PERFORMANCE IN RECREATIONAL DISTANCE RUNNERS: A BIOMECHANICAL APPROACH TO IMPROVING RUNNING ECONOMY

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Abstract

The number of people choosing to run for fitness and health has increased steadily in recent years, with the latest findings putting the figure at 7 million in England alone. Given the size of the recreational running population, it is surprising that there is a dearth of research looking at the physiology and biomechanics of this recreational distance running cohort.

This thesis compared the physiological and biomechanical performance when running overground with the same speed and comparable conditions on a treadmill. Forty participants attended two experimental sessions, not less than a week apart, and ran at their preferred 5 km pace for 5 minutes on a treadmill and overground on each occasion. There was a statistically significant difference in running economy between the overground and treadmill conditions (means: 39.11, 40.09, 42.87, 43.09 ml.kg-1.min-1 for overground 1, 2 and treadmill 1, 2 respectively; $p < 0.001$), but not between the biomechanical factors. When testing outside for running economy and biomechanical data, both were found to be reliable and ecologically valid.

Having established that testing overground is an acceptable method for investigating this cohort of runners, this thesis set out to determine whether there was a relationship between running economy and one or more modifiable biomechanical variables. The data showed that the strongest connection with running economy was stride length, accounting for 46-47% ($p < 0.001$) of the variation in running economy implying that it would be possible to improve running economy by manipulating that variable.

The novel findings of this thesis are that it is reliable and ecologically valid to test for running economy and biomechanical parameters in recreational distance runners overground and that there is evidence to suggest that training to reduce stride length could lead to an improved running economy in a recreational running population, providing potential for performance enhancement.

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Abbreviations

ASIS	Anterior superior iliac spine
ATP	Adenosine triphosphate
^oC	Degrees Celsius
CI	Confidence interval
cm	Centimetres
CO_2	Carbon dioxide
CV	Coefficient of variation
GPS	Global positioning system
HR	Heart rates
HR_{max}	Maximal heart rates
Hz	Hertz
ICC	Intra-class coefficient
IMU	Inertial measurement unit
kg	Kilogrammes
km	Kilometres
$km.h^{-1}$	Kilometres per hour
L	Litres
$L.min^{-1}$	Litres per minute
m	Metres
min	Minutes
ml	Millilitres
$ml.kg^{-1}.km^{-1}$	Millilitres of O_2, per kilogramme of body weight, per kilometre
$ml.kg^{-1}.min^{-1}$	Millilitres of O_2, per kilogramme of body weight, per minute
$m.s^{-1}$	Metres per second
O_2	Oxygen
OG	Overground
PCr	Phosphocreatine
RE	Running economy
s	Seconds
SD	Standard deviation
t	Time
TD	Treadmill
$\dot{V}O_2$	Volume of oxygen
$\dot{V}O_{2max}$	Maximal volume of oxygen
yrs	Years

Chapter 1: Introduction

1.1. General background

Running is a fundamental physical movement, the most common movement pattern in sport, dependent on continuous, mainly aerobic, energy production, which is converted into forward motion (Folland *et al.*, 2017). This energy, or metabolic cost, is known as running economy and assumes that the oxygen used directly relates to the adenosine triphosphate (ATP), the source of energy in skeletal muscles, used during sub-maximal exercise (Shaw, Ingham and Folland, 2014; Folland *et al.*, 2017). It is reported that running has mainly developed for endurance in humans as speed is not considered to play a large part of the success of human evolution (Elliott and Blanksby, 1979). Runners utilise specific biomechanical and muscular contraction patterns that are unlike other endurance sports so in order to understand how biomechanics impacts on running economy, researchers need to study runners in action to observe their biomechanical traits (Joyner and Coyle, 2008).

1.2 The rise in popularity of running and choosing to run 5 km

In recent years, running has become an increasingly popular exercise for general fitness and aiming for 5 km is seen as a reasonable entry distance, the equivalent of about 30 minutes of exercise. Completing a 5 km run in 30 minutes counts as vigorous exercise and contributes to the recommended guidelines for activity in a week, which is to do at least 150 minutes of moderate intensity exercise or 75 minutes of vigorous exercise.

In the UK, the NHS has a free version of the 'Couch to 5k' app, which is a programme of incremental steps that guides the user from no running at all to running steadily for 5 km over a nine-week period. Endorsement from the NHS for this app would seem to imply that this distance is viewed as achievable. 'Couch to 5k' is one of the most popular exercise apps available, with more than 6.5 million downloads recorded as of January 2023 since its introduction in May 2016 (Department of Health and Social Care, 2023), suggesting that there is an interest in running amongst beginners. Further, there has been a huge increase in the popularity of parkrun, a free weekly 5 km event, which has seen its numbers grow to more than 2 million registered users, and they note that the average finish time has been increasing year on year as more novice and aspiring runners register – from 22:16 minutes in 2005 to 28:55 minutes in 2021 compared to the fastest recorded of 13:48 minutes - (parkrun, 2021). Additionally, in some areas, a pilot scheme is seeing General Practitioners in local surgeries refer patients to parkrun for the benefits that physical activity can provide (Royal College of General Practitioners, 2018).

Indeed, it is well documented that there are manifold physical benefits to being active including: reduced risk of high blood pressure, stroke and of developing diabetes, heart disease and various cancers (World Health Organisation, 2020). However, there are also added benefits for mental health and well-being. It has been established that there is a link between physical activity and positive psychological response (Biddle, Mutrie and Gorely, 2015), in particular, the impact on mood has been reported. Hefferon and Mutrie (2012, p. 117) went as far as to say that physical activity was the "stellar" intervention for improving positive mood and emotions.

In tandem, there is a growing body of evidence to show the additional positive impact of exercising outside over exercising indoors, referred to as green exercise (Pretty *et al.*, 2003). Given that the majority of recreational runners run overground outside (Hitchings and Latham, 2016), this suggests that conducting research in the field rather than a laboratory makes ecological sense. Additionally, the setting where exercise takes place has an impact on how the participant perceives the level of exertion, their performance and satisfaction, with outside having a more positive effect, recording a large effect size ($d = 0.76$, $p < 0.01$) (LaCaille, Masters and Heath, 2004).

Despite this growing body of recreational runners whose experience of running is in the field, much of the research to date has been conducted on a treadmill in a laboratory, but it is worth noting that this does not replicate conditions found in the field or track, where overcoming air resistance incurs a significant metabolic cost (Hoogkamer, Kram and Arellano, 2017). There are recognised physiological and biomechanical differences between the two sets of conditions (Barnes and Kilding, 2015a). However, setting the treadmill at a 1% incline is accepted as going someway to offset this (Jones and Doust, 1996).

Although there is a large population of recreational runners, generally considered those running 3.4 ± 2.8 $km.wk^{-1}$ or at least twice a week who consider running to be their primary sport (Chapman *et al.*, 2008; Folland *et al.*, 2017; Borgen, 2018), there is a dearth of research looking at their physiology and biomechanical characteristics when compared to elite and well-trained athletes, i.e. those that could compete at a national or international level. In examining this phenomenon, Borgen (2018) reported a belief among researchers that to understand elite performance, you have to study elite athletes and cannot consider all runners, which may explain both why, to date, the focus of study has been on competition level athletes and the lack of research on this large cohort of recreational runners. Hence, there is an opportunity for specific research on the performance of recreational runners. Figure 1.1 illustrates the different running patterns or biomechanical running techniques of recreational and elite runners. It can be seen, for example, that the recreational runners have shorter stride lengths and have noticeably different angles at the knee and hip. Given these observable differences, it suggests that findings from one group might not be a good fit for the other and therefore specific research into recreational runners is needed if their biomechanical patterns are to be understood.

Figure 1.1: Recreational runners (left) (parkrun, 2020) and elite runners (right) (BBC, 2020) exhibit different running patterns.

1.3 The case for conducting research in the field

Much consideration has been given to considering the conditions in which recreational runners generally run. Barnes and Kilding (2015a) suggested that researchers should focus on ways to improve running economy outside of a laboratory environment because they noted that the way people run on a treadmill is different to how they run overground, meaning there is greater ecological validity when testing running overground, as well as the practicality of doing so. This suggests that focussing on and adapting treadmill running technique might not translate into an adapted overground running technique. Often, the treadmill is used for convenience – climate can be controlled, less space is required - however, using the results of running biomechanics (the way the participant runs) from treadmill tests to generalise about overground running is not useful as they are not shown to be the same (García-Pérez *et al.*, 2013).

Miller *et al*. (2019) reported that runners perceive that treadmill running requires more effort, and so tend to run at a slower pace, adding that if runners are more comfortable to run overground and it is reliable this should be the preferred testing option. Testing overground is supported by Murray, Beaven and Hébert-Losier (2018) who found that the use of treadmills for analysing overground running is impractical and not a true reflection of the real movement patterns in the field. Whilst using a treadmill might prove reliable for analysing gait patterns, this is not where most recreational runners train, decreasing the validity of this approach compared to field work.

Although König *et al.* (2014) examined walking gait patterns, they found that treadmill use affected the temporal rhythm of gait, and introduces prescribed spatiotemporal feedback, that is the stride rate and length is determined by the constant speed of the treadmill, and so the variety of stride rate and length seen when moving overground does not happen. Early research, such as that done by van Ingen Schenau (1980), also suggested that differences between the two conditions can be linked to visual and, possibly auditory, information. Unlike treadmill running, the surroundings move with respect to the runner which could lead to differences in regulation of the movement pattern leading to differences in energy consumption and / or kinematics. Therefore, a further aim of this study is to examine the case for conducting research in the field, not the laboratory.

1.4 The role of running economy in endurance running

The performance of a distance runner is determined by a number of factors - environmental, biomechanical, physiological and psychological. It has been demonstrated that there are three important physiological parameters that can be used as indicators of running performance, namely, $\dot{V}O_{2max}$, lactate threshold and running economy (Joyner and Coyle, 2008). $\dot{V}O_{2max}$ is defined as the maximum rate at which a person can take in and use oxygen. Lactate threshold is the point at which the concentration of blood lactate changes from a linear to an exponential increase as the body can no longer process the lactate as quickly as it is being produced (Joyner and Coyle, 2008). Both these tests have traditionally required a laboratory setting and can be intrusive, as, for example, blood needs to be taken at regular intervals. The third physiological parameter, running economy, is the metabolic cost of running, or the steady-state oxygen consumption at a sub-maximal velocity (60-90% of $\dot{V}O_{2max}$), and has been shown to be a useful predictive tool for endurance events, distances of 5 km or more in highly trained male athletes (Hausswirth and Lehénaff, 2001; Tartaruga *et al.*, 2014). Conley and Krahenbuhl (1980) showed that with athletes of a comparable $\dot{V}O_{2max}$, running economy was credited with a substantial part, 65.4%, of the variation in performance among athletes. Further, running economy has the advantage of being relatively simple to measure, is acceptably reliable and can detect change (Barnes and Kilding, 2015a).

Improving running economy will enable a runner to need less metabolic energy to run at a particular speed, leaving them with more reserves towards the end of a race, or to run faster or further for the same metabolic demands. Notably, of the three physiological factors identified, running economy is the only one that can be improved by introducing biomechanical changes to running technique, as running, it can be argued, is as much of a skill as hitting a ball or scoring a basket, so can be trained (Anderson, 1996; Moore, 2016; Hoogkamer, Kram and Arellano, 2017). However, Hitchings and Latham (2017) found that unlike their well-trained counterparts, recreational runners were less concerned with technique, choosing running as an activity in which there is no 'right or wrong way of doing things' and often opting to run alone, rather than join a running group. Despite this apparent lack of interest in technique, there was evidence to show that recreational runners did seek expert help when injured or replacing shoes and showed an interest in improving how long, fast or far they could run, factors which can be influenced by running economy. This suggests that using biomechanics or aspects of technique to improve their running economy, could be a way to help improve their performance so they can achieve these goals. Folland *et al.* (2017) suggested that technique may account for as much as 39% of variance in running economy.

1.5 Biomechanical factors and their role in running

Arellano and Kram (2014a) suggested that approximately 89% of the metabolic cost of running is down to supporting body weight (74%) (Teunissen, Grabowski and Kram, 2007), forward propulsion and the biomechanical tasks involved. Of the biomechanical factors employed during running, several of them have been identified as modifiable, such as stride length, amount of arm swing and levels of muscle activation during the propulsion phase of the run. Introducing adaptations to some of these factors could help identify an optimal biomechanical running performance to optimise running economy and therefore distance running performance.

There are a number of biomechanical tasks that occur during running that have been identified for their potential impact on running economy, they can be classified as either intrinsic, referring to an individual's biomechanics, or extrinsic, essentially shoes and running surface. Intrinsic factors can be broken down into four main sub-sections: spatiotemporal aspects, which would include stride length and frequency; kinematic or descriptive factors, such as angles at maximal knee and hip flexion; kinetic factors, which look at the forces involved, for example the components of ground reaction force; and finally neuromuscular elements, which are concerned with the various activation levels of the muscle groups (Moore, 2016).

Considering first spatiotemporal aspects, this includes a number of areas that are potentially trainable such as stride length and frequency (gait). The gait cycle is generally accepted as being from initial contact, such as heel strike, to the next contact on the same side (De Asha, Robinson and Barton, 2012). New runners have been shown to self-optimise their gait over a period of 10-weeks for the best running economy without any specific coaching, suggesting that experience is a factor in improving gait, and subsequently running economy, during the early stages of running (Moore, Jones and Dixon, 2012; Moore, 2016). However, mathematically, the optimal has been shown to be this self-optimised distance plus or minus 3% of the preferred gait, with experienced runners ($p < 0.05$) running closer to this than new runners (de Ruiter *et al.*, 2014a).

The next adaptable variable to consider is ground contact time, which involves many biomechanical functions that occur during the propulsion or push-off phase of running, such as changes in angles of hip, knees and ankles, and breaking forces. This suggests ground contact force has, potentially, a big influence on running economy so optimising contact time could be important (Moore, 2016). Little work has been done on the impact of ground contact time on running economy to date, but what has been done has surrounded elite Kenyan runners who have dominated distance running in recent years, and have 10% shorter ground contact time than their contemporaries (Tawa and Louw, 2018). There is, however, conflicting evidence as to whether this has a positive, negative or any effect on running economy (Williams and Cavanagh, 1987; Nummela, Keränen and Mikkelsson, 2007). Tawa and Louw (2018) also identified an increased lean forward in the torso, one of the few postural elements that has been considered and is consistent with others which found a slight lean forward of 5.9˚ to be beneficial to running economy in established distance runners at 13 $km.h^{-1}$ (Williams and Cavanagh, 1987; Barnes and Kilding, 2015a).

Another area for consideration in this area is vertical oscillation and movement of the centre of mass during the swing phase, where there has been little research to date (Moore, 2016). There is conflicting evidence on the impact on running economy; however, several studies have shown that less vertical oscillation does associate with better running economy in trained, distance athletes. Again this has not been explored among recreational runners (Heise and Martin, 2001; Halvorsen, Eriksson and Gullstrand, 2012), but if vertical oscillation is shown to effect running economy in recreational runners, it is a modifiable parameter so can be altered and any changes measured (Moore, 2016).

Related to vertical oscillation are kinematic patterns associated with arm movement as this can impact on the total upper body movement and the degree of oscillation of the centre of mass. To date, there has been little research examining arm swing and its contribution to running economy, although early evidence suggests that arm motion plays a vital role in an individual’s technique (Moore, 2016) and is yet to be explored in recreational runners. Also to be considered are optimal kinematic patterns with greater maximum thigh angles, acute knee angles and plantar flexion during toe-off, all associated with better running economy (Barnes and Kilding, 2015).

Turning to a neuromuscular perspective, there is evidence to link running economy with stiffness in the propulsive leg (Barnes and Kilding, 2015). This has been addressed in a number of studies with resistance training. Altering the level of stiffness in the propulsive leg has been shown to improve economy in runners, including recreational runners, with an effect size of between 0.45 and 1.76, and is designed with the aim of improving muscle strength, power or endurance or to lead to neural adaptations (Balsalobre-Fernández, Tejero-González and Del Campo-Vecino, 2015; Alcaraz-Ibañez and Rodríguez-Pérez, 2018). The aim of incorporating resistance training for a runner, is to increase the strength of the muscle without achieving hypertrophy as this can lead to an increase in body mass, which has a negative impact on running economy. It is widely agreed that initial improvements following strength training are due to neuromuscular adaptations leading to increased recruitment of motor units. However, Johnston *et al*. (1997) suggested that a consequence of strength training is an improvement in biomechanical efficiency and a number of biomechanical variables have been identified to support this.

Strength training can be achieved through plyometric training, which aims to improve a muscle's ability to generate power through exaggerating the stretch-shortening cycle with activities such as jumping or hopping, as these actions resemble the eccentric phase during running (Paavolainen *et al.*, 1999; Turner, Owings and Schwane, 2003). Researchers have suggested that improvements were due to enhanced biomechanical efficiency and neuromuscular characteristics which presented as a shorter stance phase due to increased stiffness of the muscle tendon (Paavolainen *et al.*, 1999; Spurrs, Murphy and Watsford, 2003). The consensus seems to be that 2-3 sessions of plyometric training per week are required alongside running with improvements showing at around the 9th or 10th week (Millet *et al.*, 2002; Fletcher, Esau and MacIntosh, 2010).

Considering all the potential biomechanical variables, this thesis will aim to identify the most significant modifiable biomechanical factors that have an impact on running economy. Then, having determined which factor(s) to investigate further, devise a training programme to manipulate the identified factor(s) and with the aim of improving running economy. For the purposes of this thesis, the study to investigate the impact of manipulating the biomechanical variable is included as a theoretical protocol (Chapter 7), as due to the impact of the Covid-19 pandemic, it was not possible to conduct this further piece of research.

1.6 How technology contributed to the novelty of this research

This section is included to outline the developments in technology which now make this piece of research possible and highlight how this is novel in the field of sports science. To date, there are a number of studies that have examined aspects of biomechanics using three-dimensional (3D) motion capture cameras inside the laboratory, using treadmill running (Handsaker *et al.*, 2016; Fisher *et al.*, 2018). This has been in part due to the limitations of the technology available, since the 3D cameras had to be static so there was no option but to require the participant to be filmed on a treadmill in the laboratory. Additionally, some previous studies have suggested that the mechanics of running inside and outside were similar (van Ingen Schenau, 1980; Riley *et al.*, 2007, 2008). However, due to developments in wireless sensor and wearable technology, it is possible to assess biomechanical performance outside the laboratory using wireless inertial magnetic measurement sensors or units (IMMUs). IMMUs have been shown to have acceptable levels of reliability and accuracy and the ability to measure sport-specific movement (Dellaserra, Gao and Ransdell, 2014; Chambers *et al.*, 2015; Magalhaes *et al.*, 2015; Reenalda *et al.*, 2016). The University of East London has such a system in the form of the Xsens motion capture system and MVN Analyse software. In physiology, there have been advances in ergospirometry, the continuous measurement of respiration and gas metabolism, and the Cosmed K5 has been shown to be a highly reliable piece of portable, wireless technology for measuring oxygen consumption in the field, when compared to a stationary metabolic cart used in the laboratory (Perez-Suarez *et al.*, 2018).

On an individual level, many recreational runners have smart phones, smart watches or similar which have the potential to provide the runner with feedback and information about their running. Tapping into this rich seam of technological advancement is an area which could be explored further to provide assistance to recreational runners.

1.7 Summary

For the purpose of this thesis, considering previously published explanations, running economy is defined as the metabolic cost of running at a consistent, submaximal speed, in a steady state, measured in $ml.kg^{-1}.min^{-1}$. Previous research has showed that there is a clear link between running economy and biomechanics and that there are aspects of biomechanical technique that can be trained to have a positive impact on running economy; even short-term interventions of up to 13 weeks have been shown to yield good results. However, almost all the research to date has looked at elite and well-trained runners, typically running at 16 $km.h^{-1}$, and very little is known about the running patterns of recreational runners. Indeed, a recent study found that not only do many of this cohort run at slower speeds, with up to 25% at a 10.1 $km.h^{-1}$ pace or slower, but they do not always present a clear flight phase (Bonnaerens *et al.*, 2019), suggesting there may be additional biomechanical differences between the two cohorts.

To conclude, much of the work in this field has considered elite and well-trained athletes (Folland *et al.*, 2017), using predominantly laboratory-based tests, due in part to the limitations of the equipment available. Therefore, the rationale for this thesis is that there is a growing population of recreational runners who habitually run outside, with noticeably different gait patterns to elite runners. The unique purpose of this study is to firstly establish whether it is possible to test recreational runners solely in a field environment, then identify which biomechanical changes can have improve running economy in recreational runners when running outside.

Chapter 2: Literature Review

2.1. Introduction

Running has been described as a primal and instinctive activity, and while it might have started as being a necessity for evading predators and finding food, in recent times it is more likely to be done by desire (Spiers *et al.*, 2015). It is well documented that there are manifold physical and mental health benefits to being physically active including reduced risk of high blood pressure, stroke and of developing diabetes, heart disease and numerous cancers, alongside a positive impact on mental health (World Health Organisation, 2020). Running, a fundamental physical movement, is something which is never really taught, but is instinctive. The process of turning energy into movement is possibly the simplest definition of running economy (Folland *et al.*, 2017). Earlier definitions describe running economy as the rate that oxygen is consumed when running at a steady submaximal speed (Conley and Krahenbuhl, 1980; Daniels, 1985).

There are several aims for this literature review, firstly, to look at the recreational running population and how this has been defined in past studies to explain who this population is, why it is of interest and what is the value of investigating this specific cohort. The review will then examine how testing for running economy evolved and the value of doing so as identified by previous studies and the potential benefits for the recreational running population. Following on from this will be a review of previous studies examining running economy and its relationship with biomechanical factors that have been seen to impact on running economy in other running populations. The aim of this process, examining the results of previous work, is to identify gaps in knowledge that exist, which will subsequently inform both the testing methods to be used, and purpose of this thesis.

2.2 Recreational runners and the rising popularity of running

Across the globe, there has been a steady increase in sedentary behaviour in recent decades, due in part to the use of technology in the workplace, home, and for entertainment (Ng and Popkin, 2012; López-Valenciano *et al.*, 2020; Lam *et al.*, 2022). This decrease in physical activity has contributed to a rise in obesity and a subsequent rise in, often preventable, chronic conditions. In response to this, governments have set physical activity targets for their populations to encourage movement. Possibly as a direct consequence of this, there has been an increase in the running population consisting of many recreational runners, for example, the number of parkrunners now stands at over 3 million in the UK alone (parkrun, 2024) and 6.3 million people are regular runners (Sport England, 2022). This large population of recreational runners has so far been under investigated (Cook, Shaw and Simpson, 2016).

