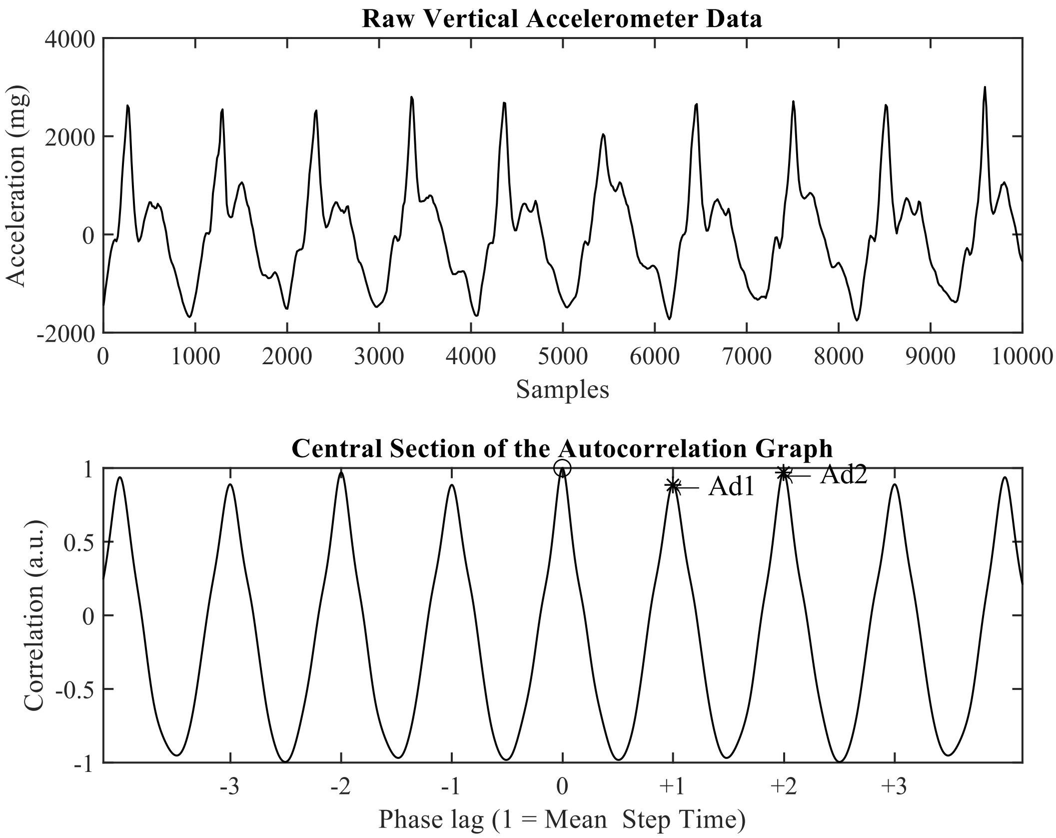

Figure 3.8: The *top* graph represents the raw accelerometer data in the vertical direction. The *bottom* graph illustrates the final product of the unbiased autocorrelation procedure, with the two dominant peaks (*Ad1* and *Ad2*) following the zero-lag peak. (a.u = arbitrary units; mg = micro '*g*', whereby 1 *g* = 9.82m/s^2). (source Oloff CW Bergh)

An autocorrelation procedure is a mathematical method of comparing a signal wavelet to itself, at increasing time lags in order to evaluate the correlation of each sample point (Moe-Nilssen & Helbostad, 2004). When using an autocorrelation method on running accelerometer data, there are distinctly formed peaks. These peaks are termed the dominant periods (Moe-Nilssen & Helbostad, 2004). The first dominant period (*Ad1*) represents the regularity of steps and the second dominant period (*Ad2*) the regularity of strides. *Ad1* is the value of difference whereby the original wavelet is compared to itself at a time-lagged equivalent of one mean step time. Similarly, *Ad2* is the value of difference whereby the original wavelet is compared to a time-lagged equivalent of one mean stride time. **Figure 3.8** (previous page) illustrates both the raw accelerometer data and an autocorrelation graph and includes the dominant peaks.

The unbiased autocorrelation procedure is an appropriate method to use during running, due to the cyclical nature of steps that resemble other steps during locomotion (Moe-Nilssen & Helbostad, 2004). However, including challenging terrain would elicit changes in the regularity of these steps that would be perceivable in the autocorrelation procedure and would provide further information regarding dynamic stability (Schütte, *et al*., 2016). Hence, during this study the researchers used MATLAB R2020a (Version 9.6) accompanied by the software's Statistics and Machine Learning Toolbox (The MathWorks Inc., Natick, MA, USA) to write a custom script to perform the autocorrelations. According to Moe-Nilssen and Helbostad (2004), the "xcov" function is a valid method and was incorporated in this study. Following the "xcov" calculations, the values were then normalized to one, at zero-lag. An "unbiased" autocorrelation was chosen during this study, as it does not produce any "tapering" towards the edges of the graph and does not skew the data, as the biased procedure would (Moe-Nilssen & Helbostad, 2004). **Figure 3.9** (following page) shows a simplified sine-based graph, with four repetitions, and the difference between a biased, unbiased autocorrelation procedure and normalized unbiased autocorrelations graph.

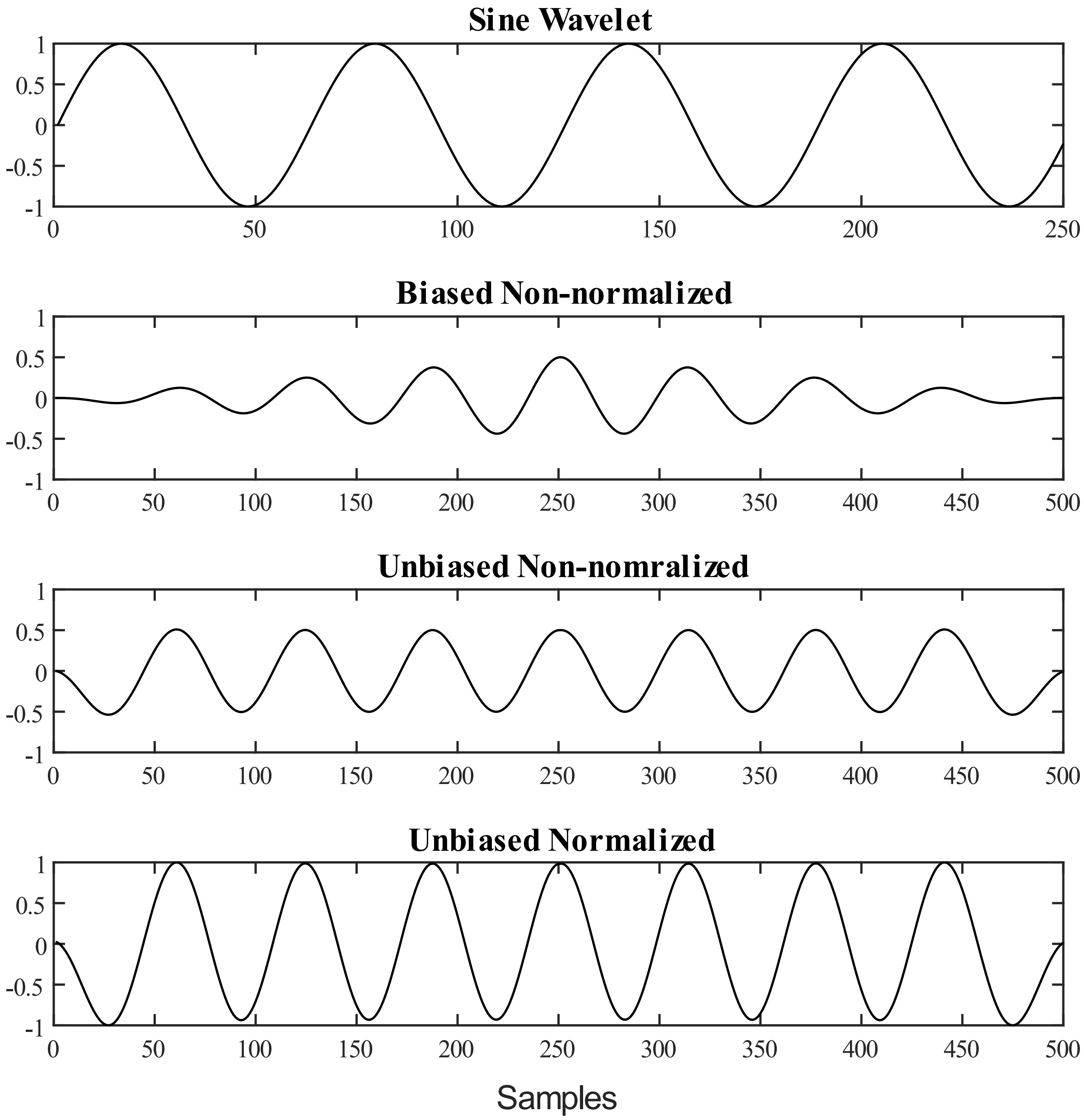

Figure 3.9: Four graphs representing the different methods that could be incorporated during the autocorrelation procedure. The normal sine graph (top) shows four repetitions of a normal sine wavelet structure. The biased non-normalized graph (second from top) shows the tapering towards the sides after a biased procedure was used, which is not beneficial as it reduces data. The unbiased non-normalized graph (second from bottom) shows the proper correlation, without the normalization to the central peak. The unbiased normalized graph (bottom) indicates the completed process with subsequent peaks that are normalized to the central peak. 250 samples. (source: Oloff CW Bergh)

3.7.4 TIME PARAMETERS

Time parameters were calculated within the MS Excel document, based on markers that were "pre-placed" within the Noraxon® software. These markers indicated when two key events occurred, namely initial contact and toe-off events. Basic structuring in MS Excel, meant all time data could be extracted, and step and stride times could be calculated for each participant. Mean time values for nine steps and four strides were calculated for each participant. Previous researchers have advocated for the use of not only the mean time variables, but the coefficients of variation (CV) to provide further information regarding the variability of step and stride times (Kobsar, *et al*., 2014; Voloshina & Ferris, 2015). The method for calculating the CV for both step and stride times was described as:

$$if\ x = \{Step\ times\ OR\ Stride\ times\};\ \ then\ CV\ = \left(\frac{SD}{Mean}\right) \times\ 100\ = \left(\frac{\sqrt{\frac{\sum(x - \bar{x})^2}{n-1}}}{\bar{x}}\right) \times\ 100$$

3.7.5 STEP AND STRIDE REGULARITY

Step and stride regularities have been used in previous research to describe the regularity of both steps and strides during walking (Moe-Nilssen & Helbostad, 2004; Kobsar, *et al*., 2014) and running (Schütte, *et al*., 2016). Step and stride regularities were calculated using the previously described autocorrelation method, to indicate values of correlation at specific time lagged points (Moe-Nilssen & Helbostad, 2004). Regularity values were extrapolated from the autocorrelation graphs, as in **Figure 3.10**.

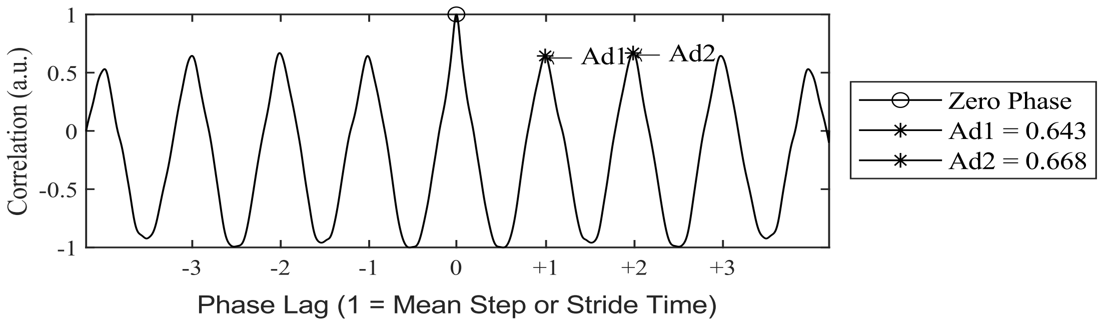

Figure 3.10: Following the autocorrelation procedure, the values for both step and stride regularities can be printed and saved for each individual, over the treadmill and trail surfaces. (source: Oloff CW Bergh)

3.7.6 SYMMETRY

Following the unbiased autocorrelation procedure, gait symmetry could be calculated using the step and stride regularities of all three directions of measurement. The method of calculation used was described by Kobsar *et al*. (2014), and not the original method as proposed by Moe-Nilssen and Helbostad (2004). The original method by Moe-Nilssen and Helbostad (2004) simply used the *Ad1* divided by the *Ad2*, to represent symmetry between the step and stride regularities. However, the method described by Kobsar *et al*. (2014) further illustrates the differences in regularity based on the absolute differences and the mean differences, to show the percentage difference rather than simply the absolute difference. This was done by dividing the absolute difference between the *Ad1* and *Ad2* values, by the mean difference of the two, and multiplying it by 100. The following equations demonstrate the calculations for the two different methods.