Running as a recreational activity in its own right has not always been as ubiquitous as it is now. In 1963 a pamphlet entitled The Joggers Manual, funded by the Oregon Heart Foundation and The US National Bank of Portland, was published to describe a 'new' type of exercise to people (Latham, 2015). It has been attributed as a significant factor in introducing running as a common fitness activity. Prior to this, it was highly unusual for adults to take part in any kind of vigorous exercise outside of their working life. However, medical practitioners were beginning to encourage people to take up jogging as a way to compensate for their increasingly sedentary lives. The pamphlet was written by William Bowerman, a professor of physical education at the University of Oregon, he became involved in the push to encourage more people to take exercise after being approached by Seymour Lieberman in 1961. Lieberman (1961) was concerned about the sedentary behaviour of the population which is linked to the onset of heart disease and other conditions associated with an aging population and was convinced that physical activity was the ideal way to improve people's health and prevent the development of these conditions. Lieberman had described a method of jogging in a pamphlet entitled 'Lieberman's rhythmical jogging' that he believed everyone could achieve, a form of jogging on the spot for five minutes.

While Bowerman was keen to get involved in a project along these lines, his motivation to do this was boosted by a visit to New Zealand in 1963 (Latham, 2015). While there, he met with Arthur Lydiard, a renowned running coach, who had set up the 'Auckland Joggers Club' to encourage middle-aged men to run together and improve their health. Bowerman took this idea back to Oregon where he launched a jogging group of his own, 200 people turned up for the first meeting, rising to 1,500 by the third. At this time, there was little research into the effect of cardiovascular exercise on the health of middle-aged people, most studies had been concerned with children and young adults, with the assumption that older people are on a path of physical decline that can't be halted and there were fears that introducing strenuous exercise could in fact be detrimental to health.

To investigate this further, Bowerman teamed up with a cardiologist, Waldo Harris, to conduct a series of trials on middle-aged, sedentary participants and explore the health implications (Latham, 2015). Alongside this, they developed ways to embed jogging into a person's lifestyle, so they developed jogging as a regular habit. This led to their 1966 publication, "Jogging: A physical fitness programme for all". The first edition alone sold over one million copies. In it, they outlined how to become a successful jogger, emphasising the simplicity, accessibility, and benefits of adopting such a habit, encouraging people to jog wherever they could, that there was no need for a track. The success in part relied on the fact that being able to run is a skill that is almost universal, something that the vast majority of people learn to do as children through play, so that ability to run is embedded. The positive reputation of Bowerman helped spread the popularity of running as a recreational fitness activity around America, for example, in 1968, the Chicago Tribune ran a piece entitled 'Jogging: the newest road to fitness'.

A similar story was being told across Europe, where, prior to the 1960s, running was an activity almost exclusively done by professional athletes, in competitive sport. However, in the 1960s, governments across the continent began to see sport as a vital part of their health and welfare policies (Bottenburg, Rijnen and Sterkenburg, 2005). Organised running events began to appear; Germany held its first in 1963, Finland in 1966 and in 1969, Denmark launched the 'Eremitageløbet', an event that is still going (Breedveld, Scheerder and Borgers, 2015). Breeveld, Scheerder and Borgers (2015) suggest that improvements in living conditions alongside increases in wealth and leisure time contributed to a rise in recreational activity and encouraged governments in the Netherlands, Germany and Hungary to launch running for health campaigns in the 1960s and '70s. Around this time, there was a flurry of running books and the launch of the magazine 'Runners World'; in fact running was becoming so popular that it was pronounced the 'sport of the 1970s' by the Chicago Daily Herald (Scheerder, Breedveld and Borgers, 2015).

Since that first boom in the 1960s and ‘70s, the popularity of running has continued to grow steadily, with an ever-increasing number of mass participation events, the advent of running apps such as Couch to 5k, opportunities for companies to market shoes, clothing and specialist products, alongside government guidelines for recommended levels of activity, all help to push the growth of the sport (Scheerder, Breedveld and Borgers, 2015).

It is likely that the increasing visibility of parkrun, a free, weekly, timed event has contributed to the growth in recreational runners. This is becoming true across the world, parkrun has expanded from a single event in Bushy Park, London, UK, to now hosting events in 22 countries, from New Zealand to the USA with ever more venues, in ever more countries being added. The mixed ability event sees runners completing the 5 km distance in under 17 minutes to those who are closer to an hour. The opportunity this provides for recreational runners was highlighted in the wake of the Covid-19 pandemic when the UK cabinet ministers responsible for communities and culture wrote to local authorities and landowners to urge them to reinstate their local parkruns (Wills, 2021). After each parkrun event, all registered parkrunners receive the time for that day’s run within hours of completion and all results are available to see online, enabling runners to track improvements or changes.

The current number of registered parkrunners is approaching three million in the UK alone (parkrun, 2021) and the latest figures from Sport England suggest that 25% of the population ran in the past year (Sport England, 2022). Further, in the wake of Covid 19 restrictions in the UK, which denied people access to gyms and other facilities, there was a rise in people who took up or returned to running, many of whom pledged to continue to do so (ASICS, 2020; Macmillan Cancer Support, 2021).

There has been some discussion in the literature as to how to define recreational runners to differentiate them from trained runners. Some researchers have chosen to adopt boundaries for $\dot{V}O_{2max}$ as their chosen differential (Pauw *et al.*, 2013; González-Mohíno *et al.*, 2020). However, this involves either testing before selection, which would involve additional demands on the participant, who, after testing, may or may not be selected depending on their result, or a reliance on a participant’s fitness app or device such as Fitbit or Garmin. To remove the need for pre-testing, other researchers have chosen to define recreational athletes by the weekly distance they run (3.4 ± 2.8 km), the number of times a week they run (2-5), or leave the reader to assume that a non-elite athlete is a recreational runner (Chapman *et al.*, 2008; Ferrauti, Bergermann and Fernandez-Fernandez, 2010; Ache-Dias *et al.*, 2018). The consensus seems to be that anyone who runs, simply because they want to, even for fun, and not necessarily for any competitive reason, can be classed as a recreational runner (Barnfield, 2016; Roessler and Muller, 2018). For example, recreational marathon runners have been described as those who run for non-competitive reasons, for the marathon distance, have completed at least one marathon, but not qualified for champion classification based on age-adjusted times (Buman *et al.*, 2008). To qualify for champion classification, runners will have needed to complete a marathon within a time specified by the event organiser, for example, in 2024 a female runner would have had to run a marathon in under 3:14:00 to qualify for the London Marathon in the championship category (TCS London Marathon, 2024). Age-adjusted times use a method devised by World Masters Athletics, this method compares the running time of a person to the world record for a person of that age, for example, if a 53-year-old woman runs 10 km in 45:18, this is compared to the world record of a woman of that age, 35:01, divide 35.01 by 45.18 to give an age-graded result of 77.3%. For this thesis, a recreational runner has been defined as someone who is not an elite runner, runs for the purpose of pleasure and / or fitness, can run 5 km or more, and runs at least once a week.

Despite there being a large population of recreational runners, 6.3 million people claim to run on a regular basis in England alone (Sport England 2024), to date most quantitative research has focussed on elite highly trained runners and how they can change to improve (Cook, Shaw and Simpson, 2016). However, if the aim is to encourage recreational runners to change their running technique to improve their running economy, then an understanding of recreational runners’ attitude to training would be useful so as to determine how best to address the possibility of training to change technique (Hitchings and Latham, 2017). For example, unlike elite runners, recreational runners were less concerned with technique, choosing running, in part, because it is an activity in which there is no ‘right or wrong way of doing things’ and often opting to run alone, rather than join a running group. Despite this apparent lack of interest in technique, there was evidence to show that they did seek expert help when injured or replacing shoes and showed an interest in how long, fast or far they could run (Hitchings and Latham, 2017). This suggests that the findings of this thesis, linking biomechanics or aspects of technique to such an outcome, could be a way to encourage runners to improve their speed, distance run or duration of run through improved running economy, which would match the desire of runners to run faster, further or for longer as identified by Hitching and Latham (2017).

2.3 Running economy as a performance indicator

Athletes and coaches at elite level have been using laboratory based tests to assess physiological determinants associated with endurance performance, including running, for some time (Hollmann, 2001; Amann, Subudhi and Foster, 2006). The main tests typically carried out are: the lactate threshold, the point at which there is a progressive increase seen in blood lactate levels; $\dot{V}O_{2max}$, the maximal amount of oxygen that a person can take up; and running economy, defined as the oxygen cost of running in a steady state and at a constant speed (Jones and Carter, 2000; Joyner and Coyle, 2008; Tam *et al.*, 2012). It has been established that running economy is a more reliable parameter for predicting performance when considering athletes with a similar $\dot{V}O_{2max}$ (Conley and Krahenbuhl, 1980; Saunders *et al.*, 2004). Additionally, it is also noteworthy that running economy is the only performance indicator known to be directly impacted by biomechanical changes (Hoogkamer, Kram and Arellano, 2017).

Running economy has been relatively under-researched compared to other physiological variables until recently (Foster and Lucia, 2007; Barnes and Kilding, 2015b), even though its importance was recognised in the 1970s (Foster and Lucia, 2007; Barnes and Kilding, 2015b). Early research began to identify running economy as means to differentiate between elite and highly trained athletes. Conley and Krahenbuhl (1980) looked at 12 highly trained, experienced distance runners of similar ability, found that 65.4% of difference in their 10k running time could be attributed to differences in their running economy. Their mean and standard deviation for 10 km running time was 32.10 ± 1 min. They define running economy as the steady-state oxygen consumption for a given running speed, and there is a great deal of variety among trained athletes. This group were similar in $\dot{V}O_{2max}$, running speed and physical characteristics. Running economy becomes important when comparing athletes when it is established that they have similar $\dot{V}O_{2max}$, although for the purpose of this thesis, the interest in running economy is the potential for recreational runners to run faster, further or for longer if they can improve their running economy.

Following on from the work of Conley and Krahenbuhl (1980), the concept of running economy was further developed with it being described as the relationship between $\dot{V}O_2$ and velocity (Daniels, 1985). Subsequently, the focus has moved to studying running economy given that research has identified running economy as having a strong association with race performance and has been shown to be a better parameter for predicting performance than $\dot{V}O_{2max}$ at elite level (Saunders *et al.*, 2004). Saunders *et al.* (2004) suggested that it might be easier to improve running economy and subsequently performance in untrained or moderately trained athletes. This could manifest itself as an improvement in distance run, time taken or speed at which the runner can comfortably run. For example, if a runner records a running economy of 208 $ml.kg^{-1}.km^{-1}$ at a steady speed of 12 $km.h^{-1}$, it will take 5 minutes to cover 1 km, requiring 41.5 $ml.kg^{-1}.min^{-1}$. If running economy could be reduced 190 $ml.kg^{-1}.km^{-1}$, the requirement for O_2 would reduce to 38 $ml.kg^{-1}.min^{-1}$ to run at the same speed, leading to a considerably reduced energy requirement to maintain this pace, enabling any reserves of energy to be kept for later in the run.

Training levels can have an impact on running economy, Barnes and Kilding (2015a) produced a guide to expected running economy at varying abilities and speed (Table 2.1).

Table 2:1: Normative running economy for varying abilities.

Runner Classification	**Speed $km.h^{-1}$**	**Male mean (range)** Running economy $ml.kg^{-1}.min^{-1}$	**Female mean (range)** Running economy $ml.kg^{-1}.min^{-1}$
Recreational	10	36.7 (35.4-38.8)	37.7 (32.8-42.6)
	12	42.2 (40.4-45.3)	43.2 (38.5-48.1)
	14	47.4 (46.0-49.5)	47.3 (40.1-51.9)
Moderately trained	12	40.7 (37.4-48.1)	41.9 (28.9-41.7)
	14	46.8 (42.0-55.5)	47.9 (41.3-53.5)
	16	51.4 (51.6-62.3)	52.9 (45.7-61.0)
Highly trained	12	n/a	41.3 (33.3-50.2)
	14	45.0 (32.4-56.5)	48.3 (39.0-56.7)

	16	50.6 (40.5-66.8)	54.5 (46.2-61.9)
	18	58.1 (48.0-72.0)	58.6 (54.4-67.1)
	20	66.5 (65.7-71.6)	n/a
Elite	14	39.9 (36.1-44.5)	41.9 (38.7-46.9)
	16	47.9 (43.2-53.4)	48.9 (45.1-55.8)
	18	55.9 (50.5-62.3)	56.1 (51.8-63.8)
	20	63.91 (57.5-71.2)	n/a

Table adapted from Barnes and Kilding (2015a).

Much of the discussion around running economy and improving it focuses on elite runners, where shaving seconds off a time can make the difference between as much as a first and last place in a race. However, whilst recreational runners are not necessarily looking to shave tiny margins of time off their running, any improvement in running economy could be seen as an improvement in time taken, which can be seen, for example, in a parkrunner's record where they receive the time for that day's run within hours of completion and all results are available to see, enabling runners to track improvements or changes.

Shaw, Ingham and Folland (2014) questioned whether running economy, which measures solely the oxygen cost of running, is a true reflection of the energy cost of running as it does not include any variations in other substrate contribution to energy. The participants in the research conducted by Shaw, Ingham and Folland (2014) were described as highly trained and were required to run on a treadmill at a variety of different paces. However, for the purposes of this thesis, the runners will be running at one pace in a steady state, so determination of running economy from a solely oxygen usage would appear to be acceptable.

2.4 The value of outdoor, overground running compared to indoor, treadmill running

2.4.1 Introduction

Historically, it is common practice for research into running performance to be conducted in a laboratory setting with participants running on a treadmill. This is often considered a convenient way of performing tests due to the ability to control many environmental variables such as climate, as well as keeping the speed and gradient constant (García-Pérez *et al.*, 2013). One immediate disadvantage of this is the lack of portability, so the participant is restricted to travelling for testing at a fixed location and during laboratory hours. When aiming to test large numbers of recreational runners – for whom running is an exercise activity and not a job – this has the potential to limit the numbers who could potentially participate due to them not being available when the laboratory is open. Although it might be possible to change laboratory hours, this maybe outside of the control of the researcher. Secondly, as discussed earlier, recreational runners habitually run overground and often rarely, if ever, on a treadmill, which questions the real-life application of findings from treadmill research to overground running and therefore the suitability of testing a participant on a treadmill. There is some evidence to suggest that treadmill running can be stressful and impact negatively on physiological responses (Ekkekakis, 2009).

One proposed explanation for any variation in biomechanical or physiological performance between the two conditions is the different auditory and visual information received in each case (van Ingen Schenau, 1980). Unlike treadmill running, when running overground the surroundings move with respect to the runner which, it is suggested, leads to differences in regulation of the movement pattern leading to differences in energy consumption and / or kinematics (van Ingen Schenau, 1980). Other research points to the difference in ground reaction forces for the two conditions, and that given this, it would be expected that there should be differences in kinematics, joint kinetics and muscle activation (Van Caekenberghe *et al.*, 2013).

It is worth noting that treadmill surfaces have no standardised criteria among sports international federations, so observations reported from the findings on one treadmill may in fact be different if conducted on another (Colino *et al.*, 2020). To reach these findings, the researchers assessed 77 treadmills, 30 artificial turf pitches and 30 track and field pitches using an advanced artificial athlete to test the mechanical properties of the various surfaces. They noted that not only were the mechanical properties of the treadmills not consistent with each other, but were sufficiently different to overground running conditions including concrete or asphalt to suggest that applying results from treadmill data to overground would be flawed.

2.4.2 Physiology implications of treadmill versus overground running

One of the first researchers to investigate the metabolic differences between motorised treadmill and overground running had a different group of runners in each condition, with small groups of four and seven respectively, and attributed the difference - about 8% - to wind resistance (Pugh, 1970). It has been suggested that the movement of the treadmill itself, which, during the stance phase, brings the leg back under the runner's body, reduces the amount of energy needed for propulsion (Frishberg, 1983). Frishberg's study (1983) reported a greater oxygen debt, 36%, at the end of an overground sprint compared to the treadmill. Again, this study used a small number of participants, five college sprinters, so it is questionable whether the finding that treadmill running has a lower energy requirement is applicable to the recreational running cohort at a 5 km running paces.

Similar results were found in a study of elite and recreational runners, who ran at a variety of speeds overground and on a treadmill. They found that in all but two speeds, 11 and 12 $km.h^{-1}$, the metabolic cost of running overground was greater than on the treadmill (Aubry, Power and Burr, 2018). However, these were the lowest of the running speeds tested and at the higher end of the range seen in more general recreational running population. Further there is no mention of an incline in the treadmill running surface, although it is confirmed that the overground surface was flat.

In an effort to make results for running economy more comparable between treadmill and overground running, Jones and Doust (1996) conducted a study to see whether adjusting the incline of a treadmill has the same impact as air resistance does when running outside, specifically on a flat course. The runners carried out a number of trials at speeds ranging from 2.92 $m.s^{-1}$ to 5 $m.s^{-1}$ (10.51 $km.h^{-1}$ to 18 $km.h^{-1}$) and at a variety of gradients in six minute stages with running economy determined for the final two minutes of the trial.

Jones and Doust (1996) determined that at the lower speeds, 2.92 $m.s^{-1}$ and 3.33 $m.s^{-1}$ (10.51 $km.h^{-1}$ and 11.99 $km.h^{-1}$) and for a duration of five minutes, $\dot{V}O_2$ was not significantly different from outside running if the gradient was set at 0% or 1%. However, across all the speeds tested, a 1% incline was shown to be a reliable method to replicate outdoor running. Whilst many studies have subsequently adopted this practice of inclining the treadmill to 1% in the methodology, it should perhaps be considered with caution. The population studied consisted of nine men, 24.9 ± 5.2 years, described as trained runners who were fully used to indoor treadmill running and an above average $\dot{V}O_{2max}$. This is not equivalent to a recreational running population who run at speeds of 2.22 $m.s^{-1}$ (8.0 $km.h^{-1}$), are unused to treadmill running and have a much greater variation in age.

Finally, testing recreational runners running overground has greater ecological validity than testing on a treadmill as it more accurately represents the circumstances in which recreational runners habitually run, i.e. outside and overground.

2.4.3 Biomechanical considerations when comparing overground and treadmill running

In some ways, treadmill running could be considered advantageous for gait analysis as it enables continuous monitoring at a steady state which is the best way to observe a runner's gait. However, changes in the running pattern, in part due to treadmill running leading to a more secure gait selection, can be seen between the two conditions (Dugan and Bhat, 2005). Whether using treadmill data is appropriate has been particularly questioned for kinematic parameters and the need for conducting research in a sport specific setting is paramount to recording valuable data (Reenalda *et al.*, 2016).

The suggestion that it was unwise to apply treadmill results to overground running had previously been suggested by Kachouri *et al*., (1996), who argued that applying data collected during treadmill trials to overground running was not good practice, as assumptions that running biomechanics across the two conditions were ill-founded. Although the sample size in the research conducted by Kachouri et al. (1996) was small (seven participants), they were described as trained runners, suggesting that they had an established running technique.

Murray, Beaven and Hébert-Losier (2018) looked at outdoor running, they considered the use of treadmills for analysing overground running to be impractical and not a true reflection of the real movement patterns in the field. They add that whilst using a treadmill might prove reliable for analysing gait patterns, this is not where most recreational runners train, decreasing the validity of this approach compared to field work. Their study comprised 28 recreational runners with an average running pace of ≤ 2.67 m.s^{-1} and at least a year's running experience, suggesting a competent but not elite running population. Murray, Beaven and Hébert-Losier (2018) found that analysing their chosen parameters of gait data, foot-strike angles and foot-strike patterns, from an overground performance was sufficiently reliable, with agreements of 99.4% (95% CI 97.4, 99.9). However, the dimensions under investigation were measured with a static camera, over a distance of 15m, during which the runners were asked to run at their perceived race pace. Firstly, this allows only a small number of gait cycles to be captured for analysis, and velocity was not controlled, but left to the athlete's sense of how fast they were running, which is important as there are biomechanical changes such as stride length, rate and angles at hip, knee and ankle, as velocity changes. One argument for conducting research overground is that while it is easy to control speed on a treadmill, when running overground, people will naturally speed up or slow down to react to conditions in the road, so choosing to research overground will provide more ecologically valid data than treadmill research.

The findings of Murray, Beaven and Hébert-Losier (2018) support earlier work which found that running biomechanics vary between the two conditions of overground and treadmill running (García-Pérez *et al.*, 2013). García-Pérez *et al.* (2013) studied a group of 27 participants, running at 3.33 m.s^{-1} and 4.00 m.s^{-1}, considered achievable speeds for recreational runners, on both a treadmill and overground. They reported differences in the biomechanical behaviour of the runners between the two conditions, notably, when running on the treadmill, there was an increase of ground contact time of 7.7% for the lower speed and 9.91% for the higher. They argued that if the researcher is trying to use the results from one condition to generalise about the other, this is difficult if they are shown to produce different results. Whilst this study claimed that the running speeds used were typical of recreational runners, this thesis will explore the wider recreational running field, who do not generally achieve these speeds, 2.22 m.s^{-1} to 2.78 m.s^{-1} are more commonly found. The primary claim of this study, that the speeds were used in previous research, should not mean that they are applied to the wider running community as early studies were conducted with highly trained, fast endurance runners.

Differences in the relationship between the variables stride length, stride rate and velocity have been found between treadmill and overground running. For example, Bailey, Mata and Mercer (2017) found a difference in changes of stride length between treadmill and over ground running with a statistical significance of $p = 0.031$. The study described the participants as being physically active, capable of running at a range of different velocities, but not specifically runners. This, although somewhat vague, could be a argued to be a good fit with recreational runners. However, this study looked at ten participants, all mostly young (22.3 ± 2.6 years), with seven pairs of speed matched trials over a distance of 100m. This is limited compared to the potential offered by this thesis - being able to test a large number of participants for a potentially unlimited period of time at a steady velocity. However, that a difference in stride length between treadmill and overground running over this short distance was found suggests that exploring this further over a longer distance could support the rationale for exclusively testing overground in a recreational running population.

Variations in ankle, knee and hip flexion and extension between treadmill and overground running have partially been explored. Whilst no difference could be found in the range of motion in the ankle and knee ($p < 0.05$), it was not possible to report the results for the hip due to obfuscated markers on the hip (Pink *et al.*, 1994). A point to take from that study is that there should be an advantage to using the MTw Awinda trackers - the inertial measurement units (IMUs) which are attached to the body to measure biomechanical parameters and relay directly to a computer - in that the chance of obfuscation is removed.

Differences in vertical oscillation have been observed between the two conditions, with significantly less movement found in treadmill running, 13.8 ± 2.8 cm compared to 11.2 ± 1.3 cm ($p < 0.05$) at a slower pace and 14.1 ± 2.4 cm compared to 10.7 ± 2.2 cm ($p < 0.05$) at a fast pace (Pink *et al.*, 1994). This was explained by slight, non-significant, decrease in flexion in each of the hip, knee and ankle joints, which cumulatively decreased the vertical displacement.

Finally, as with physiological testing for recreational runners, running overground has greater ecological validity than testing on a treadmill as it more accurately represents the circumstances in which recreational runners habitually run, i.e. outside and overground.