Moe-Nilssen and Helbostad (2004):

$$Symmetry = \frac{Ad1}{Ad2}$$

Kobsar *et al*. (2014):

$$if\ x = \{Ad1, Ad2\}, \qquad then\ Symmetry = \left(\frac{|\,x\,|}{\bar{x}}\right) \times 100$$

3.8 STATISTICAL ANALYSIS

Statistical analysis for this study followed a structured approach described in **Figure 3.11**. The calculations of the mean step and stride times, the coefficient of variation for the step and strides times, step, and stride regularity, as well as gait symmetry, was done by the researchers. Following the completion of data handling and calculations of the autocorrelations, the Stellenbosch University, Division of Epidemiology and Biostatistics, Faculty of Medicine and Health Sciences was consulted for statistical analysis. All statistical tests were performed using IBM SPSS Statistics 26.0 (SPSS Inc., Armonk, New York, USA). Thereafter a test for normality (the Kolmogorov-Smirnov test, with Lilliefors corrections) was used to determine the skewness of the data or the presence of a normal Gaussian distribution as done previously in similar research (Schütte, *et al*., 2016). If the data was normally distributed a standard parametric test, namely the paired t-test for dependent variables, was used to determine if significant differences were present between the treadmill and trail surfaces for the respective variables. If the data did not conform to a standard Gaussian distribution, methods of data transformation would be incorporated (i.e. log10 or square root) with visual inspections of different possible transformation methods (see **Appendix E**). However, should some variables still not conform to a Gaussian distribution after data transformation, a non-parametric test (the Wilcoxon signed rank test) would be used to determine significant differences between conditions. Effect sizes were calculated using the standard Cohen's *d* method and classified according to Hopkins (2003).

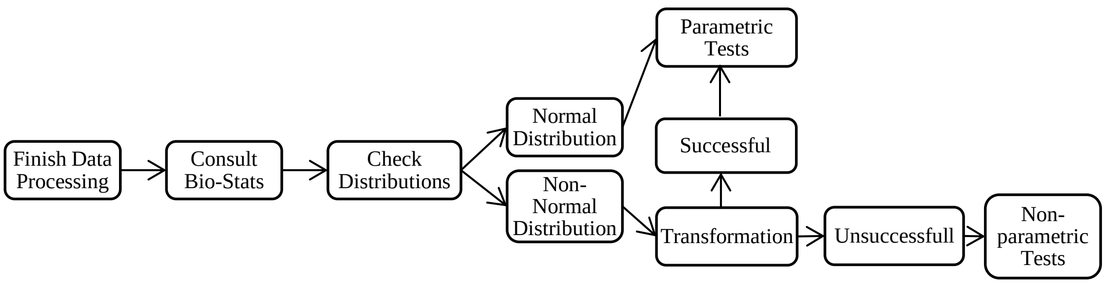

Figure 3.11: Diagrammatic representation of the process that was followed for the statistical analysis during this study.

CHAPTER 4

RESEARCH ARTICLE

Differences in dynamic stability between graded treadmill and real-world trail running

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*This article has been submitted to the Journal of Sport Science (**Appendix F**) and is currently under review. This article is included herewith in accordance with the guidelines for authors of this journal. This does not imply that the article has been accepted or will be accepted in the said journal. As a result, the referencing style may differ from other chapters of the thesis. The co-authors of the article, Prof Ranel Venter (study leader) and Mr Simon De Waal (co-study leader) hereby give permission to the candidate, Mr Oloff Bergh, to include the article in his thesis.*

Differences in Dynamic Stability Between Graded Treadmill and Real-World Trail Running

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Differences in Dynamic Stability Between Graded Treadmill and Real-World Trail Running

Abstract

A natural environment with fluctuating surface conditions and alternating gradients makes trail running considerably different to road or treadmill running. Accelerometry based trail running research, appears to be sparse. Does graded trail running have a greater influence on temporal variables and dynamic stability compared to graded treadmill running? Recreational trail runners (n = 12) ran at 10 $km.h^{-1}$ on both treadmill and trail surfaces at an eight-degree incline. Accelerometry measurements were used to determine changes in temporal variables and dynamic stability. Step and stride time CV displayed significant increases ($p < 0.01$) on the trail surface compared to the treadmill. Step and stride regularity decreased significantly in all three directions ($p < 0.01$). Symmetry only indicated significant changes in the AP and ML directions. Mean step ($p = 0.45$) and stride times ($p = 0.33$), and VT gait symmetry ($p = 0.10$), did not show significant differences. This indicated a general reduction in dynamic stability over the trail surface compared to the treadmill. No studies have shown the effects of trail running on dynamic stability. These results could help further understand how these diverse terrains affect running gait as well as expand the current body of literature regarding trail running.

Keywords: *Running Gait, Trail Running, Dynamic Stability, Accelerometry*

Introduction

Trail running is a popular form of off-road running which recently experienced an exponential growth in popularity [1]. Trail running differs from traditional road running, primarily due to fluctuating levels of graded running and the prevalence of substantial surface irregularities [2].

Several biomechanical changes and adaptations occur during graded running [3,4], including fluctuations in centre of mass movements [5], changes in ground reaction forces [3,5], increased step frequency [4] and modifications in foot strike patterns [4]. Changes in foot strike patterns, centre of mass movements and stride characteristics induce altered energy expenditure [6] and neuromuscular function [7], coupled with a potentially higher prevalence of ankle injuries due to unstable and fluctuating surface conditions [8]. Constant surface variability coupled with undulating inclines during trail running could affect dynamic stability, defined as the ability to maintain variability, regularity, symmetry, and complexity of three-dimensional trunk accelerations during locomotion [9]. A review by Svenningsen *et al*. [8] indicated a higher prevalence of lower-limb injuries in trail runners, compared to road runners. Measurement of dynamic stability in real-world environments, such as the trail, is important to evaluate the possible increased risk of lower-limb injuries [8,9].

The need to assess human movement outside the constraints of confined laboratory spaces, increases the popularity of wireless measurement devices such as the tri-axial accelerometer for gait assessment [10,11]. The lightweight user-friendly nature of accelerometers makes it ideal for trail running research, as investigating running gait characteristics in a real-world environment is important in ensuring ecological validity [8]. Accelerometers are used in a wide range of settings to evaluate human gait including the fall risk of the elderly [12-15], differences in gait patterns between men and women [14-16], as well as changes in walking gait due to illness or amputation [10,17]. However, using accelerometers to investigate dynamic stability during trail running, is not apparent in current literature [8]. A single accelerometer attached to the L3-5 region on the lower back [10], can provide data for basic gait aspects such as spatio-temporal variables [18], specific contact variables [19], peak accelerations [20], as well as more advanced characteristics such as step and stride regularity, and gait symmetry [21]. Calculating aspects such as step and stride regularity, and gait symmetry, can provide a deeper understanding of changes that occur in dynamic stability during trail running [22].

Measuring adjustments and variability in three-dimensional accelerations during trail running, could assist in further recognizing the effects these natural trails have on normal running gait and the potential risk of injuries [8]. This article reports on the changes in temporal variables and dynamic stability during a short-inclined trail run compared to a treadmill run, while using a single wireless inertial measurement device (IMU). It was hypothesized that trail running would elicit significant increases in step and stride times, as well as greater variability, and a decrease in step and stride regularity as well as gait symmetry, indicating a general decrease in dynamic stability.

Methodology

Subjects

An *a priori* power analysis (Test family: t-test; Statistical test: means, differences between two dependent means) was performed using G*Power (3.1.9.2) to determine an adequate sample size for the current study [23]. $Power_{(1\text{-}\beta)}$ values were set at $p = 0.95$ and alpha values at $\alpha = 0.05$. Effect sizes were determined from a small proof of concept study (n = 1) and data from a study by Voloshina and Ferris [24], with the final effect size set at $d = 1.05$, deemed a moderate effect size by Hopkins [25]. The *a priori* test indicated a sample size of 12 participants would more than suffice for this study. The proof of concept study only included one participant, as the goal was merely to determine the efficacy and functionality of the equipment in the outdoor environment. Through purposive sampling, a group of 12 male recreational trail runners aged between 22 and 32 years (mean: 25.2 ± 2.6 years), mass 69.7 – 88.6 kg (mean: 78.8 ± 5.9 kg) and stood at 176 – 197 cm tall (mean: 183.6 ± 7.1 cm), volunteered to participate. Recreational runners needed to run 16 – 48 km per week on a trail surface to be included in the study [26]. They were screened to ensure they had no injuries that prevented the participant from running, within the last six months. All participants willingly signed a written informed consent form prior to participation in accordance with the Declaration of Helsinki. This study was approved by the Health Research Ethics Committee of Stellenbosch University (N19/07/076).

Apparatus and procedures

A single myoMotion Research PRO IMU (Noraxon Inc., Scottsdale, Arizona, USA) was used to collect data. The size of the IMU (37 g) was 52.2 x 37.8 x 18.1 mm with an accelerometer capable of collecting linear acceleration data at 200 Hz and up to ± 16 *g* force. The IMU was attached at the L3 region of the lumbar spine [27,28], using a neoprene sleeve belt as well as double-sided taping to limit unnecessary IMU movement [28]. Treadmill running was conducted on a Bertec instrumented treadmill (Bertec Corporation, Columbus, Ohio, USA) inside the Stellenbosch University Neuromechanics Unit (Sport Science complex, Coetzenburg, Stellenbosch).

Participants ran two tests: a submaximal instrumented treadmill test and a submaximal outdoor trail section (order randomized per individual). Treadmill running included a two-minute warm up (one minute at 5 km.h^{-1} and the next at 8 km.h^{-1}), followed by a one-minute trial with 30 seconds at 8 km.h^{-1} and 30 seconds at 10 km.h^{-1}. The treadmill was set at eight-degrees to resemble the selected natural trail section. The trail surface consisted of compact dirt with several small rocks and surface undulations, at an average inclination angle of eight-degrees, representing a typical short section of a trail run. The average angle was calculated via trigonometrical functions, using the distance from the floor at the start and the perpendicular distance to the end. This measurement provided an average angle over the 10 m, which contained minor fluctuations in gradient. On the trail surface participants were asked to maintain running speed and had three attempts to complete a 60 m segment within 20 - 22 seconds to simulate an approximate 10 km.h^{-1} run. Participants were informed if they ran too slow or too fast and then had two minutes to rest and then run the test again, to best simulate a relative incline speed of 10 km.h^{-1}. Testing commenced over several days, with an average temperature of 23.9 degree Celsius and wind speeds ranging between 2.77 – 21.4 km.h^{-1} on testing days.

Accelerometry variables

Accelerometer measurements were recorded and streamed directly into Noraxon® myoRESEARCH software with the IMU being examined between each trial to ensure steadiness and proper placement. Prior to participation, the individuals were asked to stand in the anatomical position to calibrate the IMU system. Previous studies have used 10 strides [22,29] or a short distance of seven meters [15]. The current study used a total outdoor running distance of 60 m, but only 10 m of trail surface was used for analysis per participant. Nine steps were extracted during the trail section for each participant. As such, data was also analysed for nine consecutive steps in the middle of the incline portion of the treadmill test, at 10 $km.h^{-1}$. Following data capture, the raw accelerometer data was trigonometrically corrected within the Noraxon® software, adjusting for the arbitrary tilt of the IMU due to the increased trunk lean at incline [30] and to remove the static gravitational component [21]. Thereafter, accelerometer data was filtered using a zero lag, 4^{th} order Butterworth low-pass filter with a cut-off frequency of 50 Hz [9,22,29]. Markers were pre-set within the Noraxon® software to indicate foot-strike and toe-off, with resultant step and stride times calculated using Microsoft Excel (Version 16.0.6742.2048). Participant step and stride time variables were extrapolated from the raw data, with the coefficient of variation being calculated, as the standard deviation divided by the mean multiplied by 100, to illustrate the variability within participants mean step and stride times [12].

Further data processing and calculations were performed using custom scripts within MATLAB R2020a (Version 9.6) accompanied by the software's Statistics and Machine Learning Toolbox (The MathWorks Inc., Natick, MA, USA). The unbiased autocorrelation coefficients were calculated comparing the acceleration wavelet to itself at increasing time-lags [21]. Due to the cyclical nature of running, the unbiased autocorrelation procedure would typically illustrate specific peaks known as the dominant periods [21].

Values were then normalized to the central peak where there is zero time-lag (i.e. the wavelet is compared to its exact self, with a value of one). The first dominant period (*Ad1*) of the autocorrelation coefficient illustrated the regularity of subsequent steps, and the second dominant period (*Ad2)* the regularity of subsequent strides. *Ad1* and *Ad2* were indications of the original wavelet compared to time-lagged equivalents of one mean step and one mean stride time respectively [21]. **Figure 1.1** represents an unbiased autocorrelation plot for the vertical direction, in both treadmill and trail running conditions. Step regularity (*Ad1)* and stride regularity (*Ad2)* values were calculated in all three directions namely: the vertical (V), mediolateral (ML) and anteroposterior (AP). The *Ad1* variable in the ML direction will consistently produce a negative value due to left and right movements from consecutive steps, and thus the analysis was done using the absolute value [29]. Step regularity was represented in all three directions as V_1, ML_1, AP_1 and stride regularity as V_2, ML_2, and AP_2 [12].