2.4.4 Running velocity on treadmill and overground

Peserico and Machado (2014) found that in trials comparing overground and treadmill running, when the participants, 18 male recreational runners, were unaware of their running velocities, they naturally ran faster overground ($p=0.001$). This study supports the findings of Kong *et al.* (2012) whose study of 7 participants, having run at a self-selected pace overground, then ran at a velocity on average 27.1% slower (3.99 ±0.78 $m.s^{-1}$ and 3.80 ± 0.74 $m.s^{-1}$ in the two overground trials and 2.73 ± 0.62 $m.s^{-1}$ on the treadmill) when asked to replicate their run on a treadmill at what they perceived to be the same speed. Given that we know different speeds demand different energy costs in an individual, it suggests that the speed needs to be controlled in order to ensure that the study is comparing like with like across different trials. It is worth noting that whilst the data was collected during a nine-minute period on the treadmill, only two sets of 4.9m over overground data capture was taken, which may be considered sufficient for considering speed perception, but is perhaps questionable when trying to make comparisons of gait analysis between the two conditions, however, Kong *et al.* (2012) were not considering gait analysis in their study.

Therefore, if participants are to run at their preferred running speed, so that they run with the same biomechanical profile that they would normally display, the findings of Kong *et al*. (2012) suggest that they might find it harder to maintain the speed on a treadmill as they would ordinarily choose to go slower than their overground speed. Therefore, the overground speed should be the one adopted as this is the pace they usually run at. Variation between speeds overground and on the treadmill were also noted when asked to run a maximal pace, which the participants believed to be the same, again differences were seen with average maximums of 3.92 $m.s^{-1}$ and 4.41 $m.s^{-1}$ achieved respectively (Bailey, Mata and Mercer, 2017).

These results lend support to the case for using a method to ensure a consistent pace for the runner during the overground testing, to ensure the velocity in the trial matches that of the treadmill test. This is important as to compare running economy across the two conditions, the same velocity needs to be maintained for each individual. Previous studies have employed various ways to ensure participants maintain a steady pace including the use of acoustic signals matched with cones indicating the rate and using a pacemaker (Kachouri *et al.*, 1996; Finni *et al.*, 2003; García-Pérez *et al.*, 2013). For the purpose of this thesis, a cyclist was chosen to take this role.

To summarise, taking all these factors into consideration, it would suggest that from a running economy perspective, it would be more beneficial to conduct research overground when studying people whose habitual running environment is outside as the research will be more ecologically valid. It could be argued that depending on which biomechanical variables are being considered there may or may not be any difference between the two conditions. However, given that both running economy and biomechanical characteristics are being considered, the ecological validity of overground rather than treadmill running has a stronger case. Further investigation will be given to this in Chapters 4 and 5.

2.5 Determining length of running trial and speed of trial

It has become established practice to use a set trial length of at least 3 minutes and up to 5 minutes when measuring running economy in steady state. For example, Barnes *et al.* (2013) used 4-minute stages and calculated the running economy as the mean $\dot{V}O_2$ during the final minute of each stage. This is because the participant is believed to have attained steady state, when the respiratory exchange ratio (RER), the volume of CO_2 exhaled divided by the volume of O_2 inhaled, remains less than one (Barnes and Kilding, 2015). This can be seen when the participant's breathing rate has settled into a regular pattern to maintain a consistent speed. It is during this period of steady state running that running economy is measured. Whilst the participants in their trials were not elite runners, they are described as 'well-trained', which although can apply to recreational runners, the average 5 km running speed of their 12 participants was 18.18 km.h^{-1}, which is outside the ability of most recreational runners. Therefore, it is necessary to examine further whether recreational runners can achieve steady state in the same time period.

Jones and Carter (2000) reported that runners are generally most economical when running at their usual running velocity; however, they did not specify the running population considered or whether this applies to all runners. Thus, studies where the participant selects their own pace may have more external validity than those conducted under laboratory conditions when studying people running in their habitual running style and environment (Szabo and Ábrahám, 2013).

García-Pérez *et al.* (2013) recruited 27 recreational runners in their study comparing overground and treadmill running and imposed running speeds of 12.0 and 14.4 km.h^{-1} on their participants as they were identified as typical speeds for recreational runners. However, this seems to be closer to the testing range of more highly trained runners as, for example, Bonnaerens *et al.* (2019) noted that in 5 km running events, half the male participants recorded an average speed of between 10.1 and 13.0 km.h^{-1}, with a further 25% averaging slower speeds than this and a further 5% attaining speeds slower than 8.1 km.h^{-1}. This suggests that trying to be prescriptive and comply with the same running speeds tested in running economy research among elite runners, typically 12, 16 and 20 km.h^{-1}, excludes a large proportion of the 5 km running population.

2.6 Factors affecting running economy

Numerous factors have been identified as having an impact on running economy; some cannot be altered by training, such as genetics, gender and anthropometrics. However, Barnes and Kilding (2015b) expanded this group of factors (genetics, gender and anthropometrics) to include additional, modifiable factors, as illustrated in Figure 2.1.

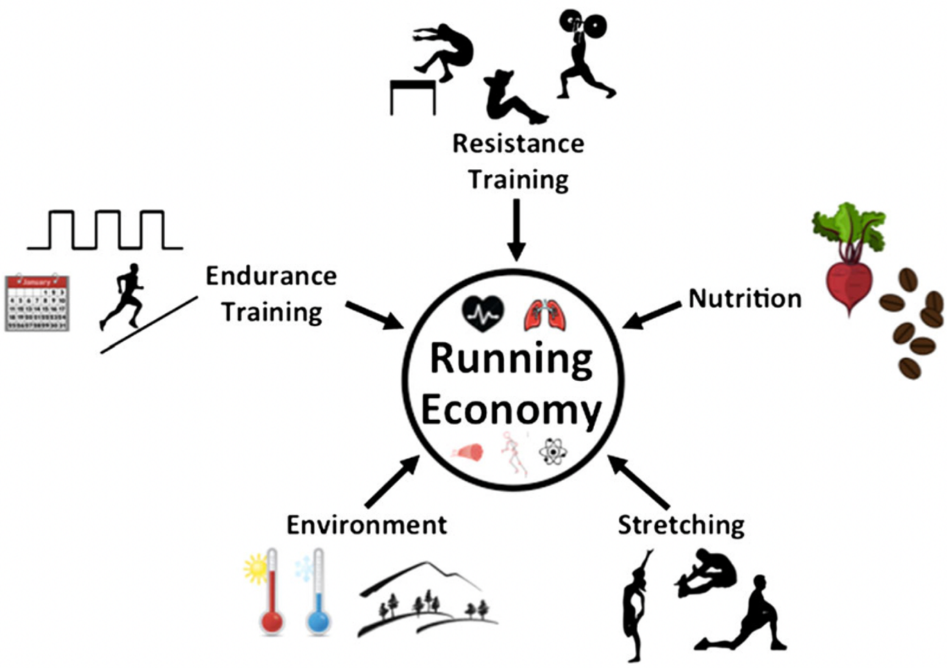


Figure 2.1: Suggested strategies to improve running economy (Barnes and Kilding, 2015).

While Barnes and Kilding do not explicitly mention running biomechanics in their schematic, they discuss the impact that resistance training has on running style, by improving biomechanical efficiency. Further, they lend support to a hypothesis that a runner's biomechanical traits can influence their running economy. However, in another piece of work, Barnes and Kilding (2015a) identified areas of biomechanical efficiency which could impact on running economy, all of which have modifiable components: running style, gait patterns, kinematics and flexibility.

2.7 Biomechanics and the relationship with running economy

The question of how to improve running economy in a recreational running population will now be considered. Of all the physiological determinates of running performance, $\dot{V}O_{2max}$, lactate threshold and running economy, it is only running economy that can be directly modified through biomechanical improvements and improving running economy increases the maximum sustainable velocity (Hoogkamer, Kram and Arellano, 2017). It is known that running kinematics change with speed (Folland et al., 2017) and running economy is speed specific so this suggests it is necessary to research both factors at a consistent speed. Previous studies have shown that over a long period of time, physiological improvements can increase running economy by as much as 15%; however, once this level is reached, no further improvement is seen just from running regularly alone and further intervention is necessary (Moore, 2016). Indeed, if a runner already has a high level of fitness, little change in running economy will be seen with a purely physiological training pattern (Moore, 2016).

High intensity running has been considered as a factor in improving running economy, however, a previous study has shown that any benefits might be lost when this is done more than twice a week (Foster and Lucia, 2007). One area of research that is emerging as a potentially beneficial way of improving running economy is its link with the biomechanics of running. A number of lower limb kinematics have been studied to explore their relationship, if any, with running economy. Areas investigated have included: flexion and extension of hip, knee and ankle joints; angular velocity at these joints at various points in the gait cycle; vertical oscillation of the centre of mass (Moore, 2016).

As part of the gait cycle, a link has been found between stride length, stride rate, step count and running economy. Participants, running at 3.4 $m.s^{-1}$, with average step count of 165 ± 4.5 $steps.min^{-1}$ saw a 14.1% ($p < 0.05$) fall in their oxygen consumption when they increased their step count to 179 ± 1.4 $steps.min^{-1}$. Similarly, at 3.8 $m.s^{-1}$, increasing the step count from 170 ± 4.9 $steps.min^{-1}$ to 180 ± 3.3 $steps.min^{-1}$ resulted in an 8.7% ($p < 0.05$) decrease in oxygen intake (Quinn *et al.*, 2021). In each case there was also a reduction in stride length, by 0.09 ± 0.03 m and 0.07 ± 0.04 m, respectively, which was expected as the velocity remained constant. However, in both trials, testing was carried out on the treadmill, as was the series of training sessions when participants ran with the aid of a metronome to set the pace. While these results are really promising in terms of improving running economy, it would be of interest to ascertain whether the same benefits could be found in a slower, recreational running population with both training and testing overground.

Another area of interest has been to consider vertical oscillation, it seems logical to argue that reducing the amount of vertical movement, which doesn't propel the body forward, will result in an improved running economy. It has been reported that increasing vertical oscillation can have a positive impact on running economy, with increases of up to 19% (Tseh, Caputo and Morgan, 2008). Halvorsen, Eriksson and Gullstrand (2012), testing a group of highly trained runners, showed the potential that reducing vertical displacement could have on running economy. However, only one participant, from the 16 taking part, showed an improvement in running economy by reducing vertical oscillation. They suggested that positive effects from altering vertical oscillation may take some time to achieve as their work entailed participants take part in seven 5-minute trials during one session, when they received verbal and visual feedback. It should also be noted that the sessions all took place on a treadmill and used national competition level male runners, running at 16 $km.h^{-1}$.

Range of motion and angles at the hip, knee and ankle have also been considered in relation to running economy. There is the suggestion of a relationship between the range of motion of the knee and hip and running economy, with less knee or hip extension during the stance phase of running contributing to a lower running economy (Pizzuto *et al.*, 2019).

There are some factors which are part of a runner's biomechanical traits which cannot be altered as they are directly the result of anthropometrics, such as lever (limb) lengths (Knechtle, 2014). However, there are particular biomechanical characteristics which pertain only to endurance running that have been identified, which seem to be absent when compared to other endurance sports. This suggests that specific characteristics could be investigated with respect to running economy (Alcaraz-Ibañez and Rodríguez-Pérez, 2018).

2.8 Modifiable biomechanical factors

In order to assess the impact changing a biomechanical parameter has on running economy, it needs to be established that a particular parameter can be manipulated using some form of intervention. For the purposes of this thesis, the focus is on those such parameters, namely, vertical oscillation, stride length and rate, and the angles of hip, knee and ankle.

Taking the first of these, the vertical oscillation of the centre of mass, the theory is that by lowering the range of vertical displacement of the centre of mass, there would be a consequential improvement in running economy as the runner has to do less work to challenge gravity so there is a lower metabolic cost (Slawinski and Billat, 2004). It has been shown that vertical oscillation is modifiable using a range of visual and auditory cues, with reductions of up to 21.7% reported (Eriksson, Halvorsen and Gullstrand, 2011; Halvorsen, Eriksson and Gullstrand, 2012; Adams *et al.*, 2018).

Stride length and stride rate are interrelated and together determine the running speed, meaning that an increase in one will cause a decrease in the other. Runners are believed to naturally adopt a stride length and rate that optimises running economy known as self-optimisation (Moore, Jones and Dixon, 2012). This process of self-optimisation was observed in a group of 10 complete beginner female runners (age = 34.1 ± 8.8 years) who went through a 10-week programme from no running at all to a point where they could run continuously for 30 minutes, similar to the Couch to 5k method of training. There was a significant improvement across the group in running economy (from 224 ± 24 to 205 ± 27 $ml.kg^{-1}.km^{-1}$) (Moore, Jones and Dixon, 2012). However, these women were starting from a point of no prior running experience and little sporting activity to speak of. It is unclear whether the improvement seen here in their running economy

(Moore, Jones and Dixon, 2012) is down to a naturally optimised running stride length, or just that they had taken up exercise and that itself led to an improved running economy. It is documented that starting any kind of exercise programme will improve running economy so further testing would need to be done to establish if there is a link. For this thesis, the plan was to recruit participants who were existing runners, so their running economy will already have reached a certain level through exercise alone, so any improvements in running economy seen, would be due to a biomechanical change. This would have been done using an experimental group who performed an intervention aimed at adjusting an element of their biomechanics to improve their running economy and comparing this with a control group who did not perform the intervention.

It has been shown that stride frequency - and therefore stride length - can be adjusted in more experienced recreational runners (Sellés-Pérez *et al.*, 2022). Their study took 12 regular recreational runners, split into a control group and an experimental group. For six weeks, the experimental group ran accompanied by music with a constant beat that was 10% greater than their current running cadence. At the end of the programme, there was a statistically significant increase in the stride frequency ($p = 0.002$) in the experimental group. This work follows a study with well-trained runners, running at speeds of 3.4 and 3.8 $m.s^{-1}$, who were able to increase their stride frequency by up to 7%, and so reduce stride length by approximately 3.7%, with a resultant drop in O_2 consumption of approximately 11% ($p < 0.05$) (Quinn *et al.*, 2021). While it is useful to know that stride frequency is modifiable over a short period of time, it would be necessary to know whether there are longer term adaptations in the participants, and whether if, for example, in the absence of music, they would return to their previous running pattern.

Further areas of biomechanical consideration are the spatiotemporal and kinematic parameters. Folland *et al.* (2017) studied 97 participants over a range of speeds to look at a number of different kinematic and spatiotemporal parameters that are also considered in this thesis: centre of mass oscillation, angles of flexion and extension of the knee. While the respiratory gas data was collected throughout the testing period, the biomechanical data was obtained from a 15-second period, 30 seconds into the stage of running which enabled 10 gait cycles to be studied using a fixed motion capture system. The most impactful of the variables on running economy related to stride length and stride rate. They recorded an average stride rate of 83.4 ± 5.37Hz and a stride length (normalised to height) of 1.28 ± 0.080 m, and recorded a correlation of 0.444 ($p < 0.001$) with running economy. While this study lends support to the examination of stride length in relation to running economy, it is worth noting that the cohort contained a number of elite runners (30% of those studied), the work was conducted on a treadmill at set speeds of 10, 11 and 12 $km.h^{-1}$, with the biomechanical data captured after 30 seconds of running, at which point the runner would not have achieved steady state for that speed (Folland *et al.*, 2017). The methods adopted for this study allow for a longer period of data collection in an overground setting at a pace of the participants' choosing.

Resistance training has been shown to improve running economy in runners (Johnston *et al.*, 1997; Paavolainen *et al.*, 1999; Alcaraz-Ibañez and Rodríguez-Pérez, 2018), including recreational runners and has been designed with the aim of improving muscle strength, power or endurance or to lead to neural adaptations. The aim is to increase the strength of the muscle without achieving hypertrophy as this can lead to an increase in body mass, which has a negative impact on running economy. It is widely agreed that initial improvements following strength training are due to neuromuscular adaptations leading to increased recruitment of motor units. However, Johnston *et al.* (1997) suggested that a consequence of strength training is an improvement in biomechanical efficiency and a number of biomechanical variables have been identified to support this.

Having established that it is accepted that biomechanical factors impact on running economy, it is vital to consider the possibility of whether these factors can be altered through a training or intervention programme, i.e., are modifiable in some way. There does need to be some degree of caution taken as encouraging runners to alter their gait significantly from their usual pattern can have a negative impact on running economy (Tseh, Caputo and Morgan, 2008).

2.9 The role of technology in developing understanding

This section looks at advancements in technology which have led to the possibility of being able to conduct this research, running outside, overground in the field with recreational runners rather than being restricted to laboratory conditions. It is the development of this equipment that has enabled this novel study to take place so as to more accurately represent the recreational runners more usual running experience.

2.9.1 Physiology data capture

Over the past few years, there has been an increase in the technology available for testing physiological parameters such as energy expenditure. This includes the development of COSMED's K5 (COSMED, Rome, Italy), a portable metabolic system which enables the user to conduct tests on participants outside of the laboratory environment. In order for any testing to be successful and meaningful, the researcher needs to be assured of the reliability of the technology used. This has been found to be valid and reliable when compared to both the Douglas bags - the gold standard of metabolic testing (Shephard, 2017) - and earlier versions of the system (Winkert *et al.*, 2020; DeBlois, White and Barreira, 2021). The research by DeBlois, White and Barreira (2021) entailed looking at the reliability of the K5 at walking speeds in a group of 27 participants aged 18-40 years, and which found that the reliability of the K5 improved as the speed increased with an ICC for $\dot{V}O_2$ ranging from 0.64-0.85, with the higher values, and so stronger reliability, seen at higher speeds. Whilst this study considered walking rather than running, it followed a sound test-retest protocol and added weight to earlier studies which had examined the reliability of the K5 with a cycling ergometer.

2.9.2 Biomechanics data capture

It has long been established that three-dimensional motion capture using static cameras which track markers placed on the body is the gold standard for determining kinematic data (Vilas-Boas *et al.*, 2019; Jakob *et al.*, 2021). Motion capture has been successfully used for gait analysis in running and walking trials both in treadmill testing and overground settings (Pink *et al.*, 1994). However, this brings with it a number of limitations. Most camera systems require the user to place markers on very accurately measured sites on the participant's body, making the system vulnerable to error and cumbersome to implement (Clark *et al.*, 2019). The nature of running motion leads to the possibility of marker occlusion, which, although this can be offset with additional markers to stand in, is not ideal. Further, because the cameras are static and with a fixed range, the number of gait cycles that can be captured is limited. This effectively prohibits the ability to capture a full minute of continuous, straight, outside overground running, and therefore the ability to capture the whole run until steady state is achieved, which is reported as being up to five minutes (Saunders *et al.*, 2004a; Barnes *et al.*, 2013; Barnes and Kilding, 2015a). In order to analyse this data, the researcher will need to use software to identify elements of the gait cycle such as toe-off, foot-strike etc., often using their judgement to identify these points.

Advances in technology have led to the development of the Xsens MTw Awinda system (Xsens, Enschede, The Netherlands), a wireless tracking system that can be used to capture data in real time. It uses an internal accelerometer and a gyroscope to track the movement of the segment of the body that it is attached to. Robust testing has also been done to investigate the accuracy of the Xsens MTw Awinda system used to capture biomechanical data (Zhang *et al.*, 2013). For ease of analysis, software package Visual3D (C-Motion Inc, Washington, US) has been adapted to enable the data collected by the Xsens MTw Awinda system to be analysed. Visual3D uses the measurements collected in the Xsens system to generate a model of each participant with the correct dimensions for each section of the body, thus enabling key gait events to be identified and the biomechanical data extracted.

2.11 Thesis aims and hypothesis

The fundamental aim and over-arching question driving this thesis was to identify key, modifiable biomechanical features that have a significant impact on running economy in recreational distance runners. Then to use this knowledge in order to propose a change that this cohort of runners can make with the result of an improvement in their running economy. As a secondary part of this investigation, a further aim of the thesis was to examine the two conditions, overground and treadmill running, to determine whether there were differences in running economy between them and whether there were biomechanical differences in the way recreational runners ran in the two different environments. While limited work on this population has been carried out, this thesis has involved examining a large recreational population, in a natural, overground environment.

Within each experimental chapter there is a subset of aims which help to contribute towards the overall aim of the thesis. These aims are outlined below.

1. The first experimental chapter examines the running economy of the participants and considers the reliability and validity of running overground compared to treadmill running (Chapter 4).

H10: Running overground will not yield reliable results for running economy when comparing different overground trials.

H11: Running overground will yield reliable results for running economy when comparing different overground trials.

H20: Running on a treadmill will not yield reliable results for running economy when comparing different treadmill trials.

H21: Running treadmill will yield reliable results for running economy when comparing different treadmill trials.

Additionally, the research will include a comparison of the results for running economy recorded to see if the values are statistically significantly different when running on the treadmill or overground.

2. The second experimental chapter examines the running biomechanics of the participants and considers the reliability and validity of various parameters: stride length, stride rate, vertical oscillation and hip, knee and ankle angles when running overground compared to treadmill running (Chapter 5).

H30: Running overground will not yield reliable values for biomechanical parameters when comparing different overground trials.

H31: Running overground will yield reliable values for biomechanical parameters when comparing different overground trials.

H40: Running on a treadmill will not yield reliable values for biomechanical parameters when comparing different treadmill trials.

H41: Running on a treadmill will yield reliable values for biomechanical parameters when comparing different treadmill trials.

Additionally, the research will include a comparison of the results for all biomechanical parameters recorded (angles of hip, knee and ankle, vertical oscillation, stride length and rate) to see if the values are statistically significantly different when running on the treadmill or overground.

3. The third experimental chapter considers the relationships between biomechanical parameters and running economy. Using linear regression, the aim is to isolate the modifiable, measurable biomechanical variables that have a significant impact on running economy (Chapter 6).

Chapter 3: General Methods

3.1. Introduction

The rationale for including a general methods chapter is to explain the approach consistently used in the subsequent experimental chapters. Additionally, all applicable calibration methods carried out before each experiment and more generally are described.

3.2 Pre-test conditions and measurements

For standardisation, participants were required to arrive at the university laboratory fully hydrated, not having eaten within the previous three hours - to avoid digestive problems and cramping - and wearing suitable sports clothing in accordance with previously established methods (Smith and Jones, 2001; Dexheimer *et al.*, 2020). It was stressed to the participants that they were required to use the same running shoes on all visits to eliminate any possible impact of the shoes on running economy (Fuller *et al.*, 2015, 2017; Moore, 2016). The participants provided written informed consent (see Appendix 2) and completed a British Association of Sport and Exercise Sciences health questionnaire (see Appendix 3).

Initial anthropometric measurements were taken ipsilaterally on the left hand side where applicable with the participant in a standing position; mass and height using a standard weighing scale and a portable stadiometer to the nearest 0.1 kg or cm respectively (Seca, Birmingham, UK), foot size from the heel to the toe, ankle height from the lateral malleolus to the floor, knee height from the lateral epicondyle to the floor, hip height from the greater trochanter to the floor, hip width distance taken as the distance between the left and right anterior superior iliac spine, shoulder width as the distance between the left and right acromions, arm span from the tip of one middle finger to the other with arms at right angles to the body and palms facing forwards (Popovic *et al.*, 2013), and shoe sole height. Measurements were taken to the nearest 0.1 cm with a segmometer (MVN SegoMeter, Xsens, Enschede, The Netherlands). Figure 3.1 and Figure 3.2 depict the pose the participant needs to adopt during the calibration and give a clearer guide to the measurements taken across the body.

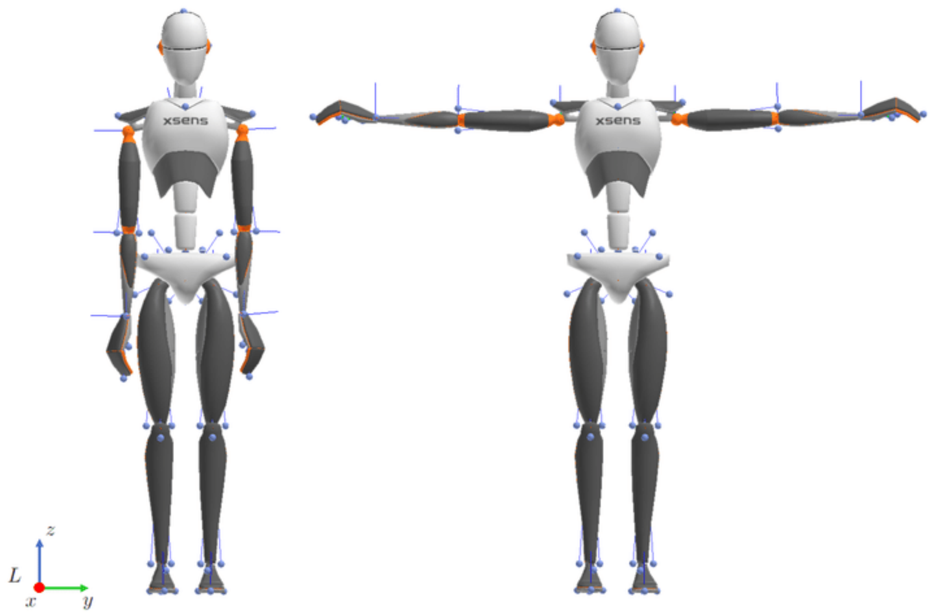


Figure 3.1: The left model shows the N-pose required by the participants for the calibration of the Xsens system, a slight variation on the traditional anatomical pose, the right model shows the T-pose which is required in order to take a number of the anatomical measurements (Xsens, 2021).

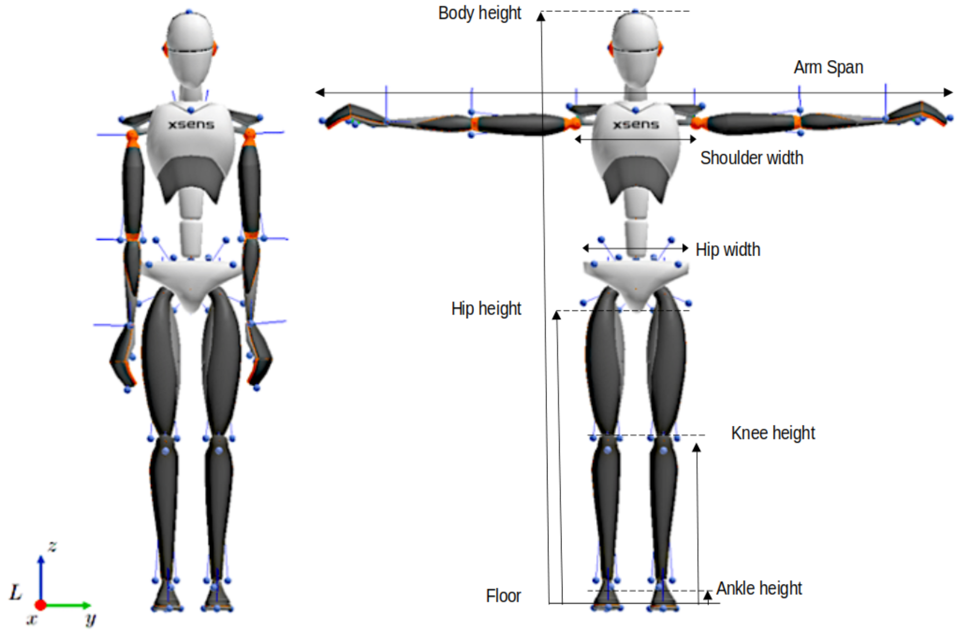


Figure 3.2: The left model shows the N-pose, the right image illustrates the body section measurements that need to be taken for the Xsens system (Xsens, 2021).

A heart rate monitor (Garmin International Inc., Olathe, Ks, USA) was fitted to the participant, then the 17 MTw Awinda motion trackers (Xsens, Enschede, The Netherlands) were placed on the participant on the following sites in accordance with the manufacture's guidelines ensuring the self-adhesive straps, where used, were secure enough not to slip. The participants were advised to wear a lightweight T-shirt under the Xsens suit. The suit is a tight-fitting shirt made from a stretchable fabric and has sites for 3 trackers (sternum; left and right shoulders). Although there is a possibility that wearing this additional layer may impact on thermoregulation, it is only the upper body that is covered, and this is consistent across all trials, so the runner experiences the same standardised conditions in all cases. Foot trackers were secured under the laces of both shoes on the middle of the bridge of the foot. The remaining trackers were held in place with straps; lower leg, where the calf muscle turns inwards, upper leg well above the knee on the lateral side, lower arm just above the head of the ulna on the posterior side, upper arm halfway between the shoulder and the elbow on the lateral side, and one on the sacrum. Gloves were secured to each hand containing a tracker on the posterior side and the final one was placed on a headband worn by the participant (see Figure 3.3). The IMUs sample at 60 Hz up to a range of 50m.

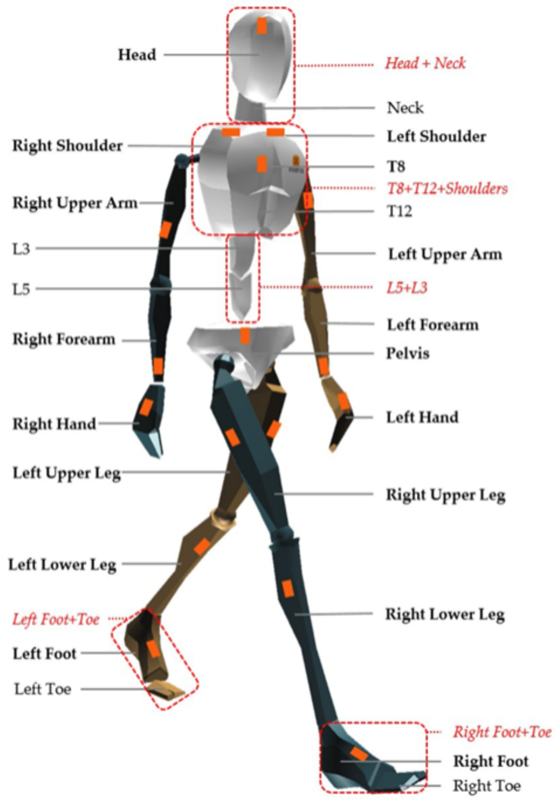


Figure 3.3: Location of IMUs identified by orange markers (Xsens, Enschede, The Netherlands).

The K5 portable metabolic cart (COSMED, Rome, Italy) was placed on the participant to enable breath-by-breath analysis during the testing period. This was fixed in place using a harness, so it was imperative to ensure that straps of the harness did not dislodge the trackers, additional tape was used to protect the trackers as required. Figure 3.4 shows the two systems in place on one of the participants, in the external location used for testing and on the treadmill.

Figure 3.4: A participant demonstrates how the two data capture systems sit in unison on the body. The left picture shows the flat, straight outdoor area where the overground running took place and the right picture is in the laboratory.

Once the apparatus had been fitted and prior to testing, participants were required to warm up for five minutes on a treadmill (Mercury, h/p/cosmos, Nussdorf-Traunstein, Germany), at a pace of their choosing at a gradient of 1%, in line with the findings of Jones and Doust (1996). This procedure performed several further functions, to facilitate familiarisation with the equipment and ensure that all the markers were fitted securely and didn't slip during running. The warm-up run was followed by 5 minutes of self-selected stretches in line with previously established methods (Smith and Jones, 2001) and research indicating that pre-exercise stretching does not have any significant impact on running economy (Hayes and Walker, 2007). For standardisation, the participant was required to perform the same warm-up stretches on each visit to the testing site.

A comfortable, regularly achieved, 5 km running pace to be used for both running conditions was selected for each participant. This was either something which they knew from experience if, for example, they used some sort of wearable technology so were aware of their usual 5 km pace, or they knew how long a 5 km run took them, or, for the parkrunners, this information could be found on the parkrun website, and the pace could be determined from that. The reasoning for this was that the variable being investigated was concerned with running at submaximal levels, not maximum effort and given that the two testing periods were approximately one week apart, for a duration of 5 minutes each, it would be unexpected to see a training effect between the trials which would impact on their ability to attain that chosen pace (Warne and Warrington, 2014; Hung *et al.*, 2019).

3.3 Treadmill testing protocol

The testing procedure required the participant to run at a consistent pace and to achieve steady state running. Hence, the participant was required to run for five minutes on the treadmill. The treadmill (Mercury, h/p/cosmos, Nussdorf-Traunstein, Germany) was again set at a gradient of 1% to match that which they had experienced in their warm-up protocol and in line with the findings of Jones and Doust (1996). The treadmill was programmed to run at the pace identified by the participant and the runners completed their five-minute treadmill test at this steady pace. At the end of the five minutes, participants were asked for their rating of perceived exertion according to the Borg 6-20 scale (Borg, 1998).

3.4 Field testing protocol

Overground testing took place on a paved area at the University of East London Docklands' campus, which is a flat, straight course. This is shown in an image of the Docklands' site (see Figure 3.4). The path follows the bank of the Royal Albert Dock, the location chosen for the overground running test. To assure that the bank was flat, details of height above sea level as identified by Google Earth can be seen in Appendix 5. In order to ensure that the same pace was maintained when running overground, a cyclist on a bike they were accustomed to, fitted with a speedometer (YS-Sports, Shenzhen, China), set the pace, as determined by participant to be their typical 5 km pace, and the runner followed the bike at a constant distance. The cyclist maintained a constant speed throughout the testing procedure, verbal cues were given by the cyclist to the runner if they needed encouragement to speed up or slow down so the steady pace was maintained.

As with the treadmill test, at the end of the five minutes, participants were asked for their rating of perceived exertion according to the Borg 6-20 scale (Borg, 1998).

The order of the testing conditions was randomised by a coin toss for each participant when they arrived for the first trial. This was to ensure that each participant had an equal chance of performing the tasks in either order (Akobeng, 2005). The overground trial was set as heads, and treadmill set as tails. The participants performed the trials in the opposite order on their second visit. In between the two testing conditions, the participants had an active rest period as they walked between the two conditions which equated to 15 minutes.

Conducting both the treadmill and overground trials for a period five minutes was to ensure that the runners had achieved steady state at a sub-maximal level (Saunders *et al.*, 2004a; Barnes *et al.*, 2013; Barnes and Kilding, 2015a). Previous studies have required runners at a variety of speeds for periods of three to 15 minutes (Shaw *et al.*, 2013; Folland *et al.*, 2017; Miller *et al.*, 2019). However, the aim of this study was to look at the individual's usual 5 km running pace, so testing at a variety of speeds was not applicable for this trial and given that all that was required was for the participants to achieve steady state, a running period of no more than five minutes would be sufficient. The other main consideration was the portability of the equipment as one focus of the study was to test running in the field. This influenced the choice of equipment and design of the study, opting for the portable K5 metabolic cart and the Xsens system so the research could be carried out both in the laboratory and in the field.

3.5 Running economy calculation

Running economy was determined by averaging the last minute of $\dot{V}O_2$ (ml.kg^{-1}.min^{-1}) as previous research shows that during this phase the runner should have achieved steady state (Saunders *et al.*, 2004a; Barnes *et al.*, 2013; Barnes and Kilding, 2015a), a requirement for the accurate assessment of running economy (Jones *et al.*, 2021). During exercise in a steady state, the participant is considered to have an O_2 cost equivalent to the metabolic cost for that activity (Hayes and Walker, 2007). After each trial, for each participant, the metabolic data was checked to confirm that the participant had achieved steady state. This was identified from the VO_2 data recorded by the K5 which shows a steady climb in the consumption of O_2, until it reaches a plateau which identifies that the participant has reached steady state O_2 consumption, i.e. showing no significant increase in O_2 consumption (Jones *et al.*, 2021), see Figure 3.5 for an example. The oxygen cost was then calculated by accounting for the speed at which they were running, i.e. $\dot{V}O_2$ (ml.kg^{-1}.km^{-1}) = $\dot{V}O_2$ (ml.kg^{-1}.min^{-1}) / (speed (m.s^{-1})/60).

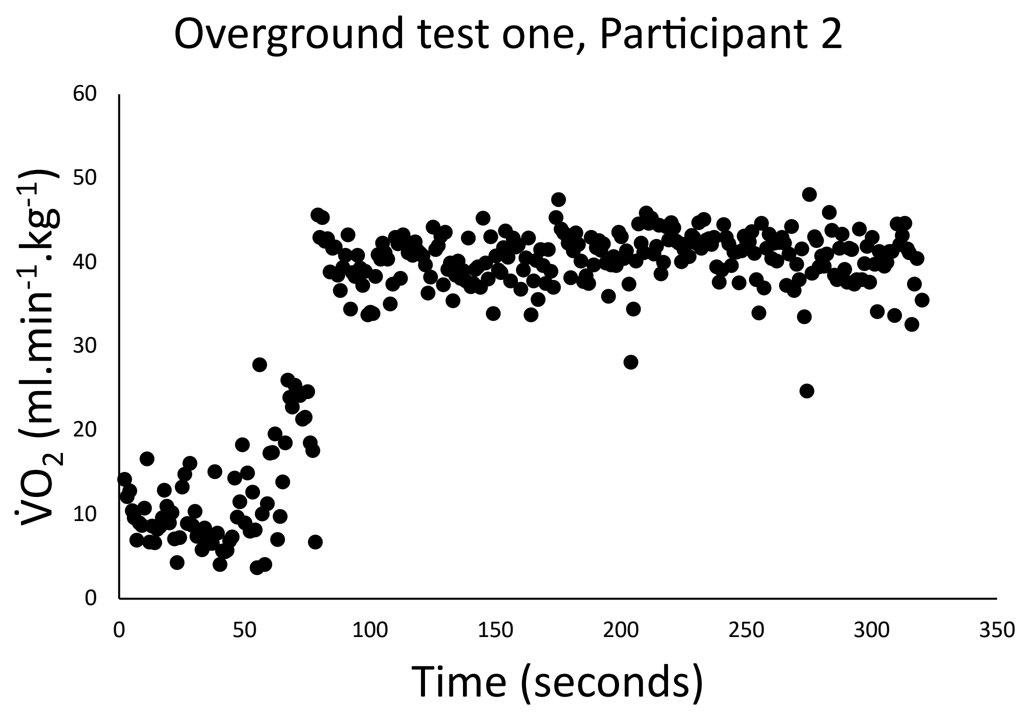


Figure 3.5: Example of running economy for a participant, the plateau indicates O_2 consumption has reached steady state.

3.6 Analysis of additional physiology support measures

Heart rate and METs were recorded by the Cosmed K5 system and an average of the readings from the final minute of the test were taken in line with the $\dot{V}O_2$ readings. Immediately at the end of each test, participants were asked to give their rate of perceived exertion according to the Borg scale (Borg, 1998).

3.7 Extraction of biomechanical data

The data captured from the Xsens system was imported into Visual3D (C-Motion Inc, Washington, US) analysis programme. This used the tracking information and segment measures to generate a working model of each participant. This system then enables the user to identify stages of the gait cycle and generate data for biomechanical parameters such as segment angles and spatiotemporal measurements using a number of commands or pipelines. Figure 3.6 shows an image from a file in Visual 3D to demonstrate how the system models the skeletal make-up of the participant.

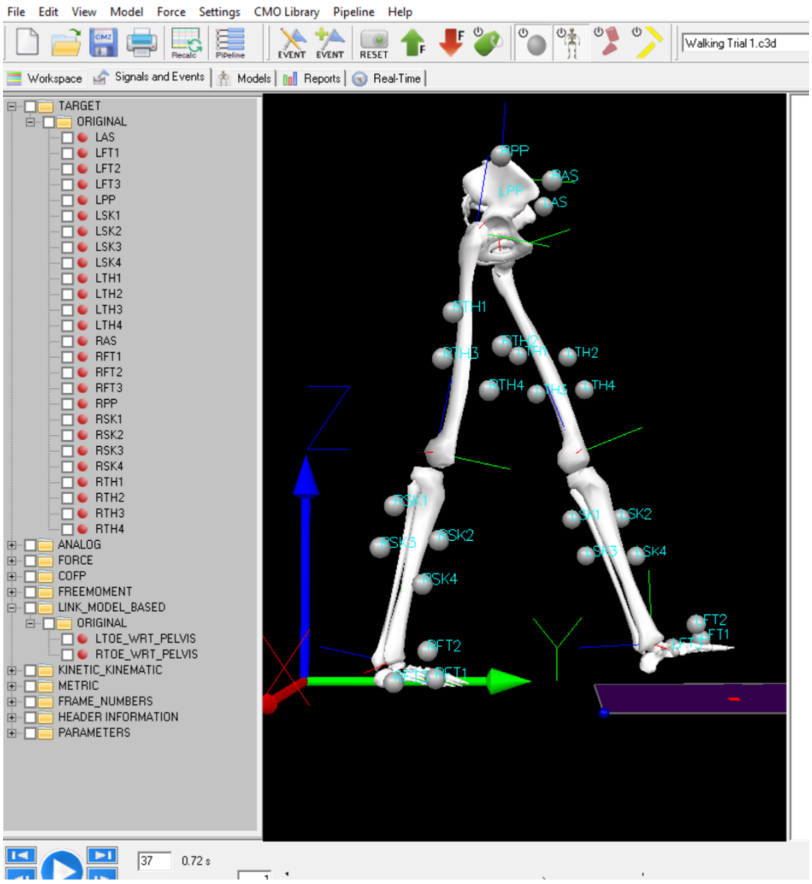


Figure 3.6: The Visual 3D software uses the data collected through the Xsens system to model the participant to enable biomechanical factors to be extracted.

Once the parameters have been identified and collated in Visual 3D, the raw data is exported as a text file which can subsequently be imported into Excel (Microsoft Corporation, v16.33, Redmond, WA, USA). A combination of Excel and SPSS (IBM SPSS Statistics, Rel. 28.0, 2021, SPSS Inc, Chicago, IL USA) were used to perform statistical tests, as required.

3.8 Methods to assess reliability

Reliability is the ability of a measure to produce reproducible values when repeating the same test on the same individuals (Batterham and George, 2003) and is a requirement for a test to be valid. If measurements are going to be in any way scientifically useful, they need to be reliable; the best way to determine this is by a test-retest on a group of participants (Lexell and Downham, 2005; Bland and Altman, 2010; Badenes-Ribera *et al.*, 2016). This is typically done by carrying out a study where two sets of measurements are collected from a group of participants, with a gap of not less than one week between the two sessions to avoid a learning effect. A learning effect comes from familiarity with a test or piece of equipment, such that an improvement might be seen in the results, which is down to this effect rather than any physiological improvement.

While the notion of reliability is a relatively straightforward concept, there is much debate around which measures to use (Hopkins, 2000; Batterham and George, 2003). Researchers have often chosen to use Pearson's correlation coefficient and a p-value indicating significance as the default, accepted measurement for reliability. However, this is purely a measure of relationship and not of agreement and, as a result, this has come in for some criticism. For example, Bland and Altman (2010) discussed whether correlation was an appropriate measure for reliability, arguing that it does not necessarily imply agreement, simply that there is a relationship between the two results. Additionally, the worth of a p-value has been questioned and their lack of ability to determine the size of an effect or the importance of it with the assertion that a p value does not in itself tell the research whether a hypothesis is true, but is merely a statement on the data relating to a hypothetical explanation and not a comment on the actual explanation (Wasserstein and Lazar, 2016).

As a consequence, the intra-class correlation coefficient (ICC) has now emerged as a preferred choice as it contains elements of both these things (Koo and Li, 2016). Additionally, it is an effective tool to use when the sample size is small – which is often the case in sports science where participant numbers are often fewer than 20 (Lexell and Downham, 2005).

As with the Pearson's correlation coefficient, the range is from 0 to 1, with 1 suggesting perfect agreement and 0 indicating no agreement. However, there is no strict rule interpreting the results of the ICC, and there is a lot of variation in the literature, the general guidelines suggest that an ICC > 0.75 could be considered excellent and anything from 0.4 to 0.75 accepted as fair to good reliability (Lexell and Downham, 2005; Murray, Beaven and Hébert-Losier, 2018) with other studies reporting a range of 0.44-0.67 as modest (Highton *et al.*, 2012). Koo and Li (2016) provide a stricter definition, less than 0.5 being poor, 0.5 to 0.75 moderate, 0.75 to 0.9 good and above 0.9 is excellent.

There are several ways to calculate an ICC, depending on the set of assumptions that are made, each may give slightly different results, so it is imperative to include information about the type used (Batterham and George, 2003; Koo and Li, 2016). For example, Murray, Beaven and Hébert-Losier (2018) clearly state that they used a “two-way mixed effects single measurement”. Other researchers include which type they have used but not necessarily why (König *et al.*, 2014). Given that an ICC looking at absolute agreement tends to give a smaller result than using consistency as a parameter, it is important to state which is being used for transparency.

It is noteworthy to add that many critics suggest that relying solely on the use of ICC for assessing reliability, even when enhanced by including confidence intervals, is not a strong enough test and that additional methods should be used in conjunction with the ICC (Batterham and George, 2003; Lexell and Downham, 2005; Haff *et al.*, 2015). To measure the variability, it is suggested that an index, independent of the units of measurement, such as a coefficient of variation (CV), expressed as a percentage should be used (Batterham and George, 2003; Abdi, H., 2010). Hopkins (2000) argued that for sports science, this was the most appropriate way of expressing typical error as other methods, such as the limit of agreements, can lead to bias. Stevens *et al.* (2015) reported that it was the main measure of reliability.