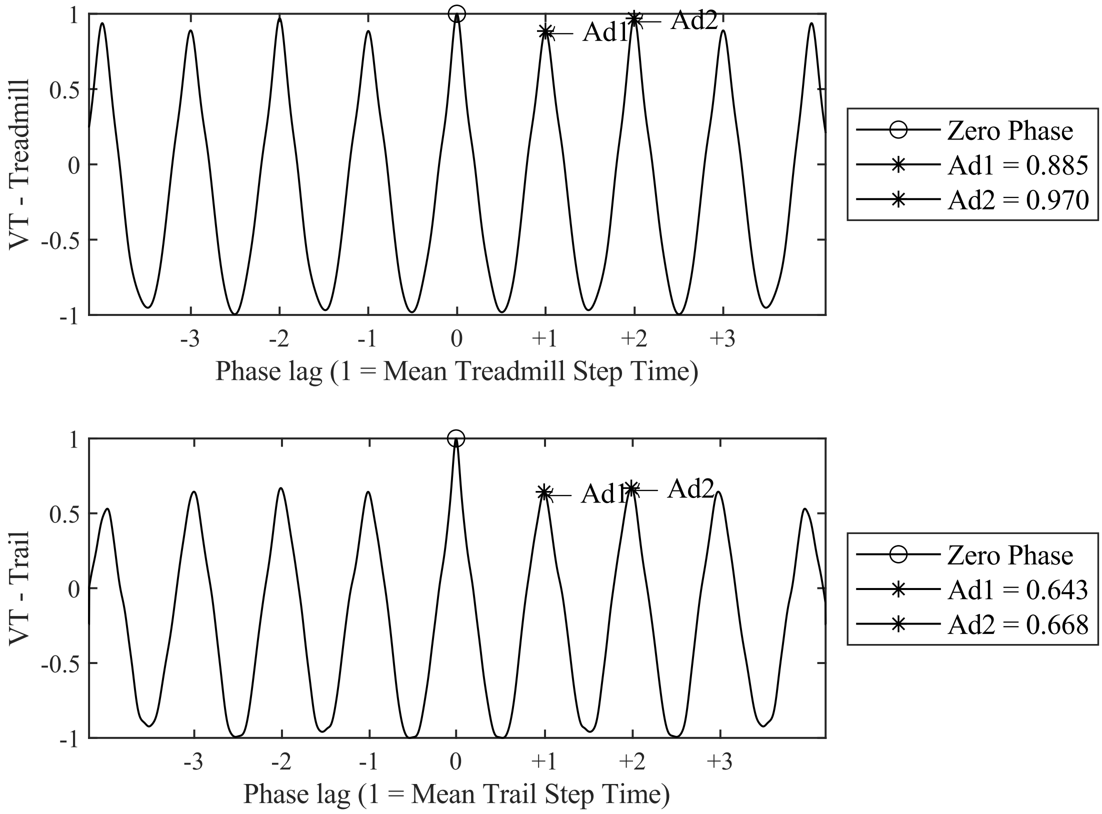

Figure 1.1: An illustration of a plotted unbiased autocorrelation of the VT (vertical direction) during both treadmill (top) and trail (bottom) running, for a single participant. Ad1 (step regularity) and Ad2 (stride regularity), are normalized to the zero lagged phase.

Figure 1.2 demonstrates the assessment of the two dominant peaks within the autocorrelation plots for a single participant during the treadmill run. Gait symmetry values were calculated using the methods (symmetry = (absolute difference between *Ad1* and *Ad2/* average of *Ad1* and *Ad2*) x 100*)* as described by Kobsar *et al*. [12] rather than the original method (*Ad1/Ad2)* described by Moe-Nilssen and Hellbostad [21], due to the greater irregularity in values observed during the trail run test. The values calculated represents the percentage difference, whereby zero equals perfect symmetry. Gait symmetry was represented in all three directions as V_3, ML_3, and AP_3 [12].

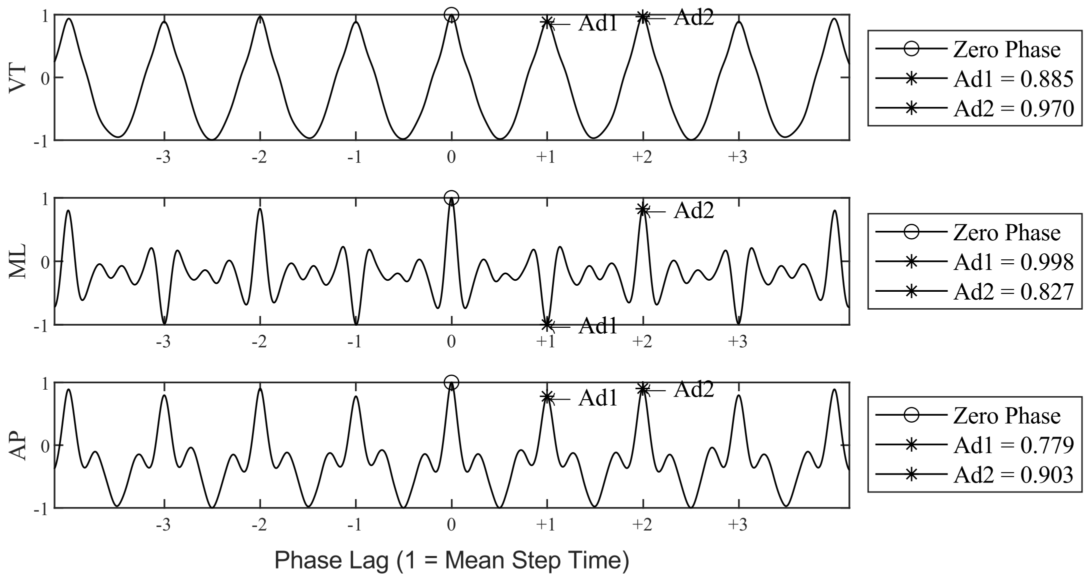

Figure 1.2: The unbiased autocorrelation procedure for all three directions of measurement (Top - VT: vertical, Middle - ML: mediolateral, Bottom - AP: anteroposterior) for a single participant, during the treadmill test. Ad1 (step regularity) and Ad2 (stride regularity) as a normalized value to the zero lagged phase. The Ad1 value for the ML direction is given as its absolute value, due to the alternating negative and positive values that relate to left and right lateral trunk movements [28].

Statistical Analysis

A *post hoc* analysis using G*Power (3.1.9.2) indicated that a sample size of n = 12 was enough to ensure the study $Power_{(1-\beta)}$ = 0.95, based on the mean and standard deviation differences for all variables [23]. Effect sizes were manually calculated as Cohen's d for each variable and defined according to Hopkins [25]. Further statistical analyses were performed using IBM SPSS Statistics 26.0 (SPSS Inc., Armonk, New York, USA). All dependent variables were tested for normality using Kolmogorov-Smirnov test with Lilliefors significance correction [29]. For normally distributed variables and non-normally distributed variables that were log or square root transformed (Treadmill ML_3, and AP_3, trail V_3, and ML_2), a standard paired t-test was used to determine differences between indoor and outdoor conditions. For non-normally distributed variables that could not be transformed (treadmill V_3 and trail AP_3), a non-parametric Wilcoxon signed-rank test was performed. The statistical significance (alpha) level for all tests was set at 0.05.

Results

No significant differences were observed when comparing the mean step times ($p = 0.45$) or mean stride times ($p = 0.33$) between the treadmill and trail running. Significant differences were observed for the coefficient of variation (CV) within participants, on the two surfaces with trail running illustrating a greater step time and stride time CV ($p < 0.01$). Cohen's d for step time CV ($d = 2.02$) and stride time CV ($d = 2.20$) indicated very large effect sizes [25]. Temporal variables are presented in **Table 1.1**.

Table 1.1: Means (SD) and statistical test results of the temporal variables in treadmill and trail running.

Temporal Variables	Treadmill (n = 12)		Trail (n = 12)		Effect Size	P Value
	Mean (SD)	95% CI	Mean (SD)	95% CI		
Mean step time (s)	0.35 (0.02)	0.34-0.36	0.35 (0.03)	0.33-0.36	0	0.45
Mean stride time (s)	0.70 (0.05)	0.68-0.73	0.69 (0.05)	0.67-0.72	0	0.33
Step time CV (%)	2.54 (0.97)	2.00-3.09	8.75 (4.24)	6.24-11.2	2.02	**< 0.01**
Stride time CV (%)	1.42 (0.48)	1.15-1.69	5.36 (2.49)	3.95-6.77	2.20	**< 0.01**

CI: confidence interval, SD: standard deviation, s: seconds, CV: coefficient of variation.
Bold values indicate significant differences between treadmill and trial surfaces.

The trail surface showed significantly lower regularity values in comparison to the treadmill, in all three measured directions for both step regularity and stride regularity ($p < 0.01$). Gait symmetry on the trail surface significantly decreased, in the ML ($p < 0.01$) and AP ($z = -3.06$, $p < 0.01$) but not in the VT ($z = -1.65$, $p = 0.10$). All statistically significant dynamic stability variables indicated large to very large effect sizes ($d = 1.34 – 4.52$) [25]. All variables that influence dynamic stability are presented in **Table 1.2**.

Table 1.2: Means (SD) of the dynamic stability variables in treadmill and trail running, with bold values indicating significant differences between treadmill and trail surfaces. Note that gait symmetry is the measurement of change, whereby zero is perfect symmetry.

	Treadmill (n = 12)		Trail (n = 12)		Effect Size	P Value
	Mean (*SD*)	95% CI	Mean (*SD*)	95% CI		
Step Regularity (a.u)						
VT_1	0.94 (0.04)	0.92-0.96	0.81 (0.09)	0.76-0.86	1.87	**< 0.01**
ML_1	0.96 (0.04)	0.92-0.96	0.65 (0.20)	0.54-0.76	2.15	**< 0.01**
AP_1	0.79 (0.10)	0.73-0.85	0.40 (0.14)	0.32-0.48	3.20	**< 0.01**
Stride Regularity (a.u)						
VT_2	0.96 (0.02)	0.95-0.97	0.78 (0.08)	0.74-0.83	3.08	**< 0.01**
ML_2	0.76 (0.12)	0.69-0.83	0.17 (0.14)	0.09-0.25	4.52	**< 0.01**
AP_2	0.85 (0.07)	0.81-0.89	0.35 (0.17)	0.25-0.45	3.85	**< 0.01**
Gait Symmetry (%)						
VT_3	2.47 (2.91)	0.82-4.12	5.42 (5.11)	2.53-8.31	0.71	0.10 *
ML_3	24.90 (16.73)	15.40-34.40	120.62 (49.09)	92.80-148.01	2.61	**< 0.01**
AP_3	10.12 (10.23)	4.33-15.92	38.14 (27.55)	22.50-53.71	1.34	**< 0.01 ****

CI: confidence interval, SD: standard deviation, s: seconds, CV: coefficient of variation, a.u: arbitrary units.
VT: vertical, ML: mediolateral, AP: anteroposterior
* z = -1.65 (Wilcoxon signed rank test).
** z = -3.06 (Wilcoxon signed rank test).

Discussion

A novelty of the current study was the use of accelerometry as an indicator of change in dynamic stability when running on an inclined trail surface. Limited studies have investigated dynamic stability, and no studies have done so during inclined trail running [8]. Using a single waist mounted IMU, the results of the current study indicated significant differences between the treadmill and trail running conditions, confirming aspects of the original hypothesis.

The use of a treadmill or consistent surfaces (track or concrete) to determine walking [12 - 15] and running [5,20,21,24,29] gait parameters is common in research settings. Tests conducted in highly controlled settings lack ecological validity and raises the question of comparability between treadmill and over-ground running. Recently, Firminger *et al*. [31] found minor differences in ground reaction forces and kinematics when comparing treadmill and over-ground running but concluded that graded treadmill running is mechanically and physiologically similar to over-ground running [31]. However, the need to evaluate the changes in dynamic stability during graded treadmill and trail running is evident.

The current study found no significant differences in mean step and stride times, when comparing the treadmill and trail running surfaces. Previous research reported no difference in mean step times regardless of surface conditions during walking [13] and running [24] but did indicate significant changes in the variability of step and stride times. Similarly, the current study did not find any changes in mean step and stride times during treadmill and trail running but did find significant differences in the coefficient of variation for step and stride times. Trail running challenges the ability to maintain step frequency [3] due to the consistently varying natural terrain coupled with fluctuating trail gradients. Athletes are generally encouraged to uphold their step frequency during incline sections [32]. However, the effect of reducing variability in step/stride times on performance has not been established and may be unique to trail running demands.

In the current study both step and stride regularities were significantly lower on the trail surface in all three measured directions, contrary to the findings of Schütte *et al*. [22] where only ML step and stride regularity was reduced on woodchips compared to concrete. The changes in VT and AP directions in the current study could be due to the introduction of an eight-degree incline on the trail surface, as running at an incline has been shown to prompt changes in the vertical displacements of the centre of mass [4,5]. However, both the treadmill and trail running occurred at eight-degree inclines, and thus the differences between the two could be due to the greater surface irregularities that are prevalent on the trail terrain. Due to the surface irregularities accompanying trail running, deviations from the normal cyclical running gait elicit changes in trunk acceleration patterns [24]. Voloshina and Ferris [24] indicated significant alterations to step width, length and height when running on uneven terrain. Acceleration patterns in the ML direction are exaggerated by adaptations in step width, as the runner shifts his centre of mass in response to a ground level obstacle. Graded running is accompanied by a higher step frequency [2,4] and a higher variability in step times which affects both step and stride regularity in the VT and AP directions. Furthermore, uneven terrain running is known to produce greater variability in stride length [24], altering the consistency of AP acceleration patterns. Uneven terrain similarly challenges stability in the direction of travel [13], thus incline running would not only alter the AP regularity, but the VT regularity of steps and strides.

To the authors knowledge no other studies have looked at calculating gait symmetry in the specific manner described by Kobsar *et al*. [12] during a trail run. The current study showed significantly decreased symmetry in the AP and ML directions for the trail run compared to the treadmill run, but not in the VT direction. Alterations in AP and ML symmetry was evident due to the inclined surface, varying terrain conditions and ground-based obstacles. The selected 10 m trail section in this study did not contain large boulders or rocks requiring hopping/leaping/jumping, allowing for a relatively consistent gait cycle. The “bouncing” mechanism diminishes when running at greater inclines resulting in decreased vertical movement of the centre of mass as running angle increases [5,31]. This could explain the significantly different step and stride regularity in the VT direction, but consistent symmetry in the VT direction. This is consistent with the findings of Menz *et al*. [33], who concluded that uneven terrain walking induces a shift in variability from vertical to horizontal plane accelerations and can be seen in the current study, as accelerations in the AP and ML directions experienced a higher ratio of diminution compared to the VT. These shifts in acceleration patterns might be altered when larger obstacles such as rocks or boulders are present. It would be worth investigating the changes in gait symmetry when obstacles are present at incline and level running, in both a controlled and natural environment.

Results from the current study suggests a general decrease in dynamic stability on the trail surface, during inclined running. The single wireless accelerometer was both a practical and suitable device to measure changes in certain gait characteristic in a real-world trail environment. There were certain limitations to the current study, including the distance the participants could run and the fixation of the running speed. A greater measurable running distance could help create a larger data set and more samples to conduct the autocorrelation procedure. Another option is to have individuals run multiple trials; however, the learning effect could cause a problem on short distances, whereby the acute changes to different surface factors would no longer be apparent. Previous studies [8] have also suggested not fixing the running speed and allowing participants to run at a self-select pace. However, a set speed of 10 $km.h^{-1}$ was used for all participants during our study and could be a potential limitation due to the negative impact on the “natural rhythmicity” of upper body accelerations during trail running [8].

Conclusion

This study adds to the current body of literature concerning trail running - reflecting the sports growth in popularity and competitiveness. The results from the current study indicate greater variability in step and stride times when athletes run on a trail surface compared to a treadmill. A potential future study could aim to investigate the effects of step and stride time variability on trail running performance. Dynamic stability is greatly affected by inclined trail running, with a general decrease in step and stride regularity and gait symmetry, compared to treadmill running. Athletes who regularly participate in trail running races will benefit from training on unstable and uneven surfaces that challenge dynamic stability. Furthermore, these results provide a deeper understanding of running mechanics and regulations in real-word environments using wireless devices.

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Conflicts of interest

The authors declare that there are no known conflicts of interest.

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CHAPTER 5

CONCLUSION

5.1 INTRODUCTION

The aim of the current study was to investigate acute changes in time variables and dynamic stability parameters, derived from three-dimensional trunk accelerations, between incline treadmill (TRD) and trail running (TR), in recreational trail runners. A group of 13 recreational trail runners volunteered to participate in the incline TRD and TR trials. Because of the article-format thesis, this chapter will not be presented in the typical format of a generic thesis. The reader should consult Chapter 4 for the discussion relating to the hypotheses below. A conclusion based on the stated hypotheses will be presented. Mention will be given to the practical applications of the study findings, limitations of this study, practical application and potential opportunities for future research will be identified.

5.1.1 **HYPOTHESIS ONE**

It was hypothesized that incline TR will result in significantly lower time parameters (mean step and stride times, and coefficients of variation for both step and stride times), compared to incline TRD, due to the complex terrain and different surface inconsistencies associated with TR.

The null hypothesis (H_0) stated that there would be no difference between incline TRD and TR regarding mean step and stride times, and the coefficients of variation (CV). The null hypothesis (H_0) is rejected.

Results indicated no changes in mean step (p = 0.45) and stride times (p = 0.33), between the two surfaces. However, there was a statistically significant increase in step (p < 0.01) and stride time CV (p < 0.01). Consequently, the null hypothesis (H_0) is rejected. This result is aligned with the findings by Voloshina and Ferris (2015), whereby no changes in the mean step parameters (p = 0.43), but significant increases in the CV for both step times ($p < 0.01$), were observed when individuals ran over uneven surfaces. This is due to the mean values not indicating inter-step and inter-stride variability and is a key reason why the CV was incorporated in the current study.

5.1.2 **HYPOTHESIS TWO**

It was hypothesized that incline TR will result in a significant decrease in dynamic stability variables (lower step and stride regularity and gait symmetry) in all three measured linear directions, compared to incline TRD, due to the complex terrain and different surface inconsistencies associated with TR.

The null hypothesis (H_0) stated that there would be no difference in dynamic stability variables (step and stride regularity, and gait symmetry) between incline TRD and TR. The null hypothesis (H_0) is rejected.

Results indicated that both step and stride regularity decreased in all three measured directions ($p < 0.01$), when the participants ran over the trail surface, compared to the treadmill. These results supported the rejection of the null hypothesis (H_0). Furthermore, this finding is relatively similar to the findings by Schütte *et al*. (2016), whereby they only found significant decreases in the step and stride regularity, but only in the mediolateral (ML) direction , when individuals ran over woodchip trails compared to concrete roads. However, the greater degree of diminution seen in all three directions of measurement during the current study could potentially be due to the incorporation of both a harsher surface (compacted dirt, greater surface undulations and a slight rut) and an eight-degree incline.

Additionally, calculations of the symmetry during TRD and TR, indicated that there was a significant decrease in both the ML and anterior-posterior (AP) directions ($p < 0.01$) when the participants ran over the TR sections, compared to the TRD. These results further support the rejection of the null hypothesis (H_0). Although, the vertical (VT) direction of gait symmetry did decrease, it was not a statistically significant result ($p = 0.10$). Incorporation of a larger amount of surface irregularities and a longer distance during the TR trial, could show a greater difference in this variable, compared to the TRD.

Objectives two to four support the rejection of the null hypothesis (H_0) and showed that TR did decrease general aspects of dynamic stability when individuals ran at an eight-degree incline, compared to TRD.

5.2 SUMMARY OF THE OUTCOMES OF THE STUDY

Table 5.1: Summary of hypotheses and outcomes based on the variables assessed.

Hypotheses	Variables			
	Rejected	**Outcomes**	**Accepted**	**Outcomes**
1. The null hypothesis (H_0) stated that there would be no difference between incline treadmill and trail running regarding mean step and stride times, and the coefficients of variation. Rejected.	Mean step time	No statistically significant difference ($p = 0.45$)	Step time coefficient of variation	Statistically significant difference ($p < 0.01$) TRD < TR
	Mean stride times	No statistically significant difference ($p = 0.33$)	Stride time coefficient of variation	Statistically significant difference ($p < 0.01$) TRD < TR
2. The null hypothesis (H_0) stated that there would be no difference in dynamic stability variables (step and stride regularity, and gait symmetry) between incline treadmill and trail running. Rejected.	Gait symmetry (vertical direction)	No statistically significant difference ($p = 0.10$)	Step regularity (all directions)	Statistically significant difference ($p < 0.01$) TRD > TR
			Stride regularity (all directions)	Statistically significant difference ($p < 0.01$) TRD > TR
			Gait symmetry (anterior-posterior and mediolateral directions)	Statistically significant difference ($p < 0.01$) TRD > TR

5.3 PRACTICAL APPLICATIONS

In conclusion, this study has shown the differences between TRD and TR, by illustrating the changes that occur in both time variables and dynamic stability when individuals run over a TR surface. This is important for future guidelines that could help with understanding injury development and performance enhancement in the sport of TR. Although TR has seen an exponential rise in participation, there is not a similar increase in research surrounding TR. This thesis as well as the article included herein, could help enhance the understanding of dynamic stability and TR.

Individuals who regularly participate in recreational TR might have already adapted to the complex terrain and different degrees of graded running associate with trails. Individuals who want to convert from TRD or conventional road running, should consider the following guidelines. Primarily, individuals who do not regularly run over complex and uneven terrain, should incorporate difficult terrain that challenges aspects of dynamic stability into their training regime prior to participating in a TR race. Additionally, a reduction in speed when first starting to run over complex surfaces, might be advisable for beginners. Secondly, incorporating a greater amount of inclines as well as declines during running sessions will improve TR performance, since graded running plays a quintessential role in TR. Incline running challenges accelerations in the VT and AP directions, and could improve running performance if the individual becomes comfortable with these altered acceleration patterns.

5.4 STUDY LIMITATIONS

Some limitations related to the present study should be mentioned. A strength of the study was that data were collected in an outdoor setting, however collecting data in an outdoor setting presented specific challenges and limitations.

The first limitation identified was the possible distance the participants could run from the receiver, before the IMU started to overwrite data, even though the IMU has a small capacity for on-board storage when outside the receiver range. Determining the range that could be used, was necessary to ensure proper data capturing. During a proof of concept study, the researchers visually inspected data recorded when a participant ran increasing distances away from the receiver. The participant ran increasing distance blocks of five meters, up to a max distance of 50 meters away and 50 meters back. Only when the participant ran to the 50 meters mark, would the initial data be affected. The researchers decided on a safe option and chose 45 meters away from the receiver as the maximum permitted distance during the study data collection process. However, during data capturing of participants, the running section contained a small tree that was in between the runners and the receiver at the top of the trail incline. The data was visually inspected to ensure that the onboard data was downloaded correctly after each trial.

Furthermore, the indication and identification of the 10m running segment within the IMU data, was a limitation to this study. This had to be done post testing, during the data handling phase. On the running trail, there was a significant turn as well as a small concrete step, 2m prior to the 10m measurement section. The IMU data could be marked at the step up (due to a sudden increase in vertical acceleration at the pelvic region) also at the 90-degree right rotation of direction of travel. A possible easier method would have been to position the receivers as well as synced cameras closer to the location of measurement (10m section), whereby the video footage could be compared to the IMU data and easily identify the 10m section.

Previous studies have advocated for the improvement of ecological validity when testing aspects related to real-world activities, specifically with regards to running speeds (Svenningsen, *et al.*, 2020). Running at a self-selected pace allows the participants to adjust their velocity based on surface alterations or graded sections, and allows for the natural rhythmicity of the trunk during running (Svenningsen, *et al.*, 2020). During the current study, the researchers chose a set speed of 10 km.h^{-1} for all participants to run over both the treadmill and the trail sections to control for the effect of speed on various spatio-temporal variables. The participants ran on the trail section, but were asked to keep their running speed consistent, especially during the incline and decline sections. It is possible that some participants had sped up during the decline and slowed down during the incline, but still attained a mean speed close to 10 km.h^{-1}. A structure could have been put in place to determine everyone's self-selected speed over-ground, and then set the treadmill to simulate that speed. This would however alter the randomization process, and potentially reduce the internal validity of the study.

Covid-19 has had an immense impact on many people's lives, with many losing their jobs and many have lost loved ones, due to the spread of this global pandemic. The pandemic had an influence on this study, as it limited access between the researcher and supervisors, the researcher could not access the laboratory and also could not enter the library, due to the nationwide lockdown that started 23 March 2020. The researcher and supervisor did their best to conduct regular meetings over Microsoft Teams® and discuss the proceedings of data handling, statistical analysis, and general thesis progressions. Due to the travel restrictions, the researchers could not enter the laboratory where the study had been conducted or have access to the computer with all stored data on. Fortunately, the researcher had created a copy of the raw data prior to the start of lockdown. Access to the Stellenbosch University library was immediately suspended for all individuals, meaning the researcher did not have direct access to library spaces or books. Thankfully, the Stellenbosch University online library website for their students provide a wide range of access to different academic journals and articles, however due to the strain of so many individuals using the website, it was sometimes inaccessible.

Due to the lockdown and limited access to certain infrastructure, the researcher only included a few aspects of dynamic stability during this study. If there was more time, access to the laboratory and statistical consultations, the researcher would have liked to include acceleration RMS, ratio of acceleration RMS and sample entropy to this study. This will hopefully be added to a future study.

5.5 RESEARCH RECOMMENDATIONS

Recommendations for future researcher using accelerometry include two aspects. Firstly, if purely linear acceleration data is required based on the purpose of the study, it would be easier to use a single tri-axial accelerometer, and not necessarily an IMU. This is due to the low cost, small construction, and the continuous steam of data onto an onboard storage over longer distances, compared to the IMU. Measuring data over longer distances and different surfaces could yield a more complete impression of dynamic stability during complex terrain running. However, using a tri-axial accelerometer would mean the researcher would have to perform their own trigonometrical corrections to compensate for the components of static gravity and arbitrary tilting of the accelerometer away from its standard measuring axis.

Secondly, having the participants run at a self-selected pace will improve ecological validity during the TR section, as the individuals can adjust their running speed based on the obstacles that are presented. This can be done during running studies, because the autocorrelation procedure can adjust for the differences in gait speed between individuals, to a certain extent. Additionally, considerations need to be made for the estimation of the self-selected speed, as well as the order of testing afterwards.

Studies that use outdoor settings to evaluate running gait, need to consider several aspects that would influence this type of testing. The weather plays an immense role, as harsh conditions would be detrimental to the participants motivation as well as increase the dangers of wet surfaces. Extremely windy conditions could also influence the runners and could influence three-dimensional acceleration patterns. Furthermore, using both an outdoor setting and the IMU technology, requires the transport of the receiving devices (laptop and receivers) to the testing location. Considerations need to be made to ensure the equipment is safe, under-cover from the sun (so the equipment does not over heat), has enough power (not too many connections of extension cords) and is located in a safe and accessible environment.

Future studies could aim to investigate the cognitive functions involved with TR. Due to the challenging and difficult nature of TR surfaces and conditions, making the correct decisions is key to both performance and injury prevention. Using a combination of questionnaires and potentially a wireless electroencephalogram (EEG), a recording can be made to demonstrate the differences in decision making processes and quantity of decisions between regular RR and TR.