The CV demonstrates a level of precision although there is not a single defined threshold which is deemed to be acceptable, simply that a low CV indicates high reliability. Whilst some researchers have taken a threshold of 20% as acceptable (Reed, Lynn and Meade, 2002), it seems to be more common practice to argue that reliability can be assured if CV is < 10 - 15% (Haff *et al.*, 2015; Murray, Beaven and Hébert-Losier, 2018).

For the purposes of this study, two measures of reliability will be used. Firstly, an assessment using ICC (2,1) with 0.4 to 0.75 accepted as fair to good reliability. Secondly, a CV with an acceptable measure of <10%. Meeting these two criteria would be a strong indicator of a reliable measure (Koo and Li, 2016; Murray, Beaven and Hébert-Losier, 2018; Padulo *et al.*, 2019).

When conducting a reliability study, Morrow and Jackson (1993) argued that 30 participants would be necessary for adequate precision in determining reliability, while

Hopkins (2000) suggested 50 participants performing three or more trials would be suitable. Koo and Li (2016) also proposed a sample size of at least 30 heterogenous participants for a reliability study. Additionally, a power analysis using G*Power 3.1.9.6, with an α of 0.05 and a power of 0.80 indicated a sample size of 34. Taking all these factors into consideration, and allowing for a level of attrition, for the purposes of this study, 40 participants were recruited, which was approved by the University of East London's University Research Ethics Committee.

Having established whether or not testing overground is a reliable method, the level of agreement was then considered. Bland-Altman plots identifying the lower and upper 95% limits of agreement were constructed for all of the conditions.

3.9 Regression analysis

Regression was identified as the best way to analyse the data for a number of reasons. Firstly, the relationship between each of multiple variables and the dependent variable can be considered. Secondly, not only the existence of a relationship between each independent variable and the dependent variable, but the strength of each of those relationships. The results found from the regression analysis would then be used to determine which of the independent variables are important and would subsequently be the variable(s) to be investigated further.

There were a number of options for regression that could be considered, one being simple linear regression analysis. There are two ways to approach this model, the first, entry, which includes all parameters and from initial correlation determines the contribution of the model as a whole and the strength of this model as it relates to running economy. The alternative version of this is stepwise, where SPSS will identify the parameters with the strongest correlation to running economy and exclude the others. There is value in both versions, but to see the full picture of what the contribution of each parameter is, the entry version is more transparent.

A more prescriptive version of regression is to perform a hierarchical regression. This involves selecting the parameters believed to be the most impactful on the dependant variable, and then determining which other factors add to this. However, this means making a subjective decision about which factors to include together. This is beyond the remit of this thesis.

3.10 Calibration methods

3.10.1 Metabolic cart

The K5 was calibrated as outlined in the manufacturer's user manual, with three procedures performed before each test was carried out. Reference gas consisting of a compressed sampling gas mixture of 20% O_2 and 5% CO_2 (BOC Gases, Guildford, Surrey, UK) was used to denote baseline measures. A 3-litre syringe (Hans Rudolph Inc. Kansas, USA) was attached and pumped several times in a steady flow rate to calibrate the turbine and flowmeter. The third was to sample the ambient air temperature. Whilst the reference gas and flow tests needed to be done only at the start of the session, the temperature was measured at the start of each trial as the outdoor and indoor temperatures need to be measured.

3.10.2 Motion sensors

The MTw Awinda system requires calibration before each test, as recommended by the manufacturer. The participant was required to stand in an N-pose (neutral pose) position. This was explained to the participant with the same wording each time, to "stand tall, absolutely still with arms straight down by the sides, so that ankles, hips, hands and shoulders all remain in a straight line". Participants were then required to hold this pose for several seconds while the software conducted its reading. This was then applied to the segment measurements to create a model for the individual participant.

3.10.3 Treadmill

To calibrate the treadmill the belt length was determined, the treadmill speed set to 10 $km.h^{-1}$, and the time taken for 10 revolutions was recorded on several occasions using a hand-held stopwatch to the nearest 0.01s and the average taken. The total distance travelled during this time was divided by the time elapsed to give the speed of the treadmill. This was repeated a number of times, with the speed recorded not varying by more than 0.02 $m.s^{-1}$.

3.10.4 Speedometer on the bike

A similar test was performed for the front-wheel mounted speedometer on the bike. The front wheel was placed on the treadmill and the speed set to 10km.h^{-1}, the speed recorded did not vary more than 0.01 km.h^{-1} from the treadmill set speed.

3.11 Summary

As set out at the beginning of this chapter, the methodology outlined here is utilised in the experimental chapters, with any variation or experiment-specific adaptations noted in the methods section for that chapter. For clarity, the subsequent chapters intend to refer back to specific sections, where necessary.

Chapter 4: A comparison of testing for running economy overground with treadmill running

4.1 Introduction

This thesis is concerned with the performance of recreational distance runners, i.e. the processes of carrying out a particular function, the function being running. It was established in Chapter 2 that the majority of recreational running takes place outside and overground. Subsequently, the aim of this chapter is to compare running economy, and a select number of other supporting physiological responses of recreational runners, when running overground compared to treadmill running. The purpose of this is to determine if the results from overground running are reliable for testing the parameters under investigation, specifically running economy, compared to the more readily controlled environment of laboratory testing, to the extent that testing in the field (overground) can be used as the main testing area for any further investigations. The additional physiological parameters analysed across the two conditions were heart rate (HR), rating of perceived exertion (RPE) and metabolic equivalents (METs). If there are differences in running economy, similar differences would be expected in these parameters. For example, a higher oxygen demand implies that more energy is needed, so the heart must be beating faster to supply the oxygenated blood. If the heart is working harder, it is likely that the effort will be perceived as harder, which is the premise of the Borg scale of perceived exertion (Borg, 1998). The Borg scale measures the rate of perceived exertion on a scale from 6 to 20 and it was designed to complement an increase in heart rate. Lastly, if the metabolic effort is greater, then the metabolic equivalent will also be greater. If it is established that testing in the field is at least as useful as using laboratory conditions, it is proposed that future testing for any changes to running economy can take place in a field setting, which it can be argued, is more ecologically valid, that is the research scenario closely resembles the real world situation which it is simulating, here this means running outside, overground (George, Batterham and Sullivan, 2003; Padulo *et al.*, 2019).

Running economy is defined as the metabolic cost of running and assumes that the oxygen used gives an indication of the adenosine triphosphate (ATP) utilised by the muscles during submaximal exercise (Shaw, Ingham and Folland, 2014). It is also established that respiratory muscles are well adapted to sustain prolonged submaximal exercise at a constant velocity (Boone, 2014), so to run for five minutes each on both the treadmill and overground should be an achievable task. Running economy has been shown to be a good predictor of endurance performance at distances of 5 km or more, and, compared to other physiological tests, such as a lactate threshold or $\dot{V}O_{2max}$ test, it is relatively simple to measure as testing for running economy is generally less intrusive than other physiological tests, and it is sensitive enough to detect change (Hausswirth and Lehénaff, 2001; Tartaruga *et al.*, 2014; Barnes and Kilding, 2015a). It is typically taken as an average of the $\dot{V}O_2$ over the last minute of steady state, submaximal exercise and measured in $ml.kg^{-1}.min^{-1}$. It is also seen reported as units of $ml.kg^{-1}.km^{-1}$ using this equation (Jones and Carter, 2000):

$$RE\ (ml.kg^{-1}.km^{-1}) = \dot{V}O_2\ ml.kg^{-1}.min^{-1} / (speed\ km.h^{-1} / 60)$$

To date, much of the work examining running economy has focussed on highly trained and elite level athletes (Paavolainen *et al.*, 1999; Foster and Lucia, 2007; Hoogkamer, Kram and Arellano, 2017; Tawa and Louw, 2018) and often in a laboratory setting using a treadmill, as it is possible to control many variables such as temperature, slope and speed (De Asha, Robinson and Barton, 2012). In these conditions, runners are tested at a variety of speeds with an average testing speed of 16 $km.h^{-1}$. However, Jones and Carter (2000) reported that runners are generally most economical when running at their usual running velocity which suggests it is not valuable to test recreational runners at anything other than this pace which has also been found to be the most stable (Jordan, Challis and Newell, 2006). Further, given that most recreational runners run outside, with one study reporting more than 87% running predominantly along paths and pavements rather than an athletics track or treadmill – 4.3% and 5.9% respectively – (Taunton, 2003; Barnfield, 2016; Cook, Shaw and Simpson, 2016), it is prudent to establish the reliability of assessing running economy overground. A method can be considered ecologically valid if it closely resembles the performance it is testing (George, Batterham and Sullivan, 2003; Currell and Jeukendrup, 2008; Padulo *et al.*, 2019), which in this case, the test is a short period of overground running, to emulate recreational overground running. Previous studies have compared treadmill to overground gait patterns. For example, König *et al.* (2014) argued that using motorised treadmills can influence the temporal rhythm of gait, so, given that this thesis is investigating the impact of aspects of gait on running economy, it might be expected that a truer assessment of a running economy for a habitual overground runner would be gleaned from overground testing.

Murray, Beaven and Hébert-Losier (2018) reported that whilst using a treadmill might prove reliable, this is not where most recreational runners train, decreasing the ecological validity compared to field work due to the sports specificity. Further, König *et al.* (2014) noted that the gait patterns were influenced by the treadmill rhythm, adding to evidence to suggest that testing overground is ecologically valid. Studies that replicate the 'real world' experience of the participants claim to have strong ecological validity, which could be argued in the case of testing recreational runners in the field (Padulo *et al.*, 2019).

It has been reported that while being able to report laboratory findings might be useful in predicting overground performance, if testing overground is reliable – and a more comfortable experience for the runner – then that approach should be preferred (Miller *et al.*, 2019). Miller *et al*. (2019) found that there is inconclusive evidence to show that treadmill running is an appropriate alternative to running overground for the evaluation of physiological parameters and this becomes more prominent when considering endurance running compared to sprinting. It has also been noted that runners tend to select slower speeds when running on a treadmill, so results may not be comparable to overground running (Miller *et al.*, 2019). Barnes and Kilding (2015a) noted that runners tend to adopt a different technique when running on a treadmill, arguing that to run overground puts more demand on the hamstrings to produce propulsive forces, both horizontal and vertical, which is not the case for treadmill running. However, there seems to be general agreement that the oxygen demand for horizontal running is similar for treadmill and overground for velocities less than or equal to 4.3 $m.s^{-1}$ (15.48 $km.h^{-1}$) ($0.1 < p < 0.25$) with differences generally attributed to visual and possibly auditory stimulation (van Ingen Schenau, 1980; Bassett *et al.*, 1985; Ceci and Hassmén, 1991; Oliveira *et al.*, 2016). Peserico and Machado (2014) reported that, compared with treadmill running, overground running led to higher average speeds ($p = 0.001$) which they attributed to sensory perception, i.e. factors such as, on the treadmill, the test environment appears monotonous and there is a greater need for concentrating on coordination and balance due to a fear of falling off the treadmill.

This supports an earlier study which reported a significant difference of 27.1% in speed between overground and treadmill running ($p = 0.039$), and found no physiological reason (Kong *et al.*, 2012). Given that the subjects for this work will be recreational runners who predominately run overground, it is suggested that testing in a field environment would be a more realistic way of assessing the participants.

Pugh (1970) was one of the first to investigate the metabolic differences between treadmill and overground running, and attributed the difference – about 8% to wind resistance. Jones and Doust (1996) questioned whether energy cost of running on a treadmill could be directly compared to that when running overground on a flat course. They concluded that at speeds of 2.92 $m.s^{-1}$ to 5.0 $m.s^{-1}$, a duration of around 5 minutes and with a gradient of 1% on the treadmill, there was no discernible difference in energy costs between the two conditions, with a high correlation ($r=0.99$) assuring the repeatability of the test. However, the nine male participants were all highly trained and fully accustomed to running on a treadmill at the speeds outlined, speeds that are commonly used for training and competing in a group of good standard or sub-elite runners, ranging from 2.92 $m.s^{-1}$ to 5 $m.s^{-1}$. Recreational runners, as discussed in Chapter 2, come from a far more diverse community, and includes a number of runners who have no access to a gym or treadmill or just prefer to run outdoors, suggesting that they will not be accustomed to treadmill running. Bonnaerens *et al*. (2019) looked at recreational runners and found that more than a quarter of the entire running population run at speeds of less than 2.8 $m.s^{-1}$. As another popular example of recreational running, it is worth noting that the average pace of a parkrunner for a 5 km run is 2.89 $m.s^{-1}$ (parkrun, 2021), so it is unclear whether any treadmill adjustments are applicable to the population under consideration.

Therefore, as outlined in Chapter 2, the aims of this chapter were to determine the reliability of assessing the running economy overground in recreational distance runners by testing the hypotheses:

H10: Running overground will not yield reliable results for running economy when comparing different overground trials.

H11: Running overground will yield reliable results for running economy when comparing different overground trials.

H20: Running on a treadmill will not yield reliable results for running economy when comparing different treadmill trials.

H21: Running treadmill will yield reliable results for running economy when comparing different treadmill trials.

Additionally, the research will include a comparison of the results for running economy recorded to see if the values are statistically significantly different when running on the treadmill or overground.

4.2 Method

4.2.1 Introduction

The methods used in this study are outlined more fully in the general methods (Chapter 3). The purpose of this section is to identify which sections of the methodology apply to this study and to provide any additional information as necessary.

4.2.2 Participants

Following ethical approval from the University of East London Ethics and Integrity Sub-committee, 40 recreational runners (male=19, female=21) were recruited for the study from local running clubs and the University of East London. Table 4:1 contains the summary details for the participants.

Table 4:1: Anthropometric data as mean ± SD with 95% CI.

	Mean ± SD	95% CI
Age (years)	37.45 ± 10.86	(34.09, 40.81)
Mass (kg)	66.86 ± 12.69	(62.93, 70.79)
Height (cm)	170.90 ± 8.41	(168.29, 173.51)
Speed ($km.h^{-1}$)	11.26 ± 1.99	

All participants had been running for a minimum of 6 months and were accustomed to running 5 km. They provided written, informed consent, and completed a BASES health questionnaire (see Appendices 2 and 3).

4.2.3 Procedure

Participants attended the University of East London's Docklands campus on two separate occasions not less than a week apart. They were asked to refrain from intense exercise for 24 hours prior to attending, not to eat for 3 hours before and arrive fully hydrated wearing suitable clothing and the same footwear on both occasions as it is known that running shoes can impact running economy (Fuller *et al.*, 2015). To try to limit any differences that could be the result of circadian rhythms, the tests were conducted as close to the same time of day as possible (Drust *et al.*, 2005).

On the first visit, anthropometric measurements were taken, mass using a standard weighing scale and height with a portable stadiometer (Seca, Birmingham, UK). Measurements were taken to the nearest 0.5 kg and 0.1 cm respectively.

Participants were fitted with a K5 portable metabolic cart (COSMED, Rome, Italy) before performing a 5-minute warm-up at a self-selected pace on a treadmill (Mercury, h/p/cosmos, Nussdorf-Traunstein, Germany), set at 1% incline to compensate for the wind resistance that would be experienced outside (Jones and Doust, 1996), and 5 minutes of self-selected stretching.

A coin toss, using the same coin on each occasion, was used to randomly allocate whether they ran on the treadmill or overground first, so that each participant had an equal probability of which trial they would perform first. There were similar numbers in each group, 18 participants who ran overground first in the first trial, and 22 who ran on the treadmill overground first in the first trial. There was a 15-minute recovery period between the two trials, the order was reversed on their return visit. For all trials, humidity, pressure and temperature were recorded, additionally, for the overground trials, wind speed was recorded. Table 4:2 contains a summary of the environmental data.

Table 4:2: Environmental data presented as mean ± SD.

	Humidity (%)	Pressure (mb)	Temp (°C)	Wind ($km.h^{-1}$)
Treadmill 1	47.03 ± 7.98	1038.30 ± 12.93	24.53 ± 0.85	N/A
Overground 1	61.68 ± 13.25	1014.35 ± 8.75	18.25 ± 4.58	12.35 ± 4.45
Treadmill 2	48.12 ± 7.06	1042.98 ± 7.41	24.45 ± 1.71	N/A
Overground 2	57.45 ± 11.83	1014.90 ± 6.58	20.80 ± 4.33	11.95 ± 4.16

The overground run took place on a paved, flat area. A Garmin Forerunner 235 (Garmin International Inc, Olathe, Kansas, USA) recorded no gain or loss in elevation, and this was cross-checked with details of height above sea level as identified by Google Earth which can be seen in Appendix 5. They ran for 5 minutes in each of the conditions at the same self-selected usual 5 km pace to enable the runners to reach steady state (Saunders *et al.*, 2004; Barnes *et al.*, 2013; Boone, Deprez and Bourgois, 2014; Barnes and Kilding, 2015a). The chosen speed was programmed into the treadmill and replicated outside by using a cyclist as a pace setter, maintaining the same steady pace with the aid of a speedometer (YS-Sports, Shenzhen, China). At the end of each trial, participants were asked to rate their level of perceived exertion using the Borg RPE scale (Borg, 1998), which was described to the participants in accordance with the instructions given in that paper.

Running economy was then determined from the last minute of the recorded data for each of the four trials when the participant will have achieved a steady state of oxygen consumption at their chosen pace (Saunders *et al.*, 2004b; Barnes *et al.*, 2013). This is typically expressed as the $\dot{V}O_2$ relative to either body mass per minute ($ml.kg^{-1}.min^{-1}$) or the volume of oxygen required to run a kilometre, relative to body mass ($ml.kg^{-1}.km^{-1}$), this is based on the speed of movement of the participant. While running economy reflects the oxygen cost of running at submaximal speeds, this doesn't necessarily tell the whole story of the energy cost which considers both the aerobic and anaerobic demands (Barnes and Kilding, 2015). Therefore, in addition to running economy, the energy cost (Ec) was calculated from the respiratory exchange rate (RER), adjusted for speed and body mass, and reported in $kcal.kg^{-1}.min^{-1}$ (Shaw, Ingham and Folland, 2014).

The data was analysed to determine the intra-class correlation coefficients (2,1) using a two-way mixed effects, absolute agreement, single rater measurement and coefficient of variance using SPSS software (IBM SPSS Statistics, Rel. 28.0, 2021, SPSS Inc, Chicago, IL USA) and Excel (Microsoft Corporation, v16.33, Redmond, WA, USA).

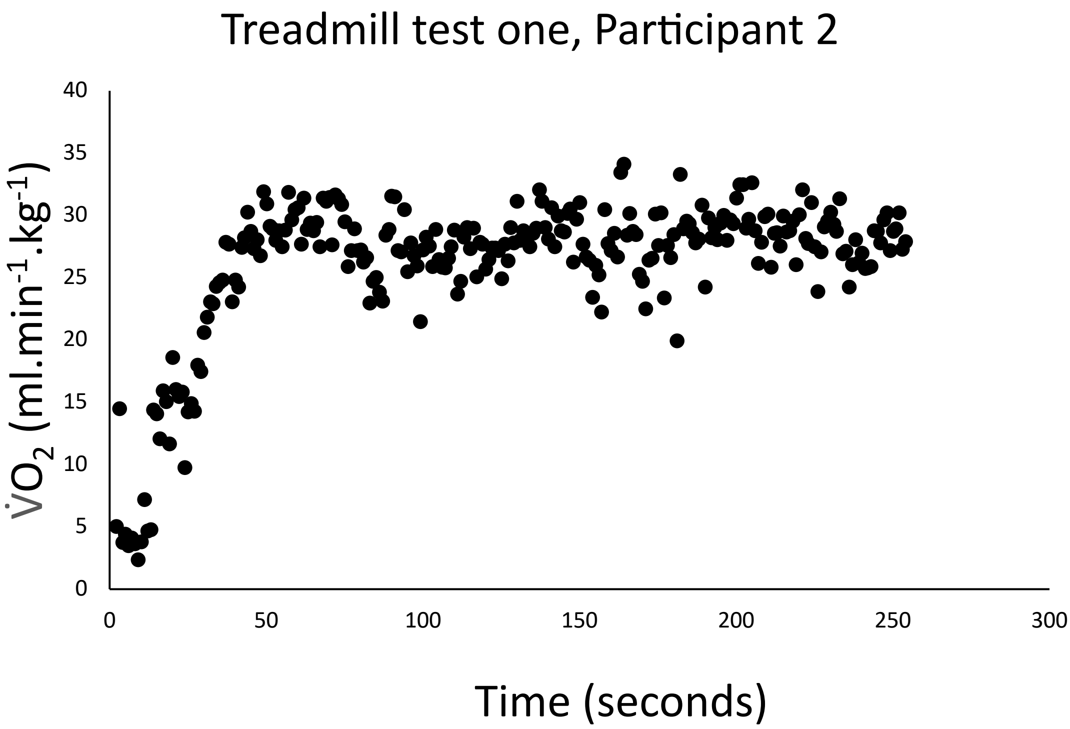
4.3 Results

The mean speed and running economy ± SD for each of the trials is presented in Table 4:3 where n=40 for each trial, giving a combined total of 160 trials. Figure 4.1 demonstrates that the participant achieved a steady state of running, that is, the $\dot{V}O_2$ levels increase until they reach a consistent steady level. The corresponding charts were checked for all participants to confirm that a steady state had been attained in all instances before any further analysis was performed.

Table 4:3: Speed, running economy (RE) and energy cost (Ec) for each of the 4 trials, expressed as mean ± SD, n=40

Condition	Speed ($km.h^{-1}$)	RE ($ml.kg^{-1}.min^{-1}$)	Ec ($kCal.kg^{-1}.km^{-1}$)	Ec ($kCal.min^{-1}$)
Treadmill 1	11.26 ± 1.99	42.87 ± 7.40	1.13 ± 0.17	13.89 ± 2.99
Overground 1	11.26 ± 1.99	39.11 ± 7.71	1.03 ± 0.13	12.79 ± 3.19
Treadmill 2	11.26 ± 1.99	43.09 ± 8.36	1.13 ± 0.13	14.06 ± 3.36
Overground 2	11.26 ± 1.99	40.09 ± 8.78	1.05 ± 0.14	13.08 ± 3.48

Note: The RE is based on the average $\dot{V}O_2$ of the breath-by-breath data collected during the last minute of the trial while the participant is running in steady state.