Another future study could incorporate the use of neural networks and an algorithmic approach to analysing and identifying wavelets. A new study (Benson, *et al.*, 2020) showed that using a binary support vector machine model, the surface on which participants ran could be classified from accelerometer data, with a relatively high accuracy of 93.17%. This is a relatively new method of evaluating accelerometer data and does involve a rather high computational cost. Nevertheless, this could be used to determine future risk of injury and enhance wearable technology. As development of software and hardware improve at an exponential rate, the use of this technology should follow suit in the academic world and more specifically in the study of human biomechanics.

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APPENDIX A

RECRUITMENT PAMPHLET

APPENDIX B

PARTICIPANT INFORMATION LEAFLET AND CONSENT FORM (ENGLISH)

TITLE OF RESEARCH PROJECT(S):	
Stellenbosch Trail and Road Running Research (STARRR) **The acute kinetic and kinematic differences between shod, barefoot and minimalist sandal running in habitually shod male recreational trail runners. – Matthew Swart** **The difference in running gait kinematics between highly trained and recreational trail runners before and after a fatigue stimulus – Emily Robertson** **The differences in lower-body muscle force production and gait variables during treadmill and trail running in recreational trail runners – Oloff Bergh**	
DETAILS OF PRINCIPAL INVESTIGATORS (PIs):	
Title, first name, surname: **Mr Matthew Swart,** **Ms Emily Robertson** **Mr Oloff Bergh** **Prof. Ranel Venter (Supervisor)** **Mr. Simon De Waal (Co-supervisor)**	**Ethics reference number:** **N19/07/077 – M. Swart** **N19/07/078- E. Robertson** **N19/07/076 – O. Bergh** **N19**
Full postal address: **10 Alphen Glade, 23 Upper Mountain Road, Somerset West, 7130** **Unit 6, Tassenywk, Marais Street Stellenbosch, 7600** **13 Goederust Street, Heldervue, Somerset West 7130**	**PIs' Contact numbers:** **079 346 8688 – M. Swart** **072 261 5045 – E. Robertson** **079 299 4974 – O. Bergh**

We would like to invite you to take part in a collaborative STARRR project at the Department of Sport Science, Stellenbosch University. Please take some time to read the information presented here, which will explain the details of this project. Please ask the study PIs or supervisor/ co-supervisor 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 to. You are also free to withdraw from the study at any point, even if you do agree to take part initially.

This study has been approved by the **Health Research Ethics Committee at Stellenbosch University.** 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 the STARRR group?
The STARRR group is a research team of three masters students (Matthew Swart, Emily Robertson and Oloff Bergh) from the Department of Sport Science, Stellenbosch University, led by two academic staff and supervisors (Professor Ranel Venter and Mr Simon De Waal). The group was formed due to a common interest in running research. Due to this common interest we will be sharing resources for the testing process. The result of this being that you have the opportunity to participate in all three masters research projects over a two day testing period. Your participation in this research will thus form part of all three projects however you may opt out of any of the projects before, during or after testing without having to state a reason. Please indicate in the boxes below which specific masters research project(s) you would be willing to take part in.

What are the research studies about?

1) The acute kinetic and kinematic differences between shod, barefoot and minimalist sandal running in habitually shod male recreational trail runners – Matthew Swart

The purpose of this study is to determine the acute kinematic and kinetic differences between running in shoes, running barefoot and running in minimalist sandals. Kinematics refers to the movement or motion of body parts without taking into account the forces that produce these movements (i.e. stride length and stride frequency). Kinetics refers to the forces and time that act on the body during these movements (i.e. ground reaction forces). This study aims to compare certain variables whilst running in three different footwear conditions, namely in your conventional trail running shoes, in Xero (Xero Shoes, Colorado, U.S.A) minimalist sandals and barefoot in order to compare the differences.

2) The difference in running gait kinematics between highly trained and recreational trail runners before and after a fatigue stimulus – Emily Robertson

The purpose of the study is to learn more about what the effect of fatigue is on running kinematics (the motion of running) for highly trained and recreational runners and if the margin of difference is large between these two groups. In this study kinematics variables such as forward trunk lean, cadence, knee angles etc. will be compared between the two samples of runners.

3) The differences in lower-body muscle force production and gait variables during treadmill and trail running in recreational trail runners – Oloff Bergh

During this study we would like to further explore the intricacies of human running, and the effect of changing surfaces on muscle activities. More specifically, looking at muscle force production changes when individuals go from a treadmill run to a more real-world setting, such as trail running. We are very lucky to have an abundance of natural environments to run in as well as perfect weather conditions for most of the year, however not all have these privileges and run on treadmills or road surfaces regularly. Due to the growing popularity of weekly off-road running events such as the Parkrun™ and Myrun™, the greater community of recreational runners (both road and trail) will benefit from knowing the changes that occur in the lower body kinetics when changing running surface and terrain. We must identify the changes that occur in the lower-body muscles when we traverse these complex trail terrains.

All the testing will be hosted by the Department of Sport Science, Stellenbosch University, and will take place at the Neuromechanics unit within the Central Analytical facilities (CAF) laboratory which is situated at Coetzenburg behind Maties Gymnasium. The total amount of participants needed for this study is 30 (15 recreational and 15 elite trail runners) with all participants required to complete the testing at the Neuromechanics unit.

Why do we invite you to participate?

In order to participate in any of the three masters' research projects within the STARRR group, you need to be familiar with the sport of trail running. Additionally, you need to have had no previous experience with minimalist running (i.e. have run barefoot or in sandals during training and racing). We have invited two levels of training status / runner to participate in the STARRR projects – recreational and highly trained. If you regularly run on trail between 20 – 30km per week, you qualify as a recreational trail runner. If you regularly run on trail between 60 – 90km per week, you qualify as a highly trained trail runner. Your participation will help make a significant contribution to the body of literature surrounding trail running.

What will your responsibilities be?

Day 1

- You will be briefed on the testing proceedings of the day and subsequently in order to participate, you will have to sign this form.
- Anthropometric data (weight, height, limb length, etc.) will be measured.
- VO2max test (high intensity running effort on a treadmill)
- Time to Exhaustion Test at 90% of VO2max at a 7degree incline. (Runners will run until volitional exhaustion is reached)

Day 2

- Vertical jump testing (3x3 Jumps in normal shoes)
- Submaximal running while wearing your running shoes.
- Submaximal running in a barefoot condition.
- The participants will run for one minute at three different speeds (8, 10 and 13km/h) on the treadmill in a shod and unshod condition. This will be done first at incline (8 degrees), then level running (0 degrees) then at decline (-8 degrees).

Will you benefit from taking part in this research?

You will not benefit directly from participating in this study. This study will however benefit the greater community of trail and recreational runners. In addition, you will acquire in depth knowledge of your own running mechanics and exposure to the research process.

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

The study will be conducted in a safe environment which will be regulated by the researchers to ensure the safety of the participant. The anthropometric tests will be conducted in a laboratory with all risks being taken into consideration, including a thorough cleaning of the laboratory prior to the commencement of testing, a none slip mat used whilst attaching equipment and safety harness for the treadmill running. You will also be required to run a short pre-selected outdoor trail adjacent to the laboratory. It is a non-technical single-track that should pose little to no risk for recreational trail runners. You will be required to use your own trail running shoe to ensure maximum comfort and less injury risk during the shod trial. For the barefoot trial, the treadmill as well as the CAF lab will be swept and cleaned prior to the commencement of the study in order to ensure safe and clean running conditions for the exposed foot. You are also allowed a familiarization with the minimalist sandal in order to determine a comfortable lacing pattern. All equipment used will be non-invasive and will be strapped on the specific bony landmark locations (ankles, knees, hips, lumbar spine and thoracic spine) using soft foam straps.

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

If participants do not agree to take part, they may drop out of the study or opt to participate in select studies or an alternative research project where they agree to the terms.

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

Background information:

- ➢ *The sponsor of a trial must ensure that the participants in health research are covered by comprehensive insurance in the event of physical (bodily) harm or injury, including death. This means that the insurance company will compensate a participant for medical expenses which* *may have resulted directly from their participation in research without the participant having to prove that the sponsor was at fault.*

- *Stellenbosch University has insurance to cover participants in all non-industry sponsored research studies that are registered with the HREC.*
- *It is important to explain to each participant that:*
  - *By agreeing to participate in this study, he/she agrees that there is a risk that the study medicine(s) or procedure(s) may cause him/her harm. If it does, the sponsor will reimburse him/her for his/her medical expenses without the participant having to prove that the sponsor was at fault.*
  - *The participant may, however, still claim for emotional pain and suffering if he/she so chooses. In this event, he/she will have to prove that the sponsor 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 payment for participation. However participants will receive a full report with the results of their testing and a practical explanation of what these results mean. After testing is completed, participants will have the option to book an appointment of 1 hour with one of the researchers. In this hour we will answer any questions that participants have about their running gait kinematics and offer advice to them in a sports science capacity.

Is there anything else that you should know or do?

- You should tell your family practitioner or usual doctor that you are taking part in a research study. If you have been warned against participating in **maximal exercise** by a doctor, then please opt not to participate in Emily's study.
- You should also tell your medical insurance company that you are participating in a research study.
- 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.

Decision to participate:
(Please indicate with a tick which research projects you are willing to participate)

☐ **The acute kinetic and kinematic differences between shod, barefoot and minimalist sandal running in habitually shod male recreational trail runners – <u>Matthew Swart</u>**

☐ **The difference in running gait kinematics between highly trained and recreational trail runners before and after a fatigue stimulus – <u>Emily Robertson</u>**

Highly trained runners may only participate in this study

☐ **The differences in lower-body muscle force production and gait variables during treadmill and trail running in recreational trail runners – <u>Oloff Bergh</u>**

Declaration by participant:

By signing below, I …………………………………….………… agree to take part in a/these research study entitled:

☐ **The acute kinetic and kinematic differences between shod, barefoot and minimalist sandal running in habitually shod male recreational trail runners – Matthew Swart**

☐ **The difference in running gait kinematics between highly trained and recreational trail runners before and after a fatigue stimulus – Emily Robertson**

Highly trained runners may only participate in this study

☐ **The differences in lower-body muscle force production and gait variables during treadmill and trail running in recreational trail runners – Oloff Bergh**

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*) …………....…… 2019.

....

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*) …………....…… 2019.

....

Signature of investigator **Signature of witness**

APPENDIX C

PARTICIPANT INFORMATION LEAFLET AND CONSENT FORM (AFRIKAANS)

TITEL VAN DIE PROJEK(TE):	
Stellenbosch Trail and Road Running Research (STARRR) **Die akute kinetiese en kinematiese verskille tussen normale skoene, kaalvoet- en minimalistiese sandale wat gewoonlik in manlike ontspanningsroetes aangebied word – Matthew Swart** **Die verskil in hardloopgang kinematika tussen hoogs opgeleide en ontspanningsroetes hardlopers voor en na 'n moegheidstimulus – Emily Robertson** **Die verskille in die produksie van laer liggaamsspierkrag en gangveranderlikes tydens loopband en roete by ontspanningsroete hardlopers– Oloff Bergh**	
BESONDERHEDE VAN DIE PRIMERE ONDERSOEKER(S):	
Titel, eerste naam, van: **Mr Matthew Swart,** **Ms Emily Robertson** **Mr Oloff Bergh** **Prof. Ranel Venter (Supervisor)** **Mr. Simon De Waal (Co-supervisor)**	**Etiek verwysings normmers:** **N19/07/077 – M. Swart** **N19/07/078- E. Robertson** **N19/07/076 – O. Bergh**
Volledige posadres: **10 Alphen Glade, 23 Upper Mountain Straat, Somerset West, 7130** **Unit 6, Tassenywk, Marais Straat Stellenbosch, 7600** **13 Goederust Straat, Heldervue, Somerset West 7130**	**Kontak Nommers:** **079 346 8688 – M. Swart** **072 261 5045 – E. Robertson** **079 299 4974 – O. Bergh**

Ons wil jou nooi om deel te neem aan 'n samewerkende STARRR-projek aan die Departement Sportwetenskap, Universiteit Stellenbosch. Neem die tyd om die inligting wat hier aangebied word, te lees, wat die besonderhede van hierdie projek uiteensit. Vra die studie-PI's of studieleier / medestudieleier enige vrae rakende enige deel van hierdie projek wat jy nie ten volle verstaan nie. Dit is baie belangrik dat jy heeltemal tevrede is dat jy duidelik verstaan wat hierdie navorsing behels en hoe jy betrokke gaan wees. Jou deelname is ook heeltemal vrywillig en jy is vry om te weier om deel te neem. Met ander woorde, jy kan kies om deel te neem, of kies om nie deel te neem nie. Niks slegs sal daaruit kom as jy nee sê nie: dit sal jou nie negatief beïnvloed nie. Weiering om deel te neem behels geen boete of verlies aan voordele of verlaging in die versorgingsvlak waarop u andersins geregtig is nie. Jy kan ook op enige stadium uittree uit die studie, selfs al stem jy in om aanvanklik deel te neem.

*This study has been approved by the **Health Research Ethics Committee at Stellenbosch University.** 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).

Wat is die STARRR-groep?

Die STARRR-groep is 'n navorsingspan van drie meesters studente (Matthew Swart, Emily Robertson en Oloff Bergh) van die Departement Sportwetenskap, Universiteit Stellenbosch, onder leiding van twee akademiese personeel en studieleiers (professor Ranel Venter en mnr Simon De Waal). Die groep is gestig as gevolg van 'n gemeenskaplike belangstelling in navorsing. Weens hierdie gemeenskaplike belangstelling deel ons bronne vir die toetsproses. Die resultaat hiervan is dat jy die geleentheid het om oor 'n twee dae toetsperiode aan al drie meesters navorsings projekte deel te neem. Jou deelname aan hierdie navorsing sal dus deel vorm van al drie die projekte, maar jy kan van die projekte voor, tydens of na toetsing intree sonder om 'n rede daarvoor te gee. Dui in die blokkies onder aan watter spesifieke meestersnavorsingsprojek (te) jy bereid sou wees om aan deel te neem.