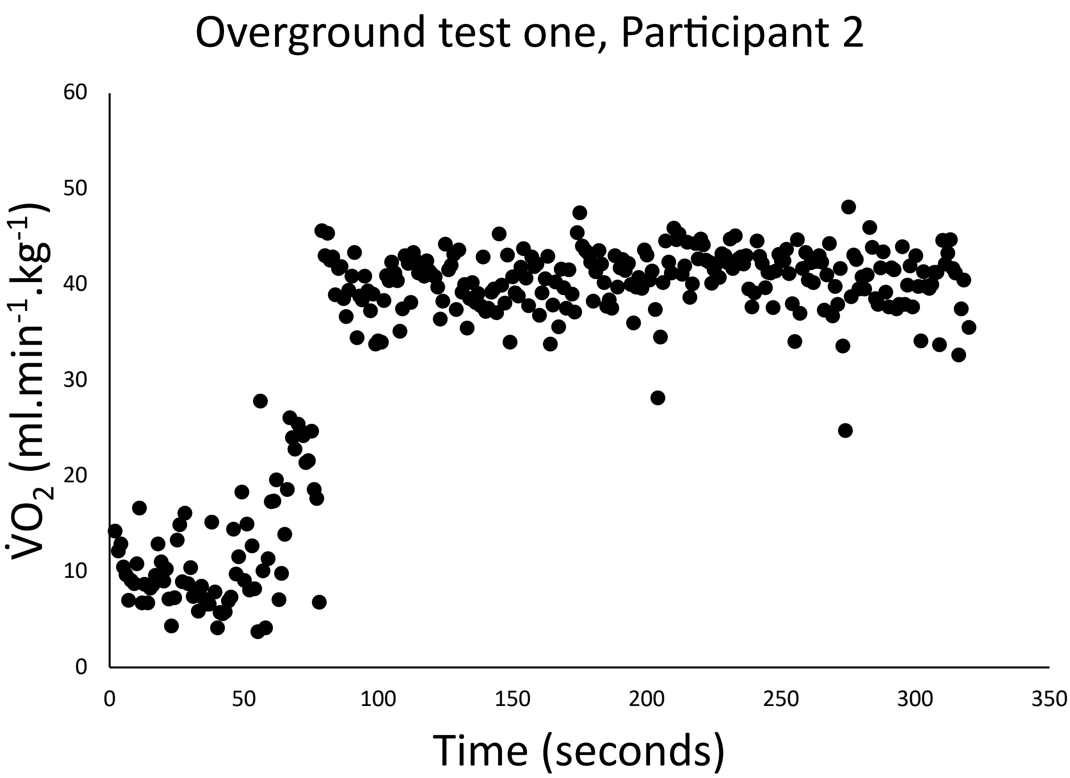


Figure 4.1: Running economy V̇O_2 (ml.min^{-1}.kg^{-1}) for a participant to demonstrate that a consistent level of O_2 is reached after an initial period, showing that the runner reached steady state. This was repeated for each participant, for each trial.

The coefficient of variation (CV) and intra-class correlation coefficient (ICC) with 95% confidence intervals (CI) for comparison is shown in Table 4:4.

Table 4:4: The intra-class correlation coefficient with a 95% confidence interval and coefficient of variation for each of the conditions

Conditions compared	CV (%)	ICC	ICC 95% CI
TD1 &TD2	8.09	0.462	(0.175, 0.675)
OG1 & OG2	7.31	0.535	(0.274, 0.723)
TD1 & OG1	7.26	0.638	(0.066, 0.8949)
TD2 & OG2	6.30	0.709	(0.131, 0.885)

Notes: TD = treadmill; OG = overground. This data is based on the RE measured in $ml.kg^{-1}.min^{-1}$ where n=40 for each of the four trials.

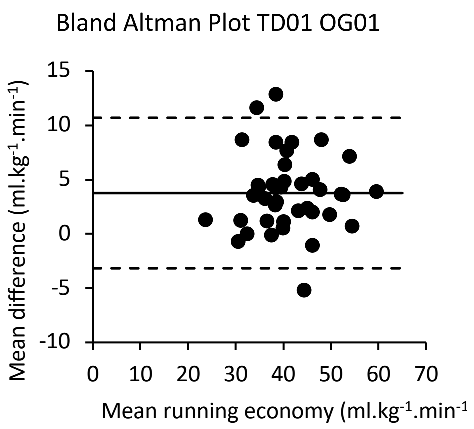
After testing for normality, a series of t-tests were performed to compare the means of overground and treadmill running results for running economy.

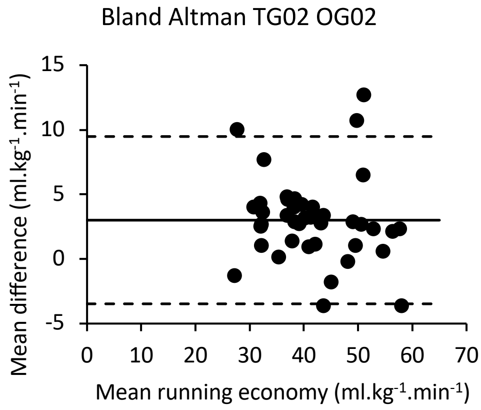
Table 4:5: Comparing the means, correlation and effect size for running economy

	t (p-value)	r (p-value)	ES (Cohen's d)	Evaluation
TD01 & OG01	6.73 (<0.001)	0.90 (<0.001)	0.50	Statistical difference, small effect size
TD02 & OG02	5.75 (<0.001)	0.93 (<0.001)	0.35	Statistical difference, small effect size
TD01 & TD02	-0.23 (0.82)	0.70 (<0.001)	0.03	No statistical difference, trivial effect size
OG01 & OG02	-1.21 (0.23)	0.81 (<0.001)	0.12	No statistical difference, trivial effect size

Notes: TD = treadmill; OG = overground. The statistic is based on a t-test where the data is normally distributed, or a Wilcoxon signed rank test where the data in not normally distributed.

Levels of agreement between the conditions are identified in Figure 4.2.





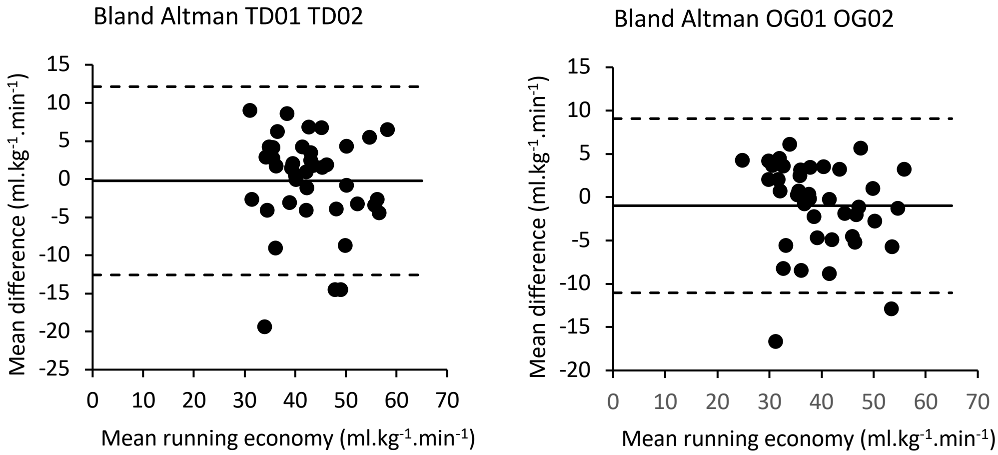


Figure 4.2: Bland-Altman plots to show levels of agreement across the difference conditions. TD = treadmill and OG = overground.

The means and standard deviations for heart rate, rating of perceived exertion and metabolic equivalents are present in Table 4:6 with the comparison data presented in Table 4:7.

Table 4:6: Heart rate (HR), rating of perceived exertion (RPE) and metabolic equivalents (METs) presented as mean ± SD.

	HR (Beats per minute)	RPE	METs
TD01	163.03 ± 11.52	13.00 ± 1.48	12.24 ± 2.20
TD02	162.38 ± 11.53	12.80 ± 1.64	12.33 ± 2.39
OG01	161.33 ± 14.88	11.73 ± 1.58	11.20 ± 2.20
OG02	159.75 ± 12.37	12.13 ± 1.88	11.44 ± 2.50

Table 4:7: Comparing the means Heart rate (HR), rating of perceived exertion (RPE) and metabolic equivalents (METs) and correlation, presented as the t (p-value) and r (p-value).

	HR		RPE		METs	
	t (p-value)	r (p-value)	t (p-value)	r (p-value)	t (p-value)	r (p-value)
TD01 & OG01	1.23 (0.23)	0.81 (<0.001)	-3.96 (<0.001)	0.45 (0.004)	-4.85 (<0.001)	0.90 (<0.001)
TD02 & OG02	2.80 (0.01)	0.88 (<0.001)	-3.34 (<0.001)	0.85 (<0.001)	6.08 (<0.001)	0.93 (<0.001)
TD01 & TD02	0.48 (0.64)	0.77 (<0.001)	-1.30 (0.19)	0.67 (<0.001)	-0.31 (0.76)	0.69 (<0.001)
OG01 & OG02	1.45 (<0.001)	0.89 (<0.001)	1.42 (0.16)	0.42 (0.006)	0.54 (0.59)	0.82 (<0.001)

Notes: TD = treadmill; OG = overground. The statistic is based on a T-Test where the data is normally distributed, or a Wilcoxon signed rank test where the data in not normally distributed.

4.4 Discussion

The purpose of this study was to determine whether calculating running economy from data collected during a field test was a reliable method when compared to the more traditional method of data collection done during a treadmill test and to compare the running economy recorded in both environments. Traditionally, testing on a treadmill has been the established testing method within the sports science field, however, the main reason for comparing the two is to establish whether overground running can be used to replace treadmill running in any future experiments involving recreational runners. The rationale for this was that recreational runners tend to run outside rather than on a treadmill so their lack of experience of treadmill running may influence their running and so impact on their running economy. However, as treadmill running has been the established testing method standard for physiological research, it is useful to have the comparison to see if there is concurrent validity, which asks the question, 'How does the does the overground test compare to the laboratory test?' (Morrow *et al.*, 2016). The r-values for the comparing the first and second treadmill and overground tests were 0.90 and 0.93 respectively, both reporting a p-values < 0.001, which shows a high level of concurrent validity which is statistically significant. It also makes sense to test the participant in a more natural environment than a laboratory setting if the results support this, as overground testing can be considered more ecologically valid, that is the results from testing in the field more accurately reflect the usual running behaviour in real-world circumstances for recreational runners. Further, it is known that treadmill running can influence a person's running gait (König *et al.*, 2014) and that participants tend to opt for lower running speeds on a treadmill (Miller *et al.*, 2019).

In Peserico and Machado's (2014) study of 18 recreational runners, they found that runners opted for a significantly slower speed (p=0.001) on a treadmill compared to overground as they considered treadmill running more strenuous. Similarly, a study of 21 participants found that when blinded to the speed on the treadmill, the runners chose to run at speeds 27.1% lower than in an overground trial even though they perceived it to be the same (Kong *et al.*, 2012). Given that running economy is described for a specific running speed, it is important that the running conditions enable consistent running speed. In this research, most participants reported that running overground had a lower rate of perceived exertion on a 6-20 Borg scale (Borg, 1998), which led to some runners naturally trying to run at a slightly faster velocity overground, reinforcing the need for a pacemaker. This suggests that if running on a treadmill is considered harder work by the individual, then it might be requiring more effort from the participants, so could lead to raised levels of running economy, which would add further weight to the argument to test recreational runners overground as it would more accurately reflect their usual running performance.

In each of the trial conditions, the coefficient of variation fell inside the acceptable level of < 10% being reliable, and all conditions returned an ICC greater than 0.4, up to 0.7, which can be accepted as fair to good. This compares well to a study from DeBlois, White and Barreira (2021) who conducted a walking trial to test the reliability of the Cosmed K5 at measuring $\dot{V}O_2$ – the variable used to determine running economy - $\dot{V}CO_2$ and other physiological measures. They reported an ICC of 0.64-0.85, which is slightly higher than this study found. Further, they reported that the results were stronger at a higher walking speed, although they did not test running, it supports the reliability of the K5 to measure physiological parameters. Saunders *et al.*, (2004a) found that the intra-individual results in a test-retest reliability for running economy at different speeds were relatively stable, with variation of between 1.5 and 5%, which is similar to this study. However, again, their research was conducted on elite distance runners but it does give a guide as to what might be expected.

The results of this study therefore demonstrate that it is reliable to perform testing for running economy where recreational runners are participants in a field environment. One of the first things to note is that the mean speed ± SD achieved by the recreational runners is slower than previous studies which have considered highly trained athletes. Typically, during testing, highly trained athletes run at 16 $km.h^{-1}$ although there has been testing in the range 12 – 21 $km.h^{-1}$ (Barnes and Kilding, 2015), which most of the recreational runners did not achieve. It is worth noting that Jones and Carter (2000) proposed that runners are generally most economical when running at their usual running velocity, so it was important to allow the participants to select their own pace.

Now that reliability has been established, the validity of the method used in the testing process can be considered as an experiment should not be conducted without this additional reassurance. Validity is one of three key aspects that form the foundations for scientific research, the other two being reliability and generalisation. Nominally, a study can only be considered valid if researchers are examining the specific thing that they set out to study. Validity is often subdivided into internal – if the actual measurements are correctly representing what is being observed – and external – how generalisable the data is. Additionally, researchers discuss ecological validity, which concerns how closely the research scenario reflects the natural or real world setting stating that field tests have greater validity than treadmill tests due to their greater specificity (George, Batterham and Sullivan, 2003; Nummela, Hämäläinen and Rusko, 2007). Further, research has found that recreational runners tend to choose the intensity and duration of their running on any given day. Thus, studies where the participant selects their own pace have more external validity than those conducted with speed determined within laboratory conditions (Szabo and Ábrahám, 2013). Given these findings, it can be argued that further research for this thesis will have greater ecological validity, with respect to the recreational running population under investigation, if the research is conducted outside, overground.

The decision to conduct further research in the field is supported by the differences in running economy between the treadmill and overground running trials, which is statistically significant ($p < 0.001$) and demonstrates a moderate effect size ($0.35 < d < 0.50$). This suggests that there is a physiological difference between the two conditions. The other physiological measures taken lend weight to this as the heart rate, rating of perceived exertion and metabolic equivalents were all lower in the overground trials compared to treadmill running. Given that the over-riding aim of this thesis is to improve running economy for recreational runners in the field, it can be argued that from an ecological validity perspective, choosing to test overground more accurately replicates the experience in the field for recreational runners. Therefore, the results are valid, additionally when factoring the concurrent validity as discussed earlier in this section, hence going forward, further experimentation can be carried out overground with the recreational running cohort.

4.5 Conclusion

The results of the study discussed in this chapter indicate that while the recorded differences in running economy between a treadmill trial and testing in a field environment are slightly different as borne out by the t-tests and effect size in the results section, conducting trials in the field is a reliable method to assess running economy in recreational runners. Additionally, r-values for concurrent validity (all $p < 0.05$) and the existence of ecological validity support that the method is also valid. The null hypotheses set out in Chapter 2, and restated at the beginning of this chapter, can be rejected, relating to the reliability of testing both in the field on a treadmill. The additional aim, to examine whether there was a statistically significant difference between running economy for overground and treadmill running in recreational runners, showed that there was ($p < 0.05$).

Further, given that much recreational running takes place outside, it is justifiable, for the comfort for the participant, to carry out research in conditions that the participant is more familiar with and so likely to perform more naturally. If the research were to be carried out using treadmill conditions, it would be advisable to introduce an additional familiarisation trial. For example, Jordan, Challis and Newell (2006) recommended a 45-minute session on the treadmill prior to testing, this is due to variations in locomotion seen on the treadmill due to the reduced variability in the stride cycle compared to overground running (Dingwell *et al.*, 2001; García-Pérez *et al.*, 2013). However, this seems an unnecessary step for the participants, given that they will not be continuing to run on a treadmill and the sole purpose of their familiarisation would be to take part in the trial for the purpose of completing this thesis and not be of benefit to them in their running generally. Given that the reliability of metabolic testing overground is acceptable and the argument for ecological validity is strong within this population of runners, the case for conducting all future research overground in the field is accepted.

Following on from this, the next chapter will compare the biomechanics of running overground to those on a treadmill and determine the characteristics in each condition. The aim is to establish whether differences in the biomechanics of running between the field and treadmill conditions will support the proposal to test solely in the field for recreational distance runners.

Chapter 5: A comparison of biomechanical function in recreational runners when running overground and on a treadmill

5.1 Introduction

The previous chapter investigated the reliability and validity of measuring the running economy of recreational distance runners overground, where they habitually run, rather than on a treadmill in laboratory conditions. This chapter focuses on the biomechanical characteristics of running and serves two functions, firstly, to examine the reliability and validity of these measurements when running overground and on a treadmill. Secondly, to compare the findings from the treadmill and overground trials to ascertain whether there are differences between the two conditions. As stated in Chapter 2, the hypotheses to be considered are:

H30: Running overground will not yield reliable values for biomechanical parameters when comparing different overground trials.

H31: Running overground will yield reliable values for biomechanical parameters when comparing different overground trials.

H40: Running on a treadmill will not yield reliable values for biomechanical parameters when comparing different treadmill trials.

H41: Running on a treadmill will yield reliable values for biomechanical parameters when comparing different treadmill trials.

Additionally, the research will include a comparison of the results for all biomechanical parameters recorded (angles of hip, knee and ankle, vertical oscillation, stride length and rate) to see if the values are statistically significantly different when running on the treadmill or overground.

Discussion surrounding the choice of statistical analysis to employ to test for reliability was had in Chapter 3, and, having established these methods as the most appropriate and in common usage, these tests will be again used to examine the data. The aims of this chapter are therefore to examine the hypotheses stated above so as to determine whether the biomechanical data adds support to the proposal to test solely in the field for a cohort of recreational, distance runners.

Sport biomechanics, the study of movement, has predominately been concerned with understanding sports performance, with one of the aims being to improve performance (Lees, 1999). The research conducted here falls within this remit as by improving running economy, improvement can follow in terms of distance covered, time taken or speed for the same energy cost. This chapter focuses on specific biomechanical parameters that are obtainable with Xsens, the motion capture system used: step count, stride length, stride rate, cycle time, vertical oscillation of the centre of mass, and angles of the hip, knee and ankle joints. These parameters have been identified as being both modifiable and potentially impactful on running economy (Moore, 2016). Further, the Xsens equipment affords the additional advantage that the parameters can all be measured in a directly comparable way with the runner either on a treadmill in a laboratory or running overground outside.

As with running economy, studies looking at biomechanical function of running have typically been done using a treadmill indoors and video analysis (Miller *et al.*, 2019). However, this has been described as being a-specific for outdoor running and it is questionable to translate results from a laboratory based study to outdoor running performance, in particular for kinematic data (Van Caekenberghe *et al.*, 2013; Reenalda *et al.*, 2016). This is discussed in greater detail in Chapter 2. Further, it is a recognised limitation of video analysis within a laboratory that it allows only a few strides to be scrutinised and so is not suitable for continuous analysis. The Xsens system allows for continuous data capture throughout the whole testing period, enabling a full minute of data - containing up to 90 gait cycles - to be analysed, as opposed to video motion capture which typically examines 10 cycles (Futrell *et al.*, 2021). One argument for testing on a treadmill is that it is considered to be convenient as many factors, such as temperature, can be controlled and so is often used as a surrogate for overground movement. However, the questions and controversy around how directly comparable the two conditions are when examining biomechanical factors suggest that this needs further clarification. While familiarisation with treadmill running has been cited as a factor when observing differences between the two conditions, recent studies have shown this not to be the case and differences were still identified (Van Hooren *et al.*, 2020). However, the majority of the studies included in van Hooren *et al*.'s study, used a short runway, typically ranging from 15 to 75m, for the overground running, which is not the same as continuous overground running in an open space. Further, the populations studied were commonly capable of speeds greater than 12 km.h^{-1}, which does not describe the more typical recreational running / parkrun population.

Turning to spatiotemporal considerations, Van Caekenberghe *et al*. (2013) tested 10 participants on a treadmill and overground on a continuous 30m indoor running track. Although the main focus of their study was acceleration, some of the parameters they considered are of interest. They found that while there were some similarities in spatiotemporal measures, step duration was significantly shorter on the treadmill when compared to overground (10 ± 9 ms and 12 ± 11 ms respectively). There were significant differences in knee and hip angles between overground and treadmill running as illustrated in Figure 5.1.

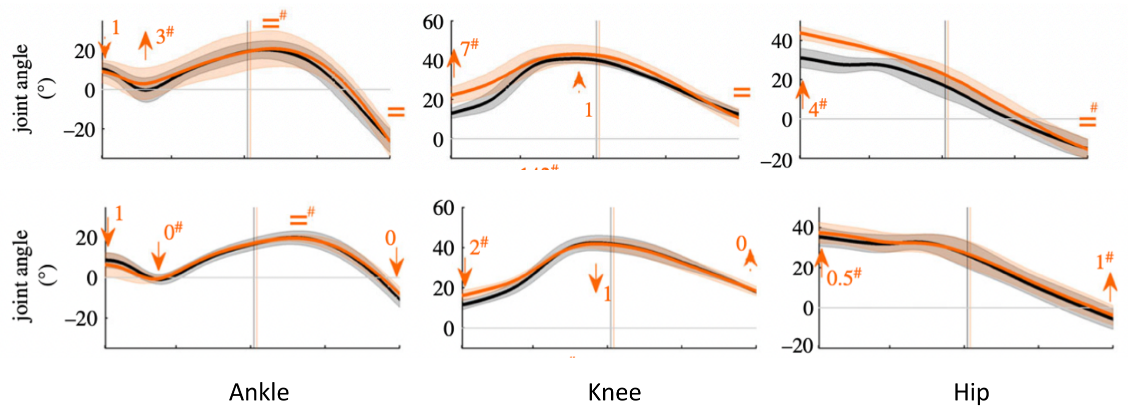


Figure 5.1: The solid black line indicates joint angles during steady state running in overground (above) and treadmill (below) running. Adapted from van Caekenberghe *et al*., (2013)

It is not specified if those taking part were experienced or recreational runners, although given that they were running in steady state at speeds up to and including 7 m.s^{-1} (25 km.h^{-1}) it suggests some level of experience and ability beyond that of typical recreational runners. Parkrun data indicates an average running pace of approximately 2.875 m.s^{-1} (10.35 km.h^{-1}) over a 5 km distance. Further, participants were running on a short, indoor track, which doesn't replicate the free overground movement experienced by the recreational running cohort. Van Caekenberghe *et al*. (2013) conclude that although studying treadmill running can be a valuable method for learning about certain aspects of locomotion, it is not possible to generalise findings from a treadmill condition to running overground. Given that the population investigated here is relatively young (26 ± 3 years) and capable of running at a faster pace than recreational runners, with the overground element being on a 30m indoor runway, this leaves a gap in our understanding of the running pattern of recreational runners between the two conditions of a natural overground running environment and treadmill running, which this study aims to address.

A further study found that there is less variability in stride patterns when walking on a treadmill compared to overground movement, this is attributed to the lack of visual cues and other sensory information which would be found when moving outdoors (Dingwell *et al.*, 2001). While this research investigated walking, it is not unreasonable to extrapolate their conclusions to running, given that the participants were comparable to this study, they were young (27.1 ± 3.25 years), fit and healthy adults with no underlying health conditions or gait issues who chose to walk at a self-selected pace.

A meta-analysis (Moore, 2016) which reviewed spatiotemporal, kinematic and kinetic parameters, found that all of these parameters were broadly similar across the two conditions, overground and treadmill running. However, there were identified differences between the two conditions in the sagittal plane when looking at angles of flexion and extension of the ankle, knee and hip joints which is pertinent to the research conducted in this chapter (Van Hooren *et al.*, 2020). Further, a study of 77 treadmills, 30 artificial turf pitches and 30 athletics tracks examined the differences between mechanical properties of the various surfaces: shock absorption, vertical deformation and energy restitution. These properties were identified as having an impact on the running technique of athletes. The strongest differences in performance were found between the treadmills and overground surfaces, including concrete. This adds support to the argument that recreational runners should be tested on an overground surface as this is where they habitually run, as this study raises questions about the reliability of generalising research conducted on a treadmill to an overground running performance (Colino *et al.*, 2020).

Pink *et al*. (1994) examined 14 recreational runners with an average age of 32 years, a population not dissimilar to that investigated in this research. Their study compared vertical oscillation and sagittal plane motion when treadmill running and overground running. Participants were fitted with reflexive markers on a toe, shin, knee, hip and lateral trunk above the iliac crest to capture the ankle, knee and hip data, and acromion of right shoulder to assess vertical displacement. Four static cameras were used to capture the data, which was then analysed with Vicon. The participants ran at a pace they self-selected, which led to a classification as slow runners, if the pace was below 3.35 $m.s^{-1}$ (12.08 $km.h^{-1}$) and fast runners if pace was greater than 3.58 $m.s^{-1}$ (12.88 $km.h^{-1}$). These speeds, they reasoned, represented joggers at the slower end and serious, non-elite runners at the faster end. Whilst some recreational runners no doubt fall within these categories, there is a large proportion of the recreational running community who are not represented here, using the mean parkrun speeds mentioned earlier. They found that there was no difference between the range of motion in the knee and ankle angles between the two conditions ($p < 0.05$), but they were unable to determine hip angles due to the marker being obfuscated by the runners' hands during the test. Additionally, they report that they recorded data for multiple running cycles, but don't specify how many, which, given the methodology implies a low number. These two factors highlight some advantages of using IMMUs for gathering this data over traditional filming techniques as there is no opportunity to obfuscate the marker and a large number of cycles can be recorded as the participant is not running past fixed camera points. Further, it is possible that when running past fixed point cameras the runner runs in their 'best form' and does not present their usual running style (Farhan, Avalos and Rosenblatt, 2023). This is known as the Hawthorne effect, whereby people modify their performance in response to being observed. Pink *et al*. (1994) did report significantly more vertical oscillation when running overground compared to when using a treadmill, which was reported for both slow and fast runners, 13.8 cm and 11.2 cm for slow and 14.1 cm and 10.7 cm for fast, respectively.

To summarise, this chapter will seek to test the hypotheses set out in Chapter 2 and restated at the start of this chapter, that overground running is reliable and ecologically valid method of experimentation with results that are not significantly statistically different when assessing biomechanical factors in comparison to treadmill running. Subsequently, it should be possible to evaluate whether further studies can confidently focus on only testing participants outside overground.

5.2 Method

5.2.1 Participants

Following ethical approval from the University of East London Research Ethics committee, 40 recreational runners (male=19, female=21) were recruited for the study from local running clubs and the university. Table 5:1 contains the summary details for the participants.

Table 5:1: Anthropometric data as mean ± SD with 95% CI

	Mean ± SD	95% CI
Age (years)	37.45 ± 10.86	(34.09, 40.81)
Mass (kg)	66.86 ± 12.69	(62.93, 70.79)
Height (cm)	170.90 ± 8.41	(168.29, 173.51)

All participants had been running for a minimum of 6 months and were accustomed to running 5 km. They provided written, informed consent and completed a BASES health questionnaire (see Appendices 2 and 3).

5.2.2 Procedure

Participants attended the UEL Docklands campus on two separate occasions not less than a week apart. They were asked to refrain from intense exercise for 24 hours prior to attending, not to eat for 3 hours before and arrive fully hydrated wearing suitable clothing and the same footwear on both occasions. To try to limit any differences that could be the result of circadian rhythms, the tests were conducted as close to the same time of day as possible (Drust *et al.*, 2005).

On the first visit, anthropometric measurements were taken, mass using a standard weighing scale and height with a portable stadiometer (Seca, Birmingham, UK). Additionally, foot size from the heel to the toe, ankle height from the lateral malleolus to the floor, knee height from the lateral epicondyle to the floor, hip height from the greater trochanter to the floor, hip width distance taken as the distance between the left and right anterior superior iliac spine, shoulder width as the distance between the left and right acromions, arm span from the tip of one middle finger to the other with arms at right angles to the body and palms facing forwards (Popovic *et al.*, 2013), and shoe sole height. Measurements were taken to the nearest 0.1 cm with a segmometer

(MVN SegoMeter, Xsens, Enschede, The Netherlands). Where appropriate, measurements were taken ipsilaterally on the left side of the body.

The MTw Awinda IMMUs (Xsens, Enschede, The Netherlands) were then placed on the participant on the 17 sites as outlined in the general methods chapter (Chapter 3).

Participants then performed a 5-minute warm-up at a self-selected pace on a treadmill (Mercury, h/p/cosmos, Nussdorf-Traunstein, Germany), which is sufficient time to count as familiarisation with the equipment (Lavcanska, Taylor and Schache, 2005; Oliveira et al., 2016). The treadmill was set at 1% incline to compensate for the wind resistance that would be experienced outside (Jones and Doust, 1996), participants then performed 5 minutes of self-selected stretching. The overground and treadmill testing protocol followed the method outlined in general methods (Chapter 3).

A coin toss was used to randomly allocate whether the participant ran on the treadmill or overground first, with a 15-minute recovery period between the two trials, the order was reversed on their return visit. The overground run took place on a paved, flat area. A Garmin Forerunner 235 (Garmin International Inc, Olathe, Kansas, USA) recorded no gain or loss in elevation, and this was cross-checked with details of height above sea level as identified by Google Earth which can be seen in Appendix 5. The participants ran for 5 minutes in each of the conditions at the same self-selected usual 5 km pace to enable the runners to reach steady state (Saunders *et al.*, 2004a; Barnes *et al.*, 2013; Boone, Deprez and Bourgois, 2014; Barnes and Kilding, 2015a). The participant's chosen speed was programmed into the treadmill and replicated outside by using a cyclist as a pace setter, who maintained the same steady pace with the aid of a speedometer (YS-Sports, Shenzhen, China). The entirety of each run was recorded using the Xsens MTw Awinda system on a laptop computer, attached to the bike when outside, and next to the treadmill when inside.

As the next phase in this research will examine the impact of biomechanical factors on running economy, in order to faithfully compare measurements, the data from the last minute of each trial was extracted so that the time examined matched the steady state period as discussed in the previous chapter. The data was then imported into Visual 3D (C-Motion, Germantown, MD, USA) and this software was used to identify both kinematic (specifically angles at hip, knee and ankle for left and right sides, vertical oscillation) and spatiotemporal parameters (specifically stride length, stride rate) for all conditions.

The data was analysed to determine the intra-class correlation coefficients (2,1) using a two-way random effects, absolute agreement, single rater measurement and coefficient of variance using SPSS software (IBM SPSS Statistics, Rel. 28.0, 2021, SPSS Inc, Chicago, IL USA) and Excel (Microsoft Corporation, v16.33, Redmond, WA, USA).

5.3 Results

The parameters examined have been grouped into three sections covering (i) centre of mass oscillation, (ii) spatiotemporal parameters; step count, stride length, stride rate, cycle time, and (iii) angle data for hip, knee and ankle. For each set of parameters, descriptive statistics, reliability, agreement and comparisons will be presented.

5.3.1 Centre of mass oscillation

Table 5:2 shows the mean values for centre of mass on both treadmill and overground tests. The mean data is determined from the maximum and minimum points of vertical displacement from each step during the final minute of running.

Table 5:2: Mean values ± standard deviation for centre of mass in metres

	Mean ± SD		Mean ± SD		Mean ± SD
OG01_CoM_max	1.09 ± 0.09	OG01_CoM_min	1.01 ± 0.09	Range	0.08 ± 0.02
OG02_CoM_max	1.06 ± 0.05	OG02_CoM_min	0.99 ±0.04	Range	0.08 ± 0.02
TD01_CoM_max	1.09 ± 0.09	TD01_CoM_min	1.01 ± 0.09	Range	0.08 ± 0.03
TD02_CoM_max	1.07 ± 0.05	TD02_CoM_min	0.99 ±0.05	Range	0.08 ± 0.02

Note: This table denotes the mean maximum and minimum points of vertical displacement of centre of mass during the last minute of each trial for the 40 participants.

Examination of the data revealed that some data points could be considered outliers. For example, a measure for one of the trials for a participant stood out for being noticeably different to the others, specifically, for three of the trials, the participant ran with a centre of mass oscillation of ranging from 11.5 cm to 12.7 cm, however in one, they produced a range of 23.7 cm, almost double that of the other events. This large difference, almost double, suggested that the result was too extreme to be legitimate.

Across the four trials, this outlier would be seen for only one of the trials, therefore, the impact of removing this trial on the mean and standard deviation was investigated and the results are presented in Figure 5.2. This demonstrated that there was little difference when the outliers were removed, therefore, the numbers – which were within three standard deviations of the mean – were left in.

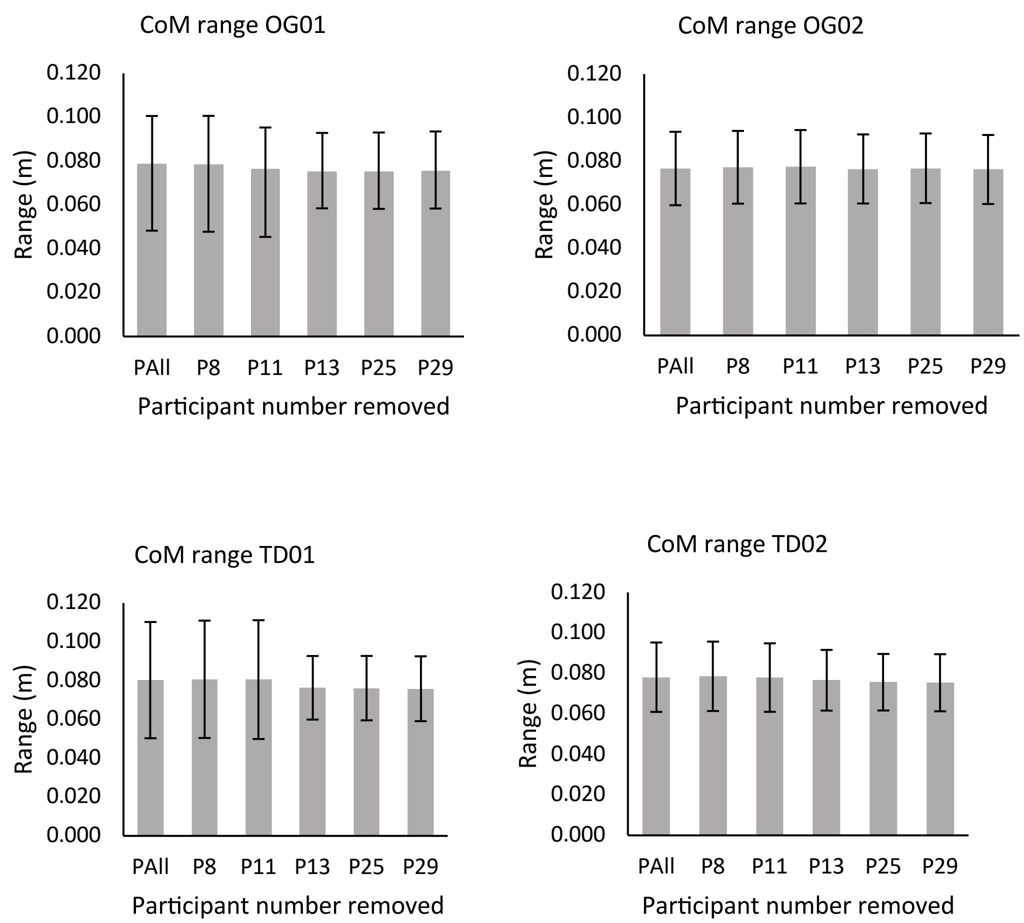


Figure 5.2: Mean and standard deviation - presented as error bars - for all participants, and as each potential outlier is removed.

Table 5:3 examines the reliability of testing in the different trials and presents the information as the standard error of the mean, coefficient of variation and intra-class correlation with the corresponding 95% confidence intervals, using the data from all steps during the final minute. As can be seen all the levels fall within the accepted levels outlined in the General Methods (Chapter 3), where a CV of less than 10% indicates that reliability is assured, reinforced by an ICC > 0.75 being good and > 0.9 being excellent.

Table 5:3: Standard error coefficient of variance (CV) and intra-class correlation (ICC), for the centre of mass maximum and minimum

	Std Error	CV (%) mean ± SD	ICC	95% CI
OG01_CoM_max	0.015	1.62 ± 0.99	0.951	(0.928, 0.970)
OG02_CoM_max	0.008	1.50 ± 0.72	0.892	(0.841, 0.933)
TD01_CoM_max	0.022	1.38 ± 0.77	0.968	(0.953, 0.980)
TD02_CoM_max	0.008	1.25 ± 0.60	0.921	(0.887, 0.951)
OG01_CoM_min	0.015	1.48 ± 1.09	0.962	(0.943, 0.977)
OG02_CoM_min	0.007	1.23 ± 0.63	0.913	(0.871, 0.947)
TD01_CoM_min	0.015	1.23 ± 0.95	0.979	(0.968, 0.987)
TD02_CoM_min	0.009	1.15 ± 0.99	0.925	(0.893, 0.954)

Note: Calculated from the last minute of data from all the 40 participants the four trials. The range of CoM is not included as it is calculated from the max and min data. OG = overground running and TD = treadmill running

Examination of the range of centre of mass oscillation using a Kolmogorov-Smirnov test found that the data was not normally distributed (tests of normality can be found in Appendix 4). Therefore, the non-parametric Wilcoxon signed rank tests were used to compare the findings from each test, with the results presented in Table 5:4. Bland-Altman plots showing the levels of agreement between the test conditions can be seen in Figure 5.3.

Table 5:4: Comparing range of vertical oscillation

Range tested	t (p-value)	r (p-value)
OG01 & OG02	-1.186 (0.236)	0.37 (0.020)
TD01 & TD02	-1.129 (0.259	0.44 (0.004)
OG01 & TD01	-1.304 (0.192)	0.73 (<0.001)
OG02 & TD02	5.511 (<0.001)	0.33 (0.039)

Note: The range of motion across the 40 trials is not normally distributed so non-parametric tests were used to compare the means and examine the correlation. OG = overground running and TD = treadmill running.

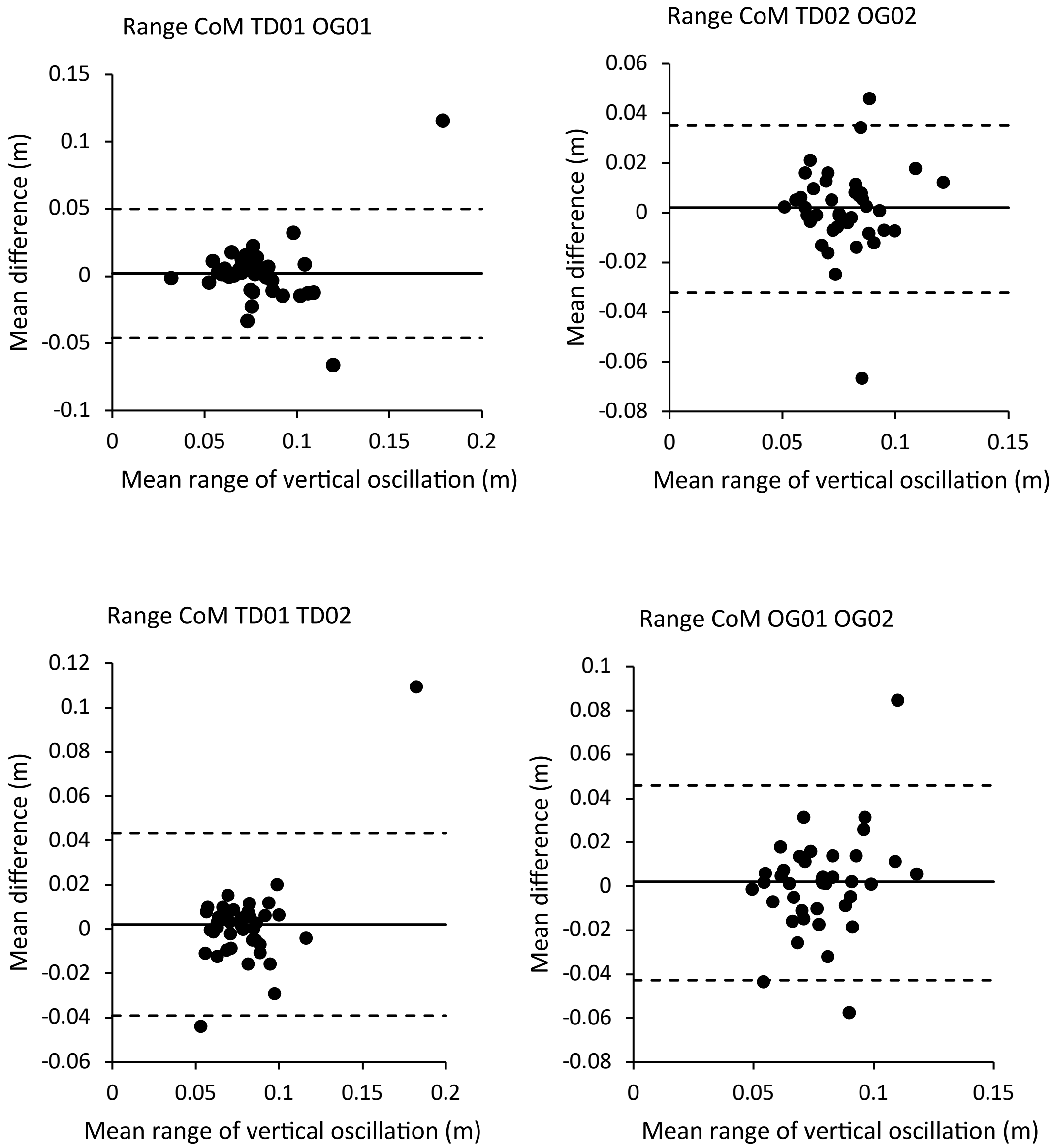


Figure 5.3: Bland Altman plots for range of centre of mass oscillation comparing the different trial. The x-axis is the range of motion (m) and the y axis denotes the mean difference (m). The dashed lines denote the 95% limits of agreement and the solid line denotes the mean bias.

5.3.2 Step count, stride rate, stride length, cycle time

Similarly for the step, stride rate, stride length and cycle time data, the mean values ± standard deviation were calculated (Table 5:5) and the standard error of the means (Table 5:6).

Table 5:5: Step count (steps per minute), stride rate, stride length and cycle time, mean values ± standard deviation

	Mean ± SD			
	Step count	Stride rate (Hz)	Stride length (m)	Cycle time (s)
OG01	171 ± 18.77	1.43 ± 0.16	2.21 ± 0.43	0.71 ± 0.06
OG02	170 ± 20.49	1.41 ± 0.17	2.24 ± 0.45	0.72 ± 0.07
TD01	170 ± 9.83	1.41 ± 0.08	2.22 ± 0.38	0.71 ± 0.04
TD02	170 ± 11.24	1.41 ± 0.09	2.22 ± 0.40	0.71 ± 0.05

Note: The mean and standard deviation for each measure was determined during the final minute of each trial for all 40 participants. OG = overground running and TD = treadmill running.

Table 5:6: Standard error for step count, stride rate, stride length and cycle time

	Standard error			
	Step count	Stride rate (Hz)	Stride length (m)	Cycle time (s)
OG01	2.966	0.025	0.067	0.010
OG02	3.232	0.027	0.071	0.011
TD01	1.551	0.013	0.061	0.007
TD02	1.777	0.015	0.063	0.008

Note: The standard error for each measure was determined during the final minute of each trial for all 40 participants.

In order to determine the coefficient of variance and the intra-class correlation, the overground trials were considered together, and the treadmill trials were considered together. The results are presented in Table 5.7.

Table 5:7: Coefficient of variance and intra-class correlation with 95% confidence intervals for step count, stride rate, stride length and cycle time

Variable	Trials	CV (%) mean ± SD	ICC	95% CI for ICC
Step count	OG01 & OG02	4.27 ± 8.01	0.128	(-0.188, 0.420)
	TD01 & TD02	1.40 ± 0.97	0.922	(0.858, 0.958)
Stride rate	OG01 & OG02	4.27 ± 8.01	0.126	(-0.189, 0.418)
	TD01 & TD02	1.40 ± 0.97	0.923	(0.859, 0.928)
Stride length	OG01 & OG02	4.27 ± 8.01	0.841	(0.719, 0.913)
	TD01 & TD02	1.40 ± 0.97	0.992	(0984, 0.996)
Cycle time	OG01 & OG02	4.27 ± 8.01	0.265	(-0.047, 0.530)
	TD01 v& TD02	1.40 ± 0.97	0.927	(0.866, 0.961)

Note: Calculated from the last minute of data from all the 40 participants the four trials. OG = overground running and TD = treadmill running.

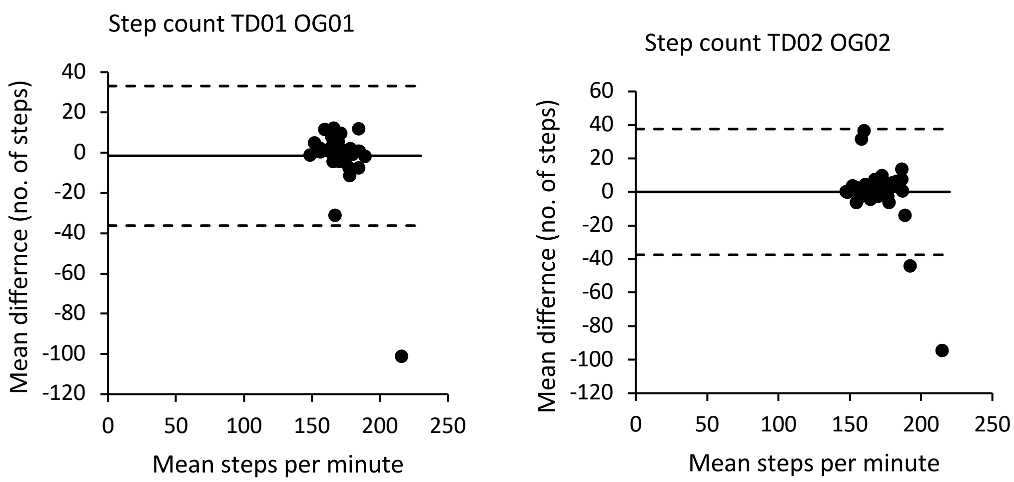
Having tested for normality (results can be found in Appendix 4), the trial conditions were compared using a student t-test, and the levels of agreement compared using Bland-Altman plots.