Waaroor gaan elke studie?

1) Die akute kinetiese en kinematiese verskille tussen normale skoene, kaalvoet- en minimalistiese sandale wat gewoonlik in manlike ontspanningsroetes aangebied word – Matthew Swart

Die doel van hierdie studie is om die akute kinematiese en kinetiese verskille tussen hardloop in skoene, kaalvoet en hardloop in minimalistiese sandale te bepaal. Kinematika verwys na die beweging of beweging van liggaamsdele sonder om rekening te hou met die kragte wat hierdie bewegings voortbring (d.w.s. skyflengte en skyffrekwensie). Kinetika verwys na die kragte en tyd wat tydens hierdie bewegings op die liggaam inwerk (d.w.s. grondreaksiekragte). Hierdie studie het die doel om sekere veranderlikes te vergelyk tydens hardloop in drie verskillende skoene, naamlik in jou gewone skoene, in Xero (Xero Shoes, Colorado, U.S.A) minimalistiese sandale en kaalvoet om die verskille te vergelyk.

2) Die verskil in hardloopgang kinematika tussen hoogs opgeleide en ontspanningsroetes hardlopers voor en na 'n moegheidstimulus – Emily Robertson

Die doel van die studie is om meer te weet oor die effek van uitputting op hardloopkinematika (hardloopbeweging) vir hardlopers en ontspanningslopers, en of die verskil tussen hierdie twee groepe groot is. In hierdie studie word kinematiese veranderlikes soos voorwaartse romp, kadens, kniehoeke, ens. Vergelyk tussen die twee groepe van hardlopers.

3) Die verskille in die produksie van laer liggaamsspierkrag en gangveranderlikes tydens loopband en roete by ontspanningsroete hardlopers– Oloff Bergh

Tydens hierdie studie wil ons die ingewikkeldhede van menslike hardloop en die effek van veranderende oppervlaktes op spieraktiwiteite verder ondersoek. Meer spesifiek, word gekyk na die produksie van spierkrag wanneer individue van 'n trapmeulbaan na 'n meer regte wêreld gaan, soos spoorloop. Ons is baie gelukkig om 'n oorvloed van natuurlike omgewings te hê, sowel as perfekte weersomstandighede vir die grootste deel van die jaar, maar nie almal het hierdie voorregte nie en loop dus meer gereeld op loopbane of padoppervlakke. Vanweë die toenemende gewildheid van weeklikse veldrenne soos Parkrun ™ en Myrun ™, sal die groter gemeenskap van ontspanningslopers (beide pad en roete) baat vind by die kennis van die veranderinge wat plaasvind in die kinetika van die onderlyf wanneer die loopoppervlak verander word en terrein. Ons moet die veranderinge wat plaasvind in die onderlyfspiere identifiseer wanneer ons hierdie komplekse roeteterreine deurkruis.

Al die toetse word aangebied deur die Departement Sportwetenskap, die Universiteit Stellenbosch, en sal plaasvind by die Neuromechanics-eenheid in die Central Analitiese Fasiliteite (CAF) laboratorium wat op Coetzenberg agter Maties Gimnasium geleë is. Die totale hoeveelheid deelnemers wat benodig word vir hierdie studie is 30 (15 ontspannings- en 15 opgeleide-spoorlopers), met alle deelnemers wat nodig is om die toetsing by die Neuromechanics-eenheid te voltooi.

Hoekom nooi ons jou om deel te neem?

Om aan een van die drie meestersnavorsingsprojekte in die STARRR-groep deel te neem, moet jy vertroud wees met die sportsoort. Daarbenewens hoef jy geen vorige ervaring met minimalistiese hardloop te hê nie (dit wil sê kaalvoet of in sandale tydens hardloop en wedrenne). Ons het twee vlakke van opleidingstatus / naaswenner uitgenooi om aan die STARRR-projekte deel te neem - ontspannend en hoogs opgelei. As jy gereeld tussen 20 - 30 km per week op die roete hardloop, kwalifiseer jy as 'n ontspanningsroete. As jy gereeld tussen 60 - 90km per week op die baan hardloop, kwalifiseer jy as 'n hoogs opgeleide baanloper. Jou deelname sal help om 'n belangrike bydrae te lewer tot die literatuur rondom spoorhardloop.

Wat sal jou verantwoordelikhede wees?

<u>Dag 1</u>

- Jy word ingelig oor die dag se toetsverrigtinge en jy moet dan hierdie vorm onderteken om deel te neem.
- Antropometriese data (gewig, lengte, lengte van die ledemaat, ens.) word gemeet.
- VO2max-toets (harde inspanning op 'n trapmeul)
- Tyd vir uitputtingstoets teen 90% van VO2max teen 'n helling van 7 grade. (Hardlopers hardloop totdat die uitputting bereik is)

<u>Dag 2</u>

- Vertikale springtoets (3x3 spring in normale skoene)
- Submaksimale hardloop terwyl u drafskoene dra.
- Submaksimale hardloop in 'n kaalvoet toestand.
- Die deelnemers hardloop vir een minuut met drie verskillende snelhede (8, 10 en 13 km / u) op die loopband in 'n onbehandelde toestand. Dit word eers gedoen met 'n helling (8 grade), dan vlak hardloop (0 grade) en dan met afname (-8 grade).

Sal u voordeel trek uit hierdie navorsing?

Jy sal nie direk baat vind by die deelname aan hierdie studie nie. Hierdie studie sal egter die groter gemeenskap van pad- en ontspanningslopers bevoordeel. Daarbenewens verwerf jy 'n diepgaande kennis van jou eie hardloopmeganika en blootstelling aan die navorsingsproses.

Is daar enige risiko verwant aan die deelname aan hierdie studie?

Die studie sal uitgevoer word in 'n veilige omgewing wat deur die navorsers gereguleer sal word om die deelnemer se veiligheid te verseker. Die antropometriese toetse sal in 'n laboratorium uitgevoer word, met alle risiko's wat in aanmerking geneem word, insluitend 'n deeglike skoonmaak van die laboratorium voor die aanvang van die toets, 'n matglipmat wat gebruik word terwyl toerusting en veiligheidsnoer aangebring word vir die loopband. Daar sal ook van jou verwag word om 'n kort vooraf geselekteerde buitespoor langs die laboratorium te loop. Dit is 'n nie-tegniese enkelbaan wat vir ontspanningsroetes min of geen risiko's inhou nie. Daar sal van jou verwag word om jou eie roete-skoen te gebruik om maksimum gemak en minder beseringsrisiko te verseker tydens die versperring. Vir die kaalvoetproef sal die loopband sowel as die CAF-laboratorium voor die aanvang van die studie gevee en skoongemaak word ten einde veilige en skoon loopomstandighede vir die blootgestelde voet te verseker. Jy kan ook vertroud wees met die minimalistiese sandaal om 'n gemaklike veterspatroon te bepaal. Alle toerusting wat gebruik word, sal nie indringend wees nie en sal op die spesifieke benerige landmerke (enkels, knieë, heupe, lumbale ruggraat en torakale rug) gebind word deur sagte skuimbande te gebruik.

As jy nie instem om deel te neem nie, watter alternatiewe het jy?

As deelnemers nie daartoe instem om deel te neem nie, kan hulle die studie verlaat of verkies om in geselekteerde studies of 'n alternatiewe navorsingsprojek deel te neem, waar hulle tot die voorwaardes instem.

Alhoewel dit onwaarskynlik is, wat sal gebeur as jy op een of ander manier beseer word omdat jy aan hierdie navorsingstudie deelgeneem het?

Agtergrond inligting:

- *Die borg van 'n verhoor moet toesien dat die deelnemers aan gesondheidsondersoeke gedek word deur omvattende versekering in die geval van liggaamlike (liggaamlike) letsel of besering, insluitend die dood. Dit beteken dat die versekeringsmaatskappy 'n deelnemer sal vergoed vir mediese onkoste wat direk voortspruit uit hul deelname aan navorsing sonder dat die deelnemer moes bewys dat die borg die skuld begaan het.*
- *Die Universiteit Stellenbosch het versekering om deelnemers te dek aan alle nie-bedryfsgeborgde navorsingstudies wat by die HREC geregistreer is.*
- *Dit is belangrik om aan elke deelnemer te verduidelik dat:*
  - *Deur in te stem om aan hierdie studie deel te neem, stem hy / sy saam dat die risiko bestaan dat die medisyne (s) of die prosedure vir die studie hom / haar skade kan berokken. As dit so is, sal die borg hom / haar vir sy / haar mediese uitgawes vergoed sonder dat die deelnemer hoef te bewys dat die borg die skuld begaan het.*
  - *Die deelnemer kan egter steeds aanspraak maak op emosionele pyn en lyding as hy / sy dit verkies. In hierdie geval sal hy / sy moet bewys dat die borg nalatig was en nie alle redelike en voorsienbare stappe gedoen het om die besering of emosionele trauma te voorkom nie. Dit sal 'n aparte wetlike aangeleentheid wees.*

Die Universiteit Stellenbosch word deur omvattende skuldlose versekering gedek, en sal enige mediese koste betaal wat vir persone veroorsaak is omdat hulle aan hierdie projek deelgeneem het (ongeag of hulle die medikasie vir hierdie proefneming gebruik het, en of hulle op ’n ander manier deelgeneem het). Skuldlose versekering beteken jy hoef nie te bewys dat die borg (die Universiteit) skuld het aan die gebeure wat die kostes vir jou veroorsaak het nie.

Sal jy betaal word om aan hierdie studie deel te neem en is daar kostes daaraan verbonde?

Daar is geen betaling vir deelname nie. Deelnemers sal egter 'n volledige verslag ontvang met die resultate van hul toetsing en 'n praktiese uiteensetting van wat hierdie resultate beteken. Nadat die toetsing voltooi is, kan deelnemers die geleentheid hê om 'n afspraak van 1 uur by een van die navorsers te bespreek. In hierdie uur sal ons vrae beantwoord wat deelnemers het oor hul loopgang kinematika en advies aan hulle gee in 'n sportwetenskaplike hoedanigheid.

Is daar iets anders wat jy moet weet of doen?

- Jy moet jou huisarts of gewone dokter vertel dat jy aan 'n navorsingstudie deelneem. As jy gewaarsku word om aan 'n maksimale oefening deur 'n dokter deel te neem, kies dan om nie aan Emily se studie deel te neem nie.
- Jy moet ook aan jou mediese versekeringsmaatskappy sê dat jy aan 'n navorsingstudie deelneem.
- Jy kan die Komitee vir Gesondheidsnavorsingsetiek skakel by 021 938 9677/9819 indien daar nog iets is wat u studielid nie aan jou verduidelik het nie, of as jy 'n klag het.
- Jy sal 'n afskrif van hierdie inligting en toestemmingsvorm ontvang om jou veilig te hou.

Besluit om deel te neem:
(Dui met 'n regmerkie aan watter navorsingsprojekte jy bereid is om deel te neem)

☐ **Die akute kinetiese en kinematiese verskille tussen normale skoene, kaalvoet- en minimalistiese sandale wat gewoonlik in manlike ontspanningsroetes aangebied word – Matthew Swart**

☐ **Die verskil in hardloopgang kinematika tussen hoogs opgeleide en ontspanningsroetes hardlopers voor en na 'n moegheidstimulus – Emily Robertson**

*** Hoogs opgeleide hardlopers mag slegs aan hierdie studie deelneem ***

☐ **Die verskille in die produksie van laer liggaamsspierkrag en gangveranderlikes tydens loopband en roete by ontspanningsroete hardlopers– Oloff Bergh**

Verklaring deur deelnemer:

Deur hieronder te teken, stem ek …………………………….………….. in om deel te neem aan hierdie navorsingstudie(s) getiteld:

☐ **Die akute kinetiese en kinematiese verskille tussen normale skoene, kaalvoet- en minimalistiese sandale wat gewoonlik in manlike ontspanningsroetes aangebied word – Matthew Swart**

☐ **Die verskil in hardloopgang kinematika tussen hoogs opgeleide en ontspanningsroetes hardlopers voor en na 'n moegheidstimulus – Emily Robertson**

*** Hoogs opgeleide hardlopers mag slegs aan hierdie studie deelneem ***

☐ **Die verskille in die produksie van laer liggaamsspierkrag en gangveranderlikes tydens loopband en roete by ontspanningsroete hardlopers– Oloff Bergh**

Ek verklaar dat:

- Ek het hierdie inligting- en toestemmingsvorm gelees, of dit is aan my gelees, en dit is geskryf in 'n taal waarin ek vlot is en waarmee ek gemaklik is.
- Ek het die kans gekry om vrae te stel en ek is tevrede dat al my vrae beantwoord is.
- Ek verstaan dat deelname aan hierdie studie vrywillig is en dat ek nie onder druk geplaas is om deel te neem nie.
- Ek kan te eniger tyd kies om die studie te verlaat en daar sal niks slegs daaraan kom nie; ek sal op geen manier gepenaliseer of benadeel word nie.
- Ek kan gevra word om die studie te verlaat voordat dit voltooi is, indien die studielid of navorser van mening is dat dit in my beste belang is, of as ek nie die studieplan waaroor ons ooreengekom het, volg nie.

Geteken by (*plek*) ....…........…………….. op (*datum*) ………....…… 2019.

....	....
Handtekening van die deelnemer	**Handtekening van die getuie**

Verklaring deur die ondersoeker:

Ek *(naam)* ……………………………………………… verklaar dat:

- Ek het die inligting in hierdie dokument op 'n eenvoudige en duidelike manier verduidelik aan
    - ....
- Ek het hom / haar aangemoedig om vrae te stel en het genoeg tyd geneem om dit te beantwoord.
- Ek is tevrede dat hy / sy alle aspekte van die navorsing, soos hierbo bespreek, volledig verstaan.
- Ek het / het nie 'n tolk gebruik nie. (As 'n tolk gebruik word, moet die tolk die onderstaande verklaring onderteken.)

Geteken by (*plek*) ....…........…………….. op (*datum*) …………....…… 2019.

....	....
Handtekening van die ondersoeker	**Handtekening van die getuie**

APPENDIX D

ETHICS APPROVAL LETTER

UNIVERSITEIT
STELLENBOSCH
UNIVERSITY

Approved

Response to Modifications

23/10/2019

Project ID #: 10384

HREC Reference #: N19/07/076

Title**:** Differences in lower-body muscle force production and gait variables during treadmill and trail running in recreational trail runners

Dear Prof Rachel Venter

The **Response to Modifications** received on 11/10/2019 10:46 was reviewed by members of the **Health Research Ethics Committee (HREC)** via Minimal Risk Review procedures on 23/10/2019 and was **approved.**

Please note the following information about your approved research protocol:

Approval date: 23 October 2019

Expiry date: 22 October 2020

Please remember to use your HREC reference number (N19/07/076) on any documents or correspondence with the HREC concerning your research protocol.

Translation of the consent document/s to the language applicable to the study participants should be submitted.

Please note that HREC reserves the right to suspend approval and to request changes or clarifications from student applicants. The coordinator will notify the applicant (and if applicable, the supervisor) of the changes or suspension within 1 day of receiving the notice of suspension from HREC. HREC has the prerogative and authority to ask further questions, seek additional information, require further modifications, or monitor the conduct of your research and the consent process.

After Ethical Review:

Please note a template of the progress report is obtainable on https://applyethics.sun.ac.za/Project/Index/16442 and should be submitted to the Committee before the year has expired. The Committee will then consider the continuation of the project for a further year (if necessary). Annually a number of projects may be selected randomly for an external audit.

Provincial and City of Cape Town Approval

Please note that for research at a primary or secondary healthcare facility permission must still be obtained from the relevant authorities (Western Cape Department of Health and/or City Health) to conduct the research as stated in the protocol. Contact persons are Ms Claudette Abrahams at Western Cape Department of Health (healthres@pgwc.gov.za Tel: +27 21 483 9907) and Dr Helene Visser at City Health (Helene.Visser@capetown.gov.za Tel:+27 21 400 3981). Research that will be conducted at any tertiary academic institution requires approval from the relevant hospital manager. Ethics approval is required BEFORE approval can be obtained from these health authorities.

We wish you the best as you conduct your research.

For standard HREC forms and documents please visit: https://applyethics.sun.ac.za/Project/Index/16442

If you have any questions or need further assistance, please contact the HREC office at 021 938 9657.

Sincerely,

Melody E Shana

Coordinator

Health Research Ethics Committee

National Health Research Ethics Council (NHREC) Registration Number:

REC-130408-012 (HREC1)•REC-230208-010 (HREC2)

Federal Wide Assurance Number: 00001372
Office of Human Research Protections (OHRP) Institutional Review Board (IRB) Number:
IRB0005240 (HREC1)•IRB0005239 (HREC2)

The Health Research Ethics Committee (HREC) complies with the SA National Health Act No. 61 of 2003 as it pertains to health research. The HREC abides by the ethical norms and principles for research, established by the World Medical Association (2013). Declaration of Helsinki: Ethical Principles for Medical Research Involving Human Subjects;the South African *Department of Health (2006). Guidelines for Good Practice in the Conduct of Clinical Trials with Human Participants in South Africa (2nd edition)*; *as well as the Department of Health (2015). Ethics in Health Research: Principles, Processes andStructures (2nd edition).*

The Health Research Ethics Committee reviews research involving human subjects conducted or supported by the Department of Health and Human Services, or other federal departments or agencies that apply the Federal Policy for the Protection of Human Subjects to such research (United States Code of Federal Regulations Title 45 Part 46); and/or clinical investigations regulated by the Food and Drug Administration

INVESTIGATOR RESPONSIBILITIES

Protection of Human Research Participants

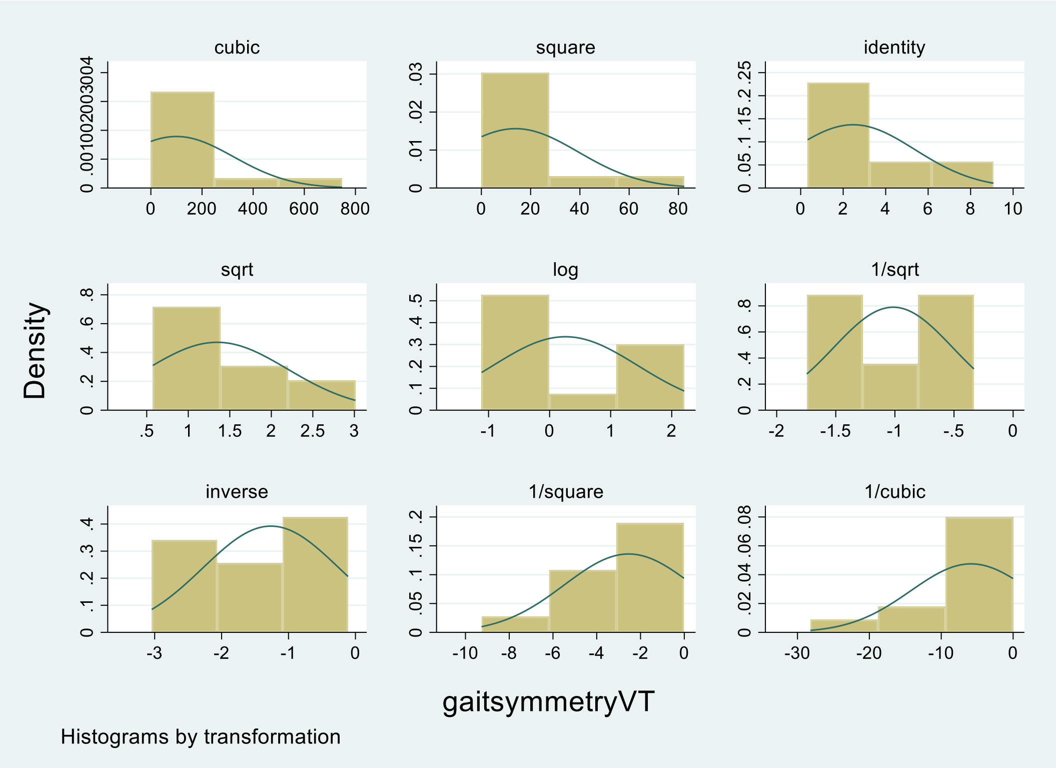
Some of the responsibilities investigators have when conducting research involving human participants are listed below:

- Conducting the Research: You are responsible for making sure that the research is conducted according to the HREC approved research protocol. You are also responsible for the actions of all your co-investigators and research staff involved with this research.
- Participant Enrolment: You may not recruit or enrol participants prior to the HREC approval date or after the expiration date of HREC approval. All recruitment materials for any form of media must be approved by the HREC prior to their use. If you need to recruit more participants than was noted in your HREC approval letter, you must submit an amendment requesting an increase in the number of participants.
- Informed Consent: You are responsible for obtaining and documenting effective informed consent using **only** the HREC approved consent documents, and for ensuring that no human participants are involved in research prior to obtaining their informed consent. Please give all participants copies of the signed consent documents. Keep the originals in your secured research files for at least fifteen (15) years.
- Continuing Review: The HREC must review and approve all HREC approved research protocols at intervals appropriate to the degree of risk but not less than once per year. There is **no grace period**. Prior to the date on which the HREC approval of the research expires, **it is your responsibility to submit the continuing review report in a timely fashion to ensure a lapse in HREC approval does not occur.** If HREC approval of your research lapses, you must stop new participant enrolment, and contact the HREC Office immediately.
- Amendments and Changes: If you wish to amend or change any aspect of your research (such as research design, interventions or procedures, number of participants, participant population, informed consent document, instruments, surveys or recruiting material), you must submit the amendment to the HREC for review using the current Amendment Form. You **may not initiate** any amendments or changes to your research without first obtaining written HREC review and approval. The **only exception** is when it is necessary to eliminate apparent immediate hazards to participants and the HREC should be immediately informed of this necessity.
- Adverse or Unanticipated Events: Any serious adverse events, participant complaints, and all unanticipated problems that involve risks to participants or others, as well as any research-related injuries, occurring at this institution or at other performance sites must be reported to the HREC within **five (5) days** of discovery of the incident. You must also report any instances of serious or continuing problems, or non-compliance with the HREC's requirements for protecting human research participants. The only exception to this policy is that the death of a research participant must be reported in accordance with the Stellenbosch University Health Research Ethics Committee Standard Operating Procedures www.sun25.sun.ac.za/portal/page/portal/Health_Sciences/English/Centres%20and%20Institutions/Research_Development_Support/Ethics/Application_package. All reportable events should be submitted to the HREC using the Serious Adverse Event Report Form.
- Research Record Keeping: You must keep the following research-related records, at a minimum, in a secure location for a minimum of fifteen years; the HREC approved research protocol and all amendments; all informed consent documents; recruiting materials; continuing review reports; adverse or unanticipated events; and all correspondence from the HREC.
- Reports to the MCC and Sponsor: When you submit the required annual report to the MCC or you submit a required report to your Sponsor, you must provide a copy of that report to the HREC. You may submit the report at the time of continuing HREC review.
- Provisions of Emergency Medical Care: When a physician provides emergency medical care to a participant without prior HREC review and approval, to the extent permitted by law, such activities will not be recognized as research nor will the data obtained by any of such activities be used in support of research.
- Final Reports: When you have completed (no further participant enrolment, interactions, interventions or data analysis) or stopped work on your research, you must submit a Final Report to the HREC.
- On-Site Evaluations, MCC Inspections, or Audits: If you are notified that your research will be reviewed or audited by the MCC, the Sponsor, any other external agency or any internal group, you must inform the HREC immediately of the impending audit/evaluation.

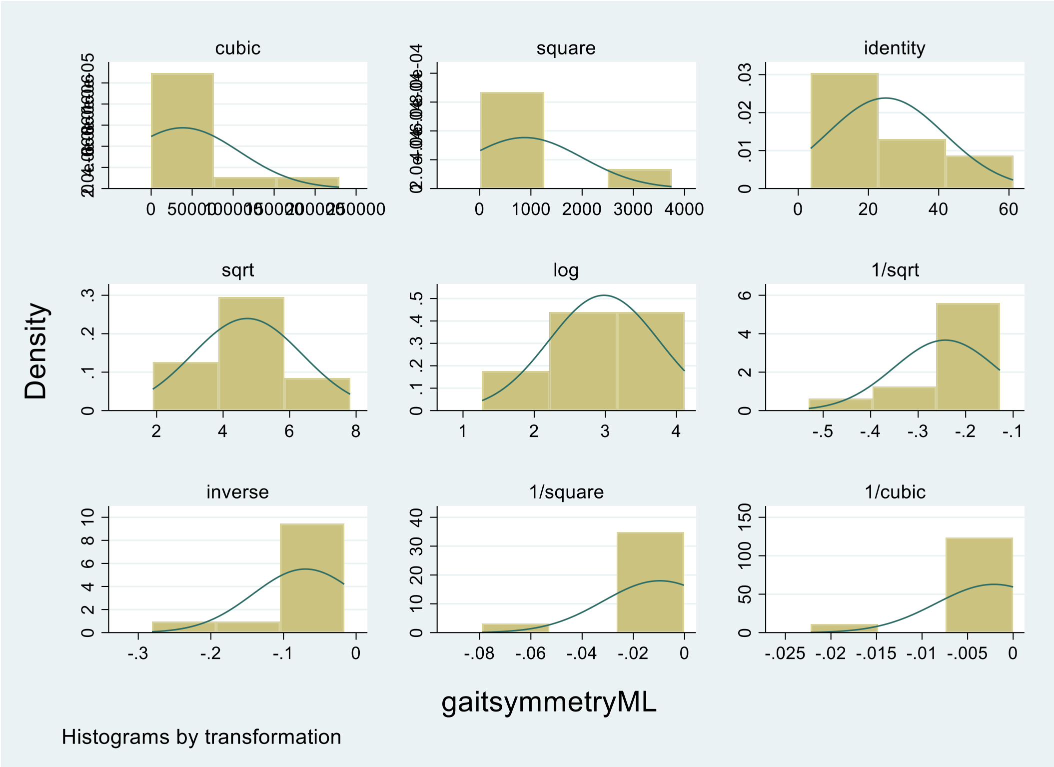
APPENDIX E

TRANSFORMATIONS FOR THE DIFFERENT VARIABLES

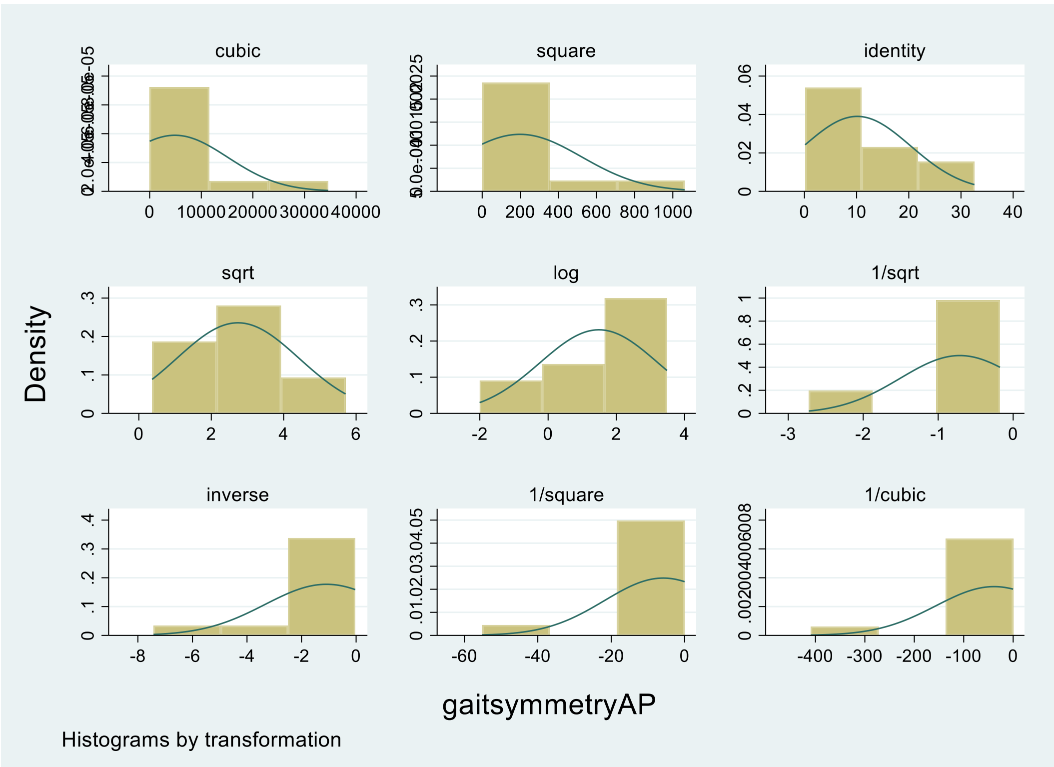
Treadmill data



None of the transformations seem to work for the Gait symmetry VT variable – may have to summarize using median (interquartile range/range) and perform non-parametric tests for any comparisons

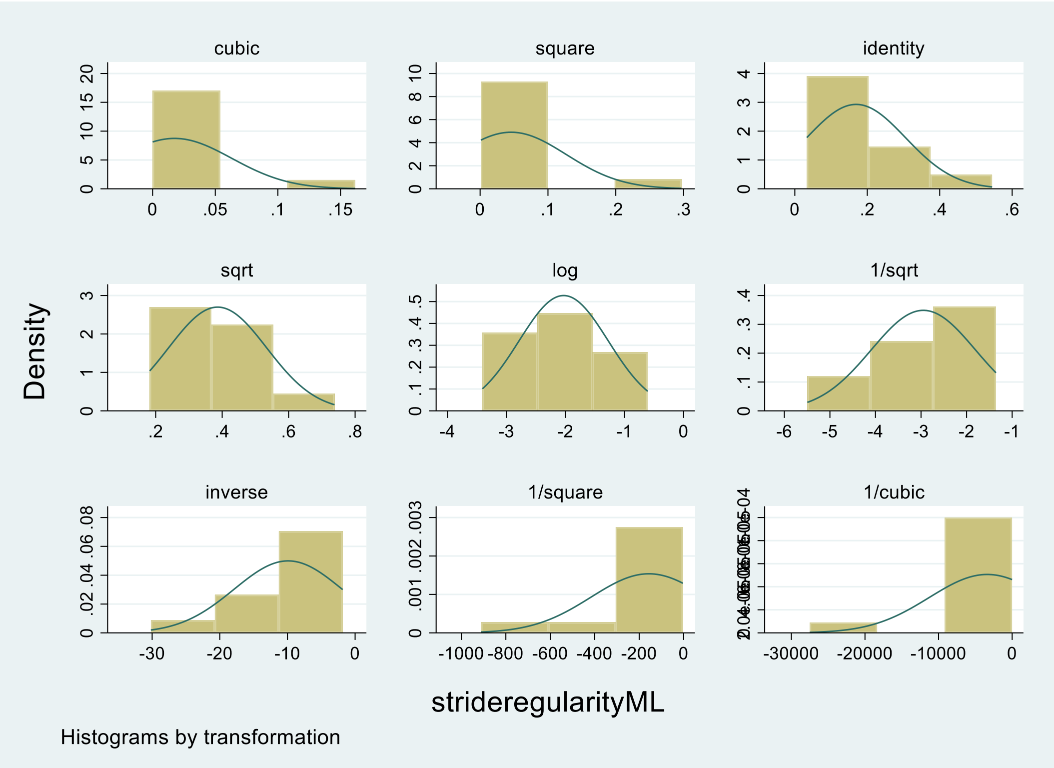


Taking the square root of Gait symmetry ML seems a good transformation as the histogram looks normal/symmetrical

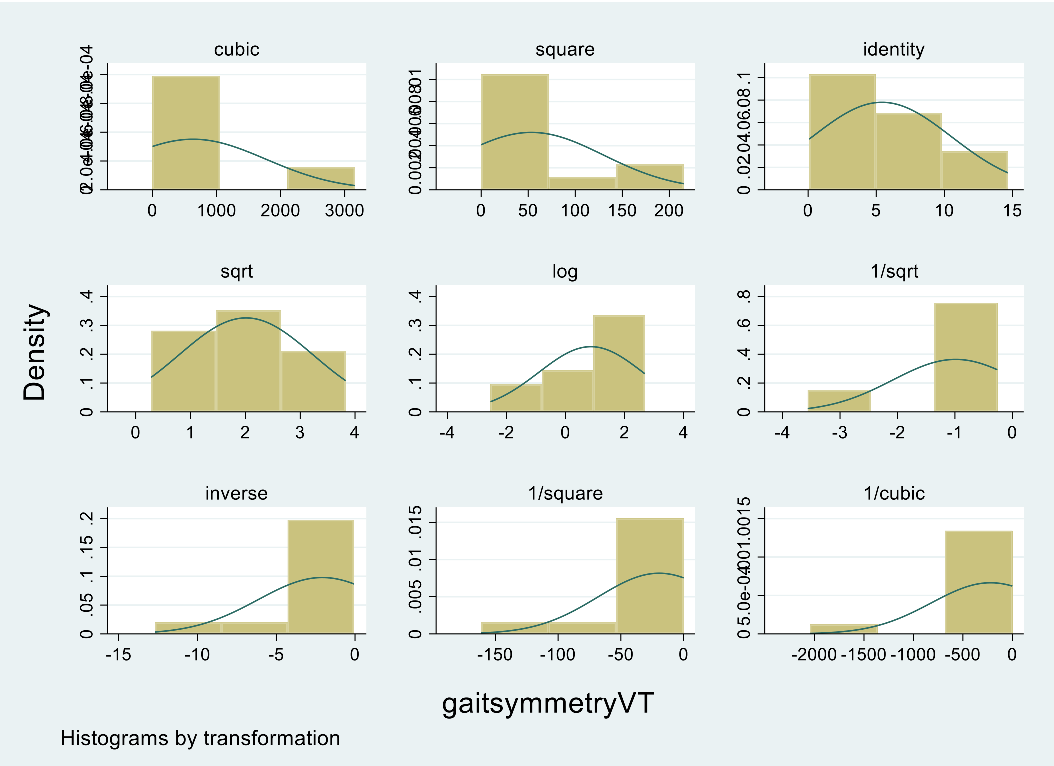


Taking the square root of Gait symmetry AP seems a good transformation as the histogram looks normal/symmetrical

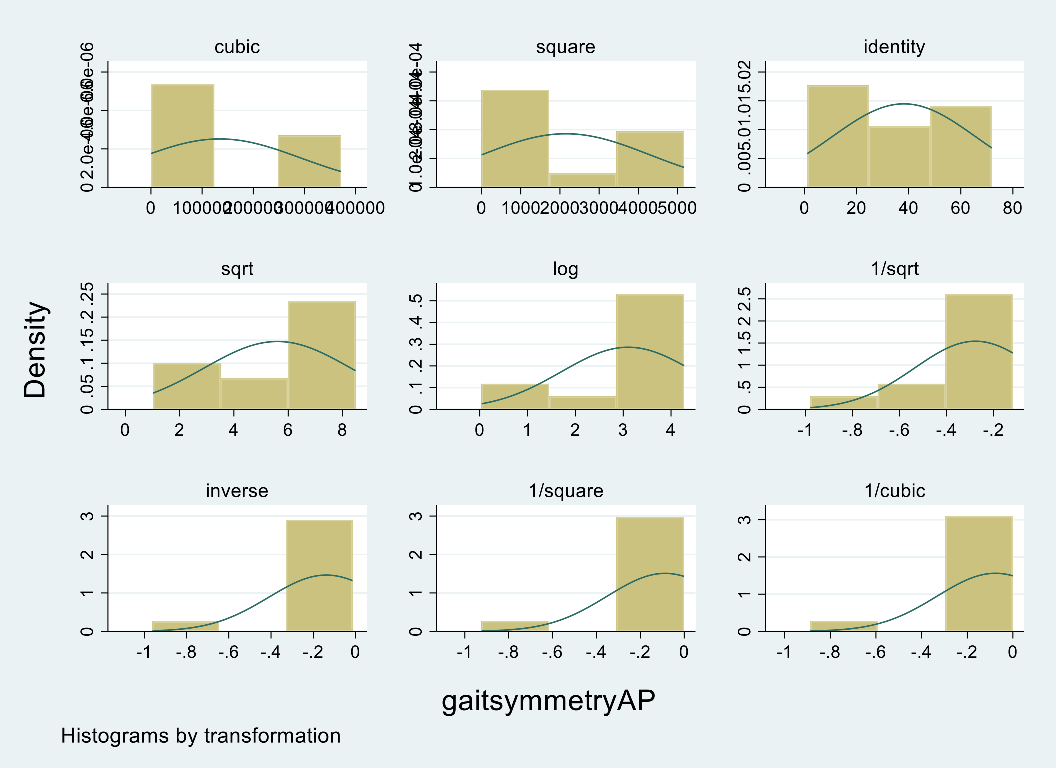
Trial data



Taking the log of stride regularity ML seems a good transformation as the histogram looks normal/symmetrical



Taking the square root of Gait symmetry VT seems a good transformation as the histogram looks normal/symmetrical



None of the transformations seem to work for the Gait symmetry AP variable – may have to summarize using median (interquartile range/range) and perform non-parametric tests for any comparisons

APPENDIX F

JOURNAL OF SPORT SCIENCES INSTRUCTIONS FOR AUTHORS

Instructions for authors

COVID-19 impact on peer review
As a result of the significant disruption that is being caused by the COVID-19 pandemic we understand that many authors and peer reviewers will be making adjustments to their professional and personal lives. As a result they may have difficulty in meeting the timelines associated with our peer review process. Please let the journal editorial office know if you need additional time. Our systems will continue to remind you of the original timelines but we intend to be flexible.

Thank you for choosing to submit your paper to us. These instructions will ensure we have everything required so your paper can move through peer review, production and publication smoothly. Please take the time to read and follow them as closely as possible, as doing so will ensure your paper matches the journal's requirements.

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Supporting Taylor & Francis authors

For general guidance on every stage of the publication process, please visit our Author Services website.

EDITING SERVICES
Supporting Taylor & Francis authors

For editing support, including translation and language polishing, explore our Editing Services website

Editorial Manager

This journal uses Editorial Manager to peer review manuscript submissions. Please read the guide for Editorial Manager authors before making a submission. Complete guidelines for preparing and submitting your manuscript to this journal are provided below.

This title utilises format-free submission. Authors may submit their paper in any scholarly format or layout. References can be in any style or format, so long as a consistent scholarly citation format is applied. For more detail see the format-free submission section below.

Contents

About the Journal

Journal of Sports Sciences is an international, peer-reviewed journal publishing high-quality, original research. Please see the journal's Aims & Scope for information about its focus and peer-review policy.

Please note that this journal only publishes manuscripts in English.

Journal of Sports Sciences accepts the following types of article: Original Articles, Case Studies, Letters to the Editor, Systematic Reviews and Meta-analysis.

The Journal of Sports Sciences is published on behalf of the British Association of Sport and Exercise Sciences, in association with the International Society for Advancement of Kinanthropometry. The emphasis is on the human sciences applied to sport and exercise. Topics covered also include technologies such as design of sports equipment, research into training, and modelling and predicting performance; papers evaluating (rather than simply presenting) new methods or procedures will also be considered.

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**Usage in 2017-2019 for articles published in 2015-2019.

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Taylor & Francis is committed to peer-review integrity and upholding the highest standards of review. Once your paper has been assessed for suitability by the editor, it will then be double blind peer reviewed by independent, anonymous expert referees. Find out more about what to expect during peer review and read our guidance on publishing ethics.

Preparing Your Paper

All authors submitting to medicine, biomedicine, health sciences, allied and public health journals should conform to the Uniform Requirements for Manuscripts Submitted to Biomedical Journals, prepared by the International Committee of Medical Journal Editors (ICMJE).

Structure

Your paper should be compiled in the following order: title page; abstract; keywords; main text introduction, materials and methods, results, discussion; acknowledgments; declaration of interest statement; references; appendices (as appropriate); table(s) with caption(s) (on individual pages); figures; figure captions (as a list).

Word Limits

Please include a word count for your paper.

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