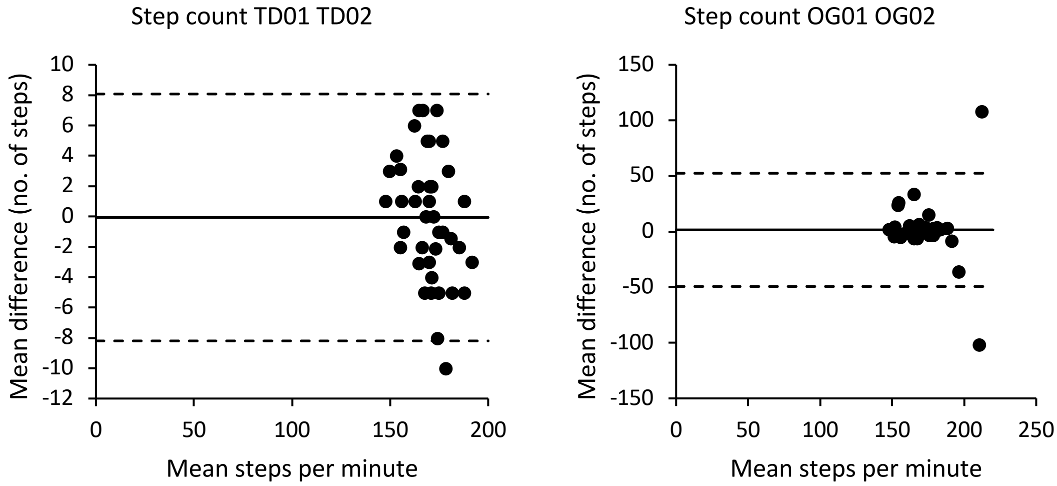
Table 5:8: Comparing steps, stride length, stride rate and cycle times

Parameter	Trial	t (p-value)	Correlation (p-value)
Steps (min^{-1})	OG01 & TD01	-0.563 (0.577)	0.368 (0.020)
	OG02 & TD02	0.050 (0.961)	0.389 (0.013)
	OG01 & OG02	0.403 (0.689)	0.128 (0.013)
	TD01 & TD02	-0.114 (0.910)	0.931 (<0.001)
Stride rate (Hz)	OG01 & TD01	-0.558 (0.580)	0.367 (0.020)
	OG02 & TD02	0.017 (0.987)	0.391 (0.013)
	OG01 & OG02	0.379 (0.707)	0.127 (0.436)
	TD01 & TD02	-0.087 (0.931)	0.931 (<0.001)
Stride length (m)	OG01 & TD01	0.176 (0.861)	0.922 (<0.001)
	OG02 & TD02	-0.661 (0.512)	0.904 (<0.001)
	OG01 & OG02	-0.708 (0.483)	0.842 (<0.001)
	TD01 & TD02	-0.368 (0.715)	0.993 (<0.001)
Cycle time (s)	OG01 & TD01	0.265 (0.792)	0.509 (<0.001)
	OG02 & TD02	-0.562 (0.602)	0.495 (<0.001)
	OG01 & OG02	-0.631 (0.532)	0.268 (0.094)
	TD01 & TD02	-0.203 (0.840)	0.935 (0.001)

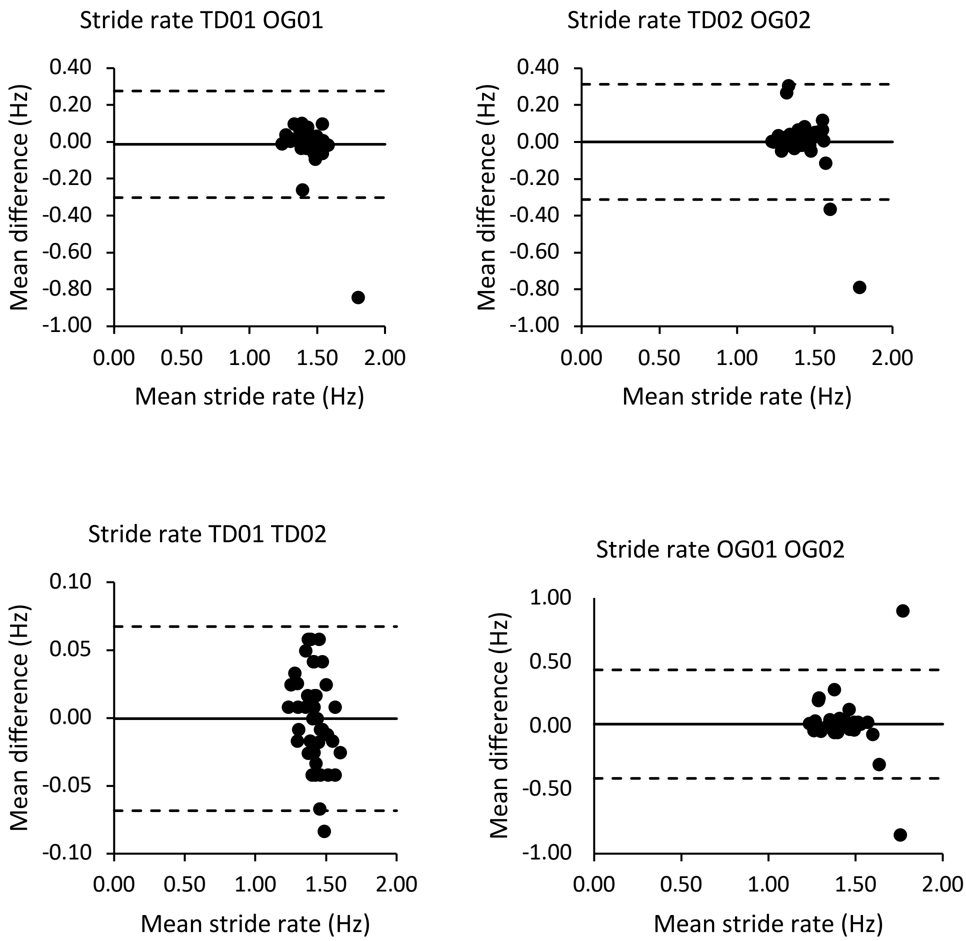
Note: All parameters are normally distributed using a Kolmogorov-Smirnov test, so a student t- test was used to compare the means. OG = overground running and TD = treadmill running.

(A)

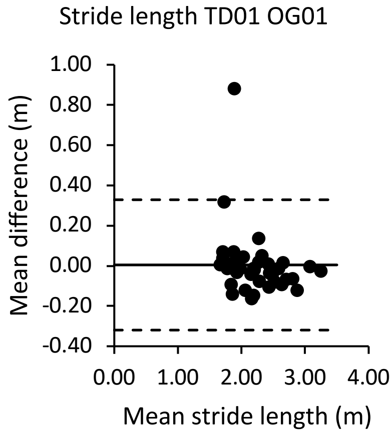


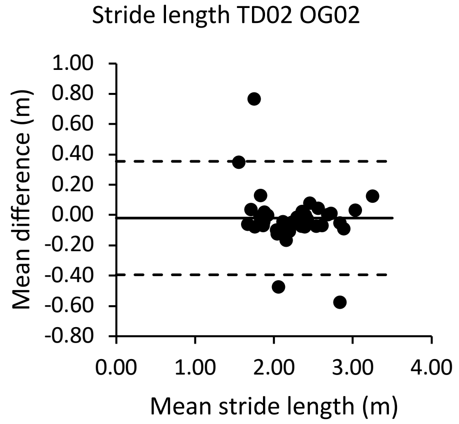

Step count TD01 TD02
Mean difference (no. of steps)
Mean steps per minute
Step count OG01 OG02
Mean difference (no. of steps)
Mean steps per minute

(B)


Stride rate TD01 OG01
Mean difference (Hz)
Mean stride rate (Hz)
Stride rate TD02 OG02
Mean difference (Hz)
Mean stride rate (Hz)
Stride rate TD01 TD02
Mean difference (Hz)
Mean stride rate (Hz)
Stride rate OG01 OG02
Mean difference (Hz)
Mean stride rate (Hz)

(C)


Stride length TD01 OG01
Mean difference (m)
Mean stride length (m)
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
0.00
1.00
2.00
3.00
4.00


Stride length TD02 OG02
Mean difference (m)
Mean stride length (m)
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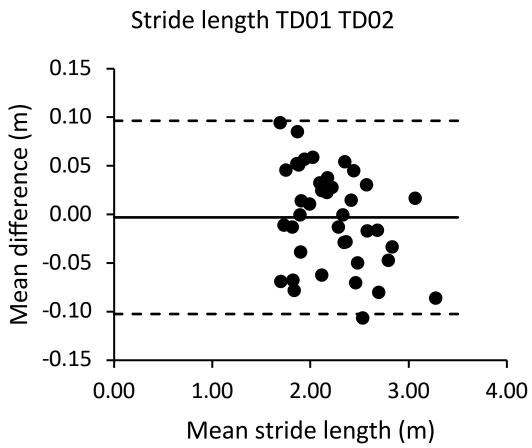
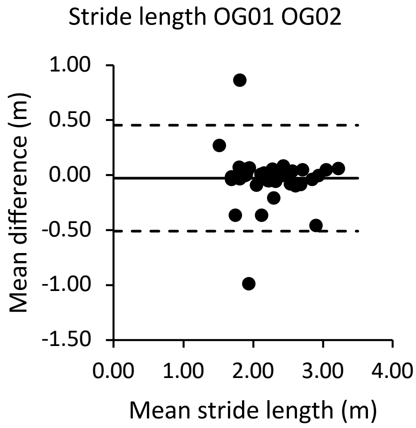
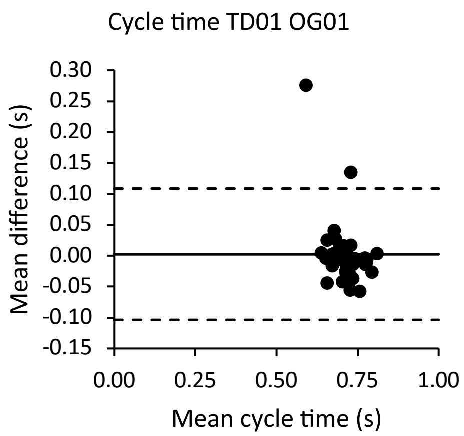
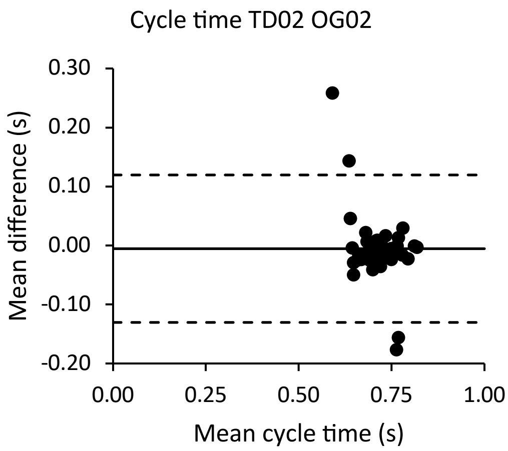
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
0.00
1.00
2.00
3.00
4.00


Stride length TD01 TD02
Mean difference (m)
Mean stride length (m)
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
0.00
1.00
2.00
3.00
4.00


Stride length OG01 OG02
Mean difference (m)
Mean stride length (m)
1.00
0.50
0.00
-0.50
-1.00
-1.50
0.00
1.00
2.00
3.00
4.00

(D)


Cycle time TD01 OG01
Mean difference (s)
Mean cycle time (s)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
0.00
0.25
0.50
0.75
1.00


Cycle time TD02 OG02
Mean difference (s)
Mean cycle time (s)
0.30
0.20
0.10
0.00
-0.10
-0.20
0.00
0.25
0.50
0.75
1.00

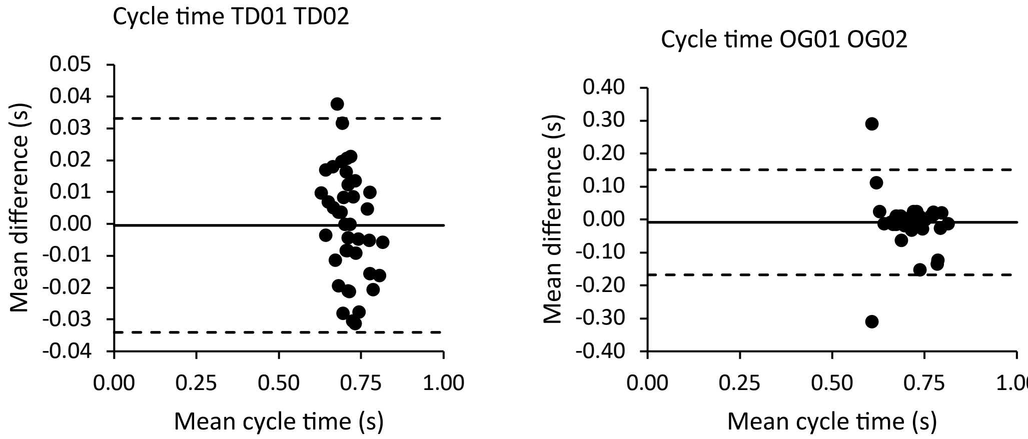


Figure 5.4: Bland Altman plots for range of (A)step count, (B) stride rate, (C) stride length and (D) cycle time. All measurements are taken during the final minute of each trial for 40 participants across each of the four trials. The dashed lines denote the 95% limits of agreement and the solid line denotes the mean bias. OG = overground running and TD = treadmill running.

5.3.3 Hip, knee and ankle angles

The average maximum and minimum angle for each of the hip, knee and ankle were calculated and used to determine the range. The mean ± standard deviation are presented in Table 5:9.

Table 5:9: Mean values ± standard deviation in ^{O} for the maximum, minimum and range of values for the left and right hip, knee and ankle.

	Mean ± SD		Mean ± SD		Mean ± SD
OG01_RH_max	21.72 ± 12.89	OG01_RH_min	-31.45 ± 15.01	Range	53.17 ± 10.90
OG01_LH_max	20.74 ± 13.12	OG01_LH_min	-30.53 ± 16.03	Range	51.27 ± 15.26
OG02_RH_max	23.82 ± 12.15	OG02_RH_min	-29.63 ± 11.87	Range	53.45 ± 10.34
OG02_LH_max	21.54 ± 10.26	OG02_LH_min	-30.45 ± 13.47	Range	52.00 ± 13.96
TD01_RH_max	23.77 ± 9.81	TD01_RH_min	-29.82 ± 10.65	Range	53.59 ± 9.87
TD01_LH_max	23.65 ± 8.01	TD01_LH_min	-32.73 ± 9.94	Range	56.38 ± 11.45
TD02_RH_max	24.06 ± 10.51	TD02_RH_min	-30.19 ± 10.03	Range	54.25 ± 8.63
TD02_LH_max	22.32 ± 9.25	TD02_LH_min	-32.56 ± 10.44	Range	54.88 ± 13.19
OG01_RK_max	65.65 ± 19.19	OG01_RK_min	7.52 ± 14.22	Range	58.13 ± 10.24
OG01_LK_max	61.67 ± 19.21	OG01_LK_min	2.13 ± 20.38	Range	59.54 ± 17.49
OG02_RK_max	69.54 ± 16.66	OG02_RK_min	7.74 ± 16.59	Range	61.80 ± 7.90
OG02_LK_max	68.57 ± 10.54	OG02_LK_min	10.45 ± 7.79	Range	58.12 ± 8.60
TD01_RK_max	69.57 ± 12.06	TD01_RK_min	9.12 ± 4.96	Range	60.44 ± 11.25
TD01_LK_max	68.75 ± 8.53	TD01_LK_min	10.46 ± 4.18	Range	58.29 ± 8.24
TD02_RK_max	69.10 ± 15.52	TD02_RK_min	7.93 ± 13.17	Range	61.18 ± 9.04

TD02_LK_max	69.67 ± 10.46	TD02_LK_min	10.49 ± 4.01	Range	59.18 ± 9.85
OG01_RA_max	26 65 ± 9.92	OG01_RA_min	-20.83 ± 4.82	Range	47.47 ± 9.54
OG01_LA_max	28.81 ± 11.03	OG01_LA_min	-20.37 ± 5.08	Range	49.18 ± 10.14
OG02_RA_max	27.51 ± 12.23	OG02_RA_min	-20.18 ± 4.93	Range	47.69 ± 10.95
OG02_LA_max	26.52 ± 8.17	OG02_LA_min	-20.74 ± 5.47	Range	47.27 ± 9.51
TD01_RA_max	24.24 ± 9.18	TD01_RA_min	-19.12 ± 4.75	Range	43.36 ± 9.65
TD01_LA_max	23.17 ± 8.52	TD01_LA_min	-19.42 ± 4.56	Range	42.59 ± 8.41
TD02_RA_max	24.72 ± 11.47	TD02_RA_min	-17.83 ± 6.04	Range	42.55 ± 10.51
TD02_LA_max	23.70 ± 9.12	TD02_LA_min	-19.90 ± 3.47	Range	43.60 ± 9.60

Note: The mean and standard deviation for each measure was determined during the final minute of each trial for all 40 participants. OG = overground running and TD = treadmill running.

However, given the large amount of data collected, comparisons between left and right for each angle was conducted using a series of Wilcoxon Signed Rank tests due to the mix of the numbers being normal and not normally distributed. In all but three of the 36 cases, the comparison between left and right showed no significant difference between the two sides of the body, with p-value set to 0.05. For this reason, results for the left side are presented from here forwards. Further, the tests were performed comparing the two overground trials with each other and, similarly, the two treadmill trials with each other. In this instance, there was only one case where the p value indicated that the trials were different (p= 0.05). Therefore, again for clarity, the results from the second of each of the trials are presented. So Table 5:10 shows the reliability data for all the left side angle data and Table 5:11 compares the means for the second overground and treadmill trials for the left side angle data.

Table 5:10: Standard error, coefficient of variance and intra-class correlation, left hip, knee and ankle min and max angles

	Std Error	CV (%) mean ± SD	ICC	95% CI
OG02_ LH_max	1.623	13.59 ± 33.36	0.951	(0.919, 0.72)
OG02_ LH_min	2.131	-5.75 ± 9.64	0.972	(0.953, 0.984)
TD02_ LH_max	1.463	6.23 ± 4.30	0.985	(0.977, 0.991)
TD02_ LH_min	1.650	-4.89 ± 2.47	0.981	(0.972, 0.989)
OG02_ LK_max	1.667	2.64 ± 1.49	0.975	(0.958, 0.986)
OG02_ LK_min	1.232	3.20 ± 59.62	0.940	(0.889, 0.968)

TD02_ LK_max	1.653	2.03 ± 1.041	0.980	(0.970, 0.988)
TD02_ LK_min	0.634	18.70 ± 22.49	0.900	(0.857, 0.937)
OG02_ LA_max	1.291	9.05 ± 6.820	0.955	(0.925, 0.974)
OG02_ LA_min	0.865	-8.16 ± 5.731	0.955	(0.926, 0.974)
TD02_ LA_max	1.441	10.48 ± 7.450	0.936	(0.907, 0.960)
TD02_ LA_min	0.548	-5.92 ± 1.934	0.893	(0.848, 0.933)

Note: Calculated from the last minute of data from all the 40 participants the four trials. OG = overground running and TD = treadmill running. LH= left hip, LK = left knee and LA= left ankle.

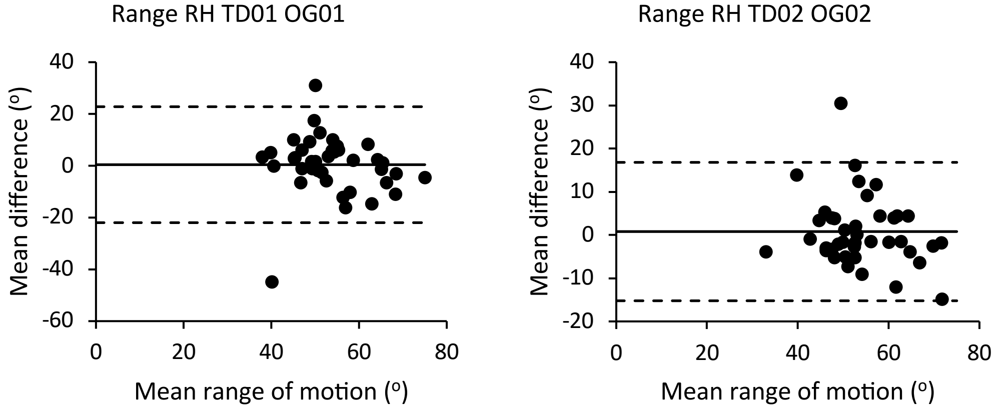
Table 5:11: Comparing the means for overground trial 2 and treadmill trial 2

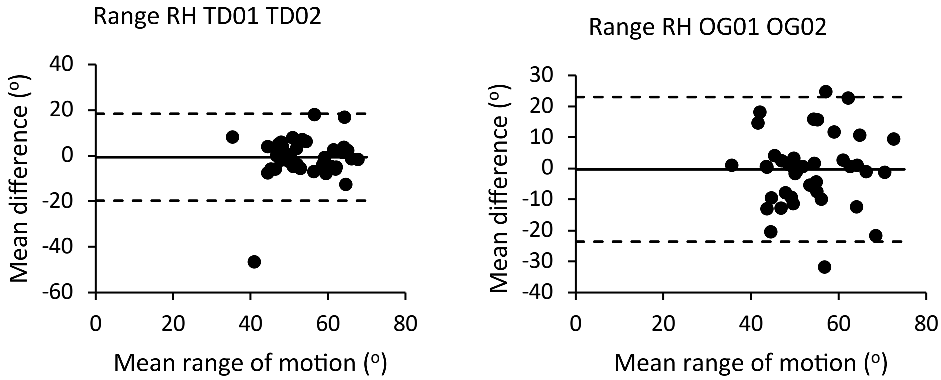
TD02 & OG02	t (p-value)	r (p-value)
LH_max	0.436 (0.665)	0.331 (0.037)
LH_min	-1.068 (0.292)	0.482 (0.002)
LH_range	1.823 (0.076)	0.730 (<0.001)
LK_max	0.588 (0.560)	0.368 (0.020)
LK_min	0.497 (0.619)	0.628 (<0.001)
LK_range	-0.538 (0.591)	0.510 (<0.001)
LA_max	-2.244 (0.031)	0.581 (<0.001)
LA_min	1.308 (0.198)	0.665 (<0.001)
LA_range	-2.749 (0.009)	0.610 (<0.001)

Note: Calculated from the last minute of data from all the 40 participants the four trials. OG = overground running and TD = treadmill running. LH= left hip, LK = left knee and LA= left ankle.

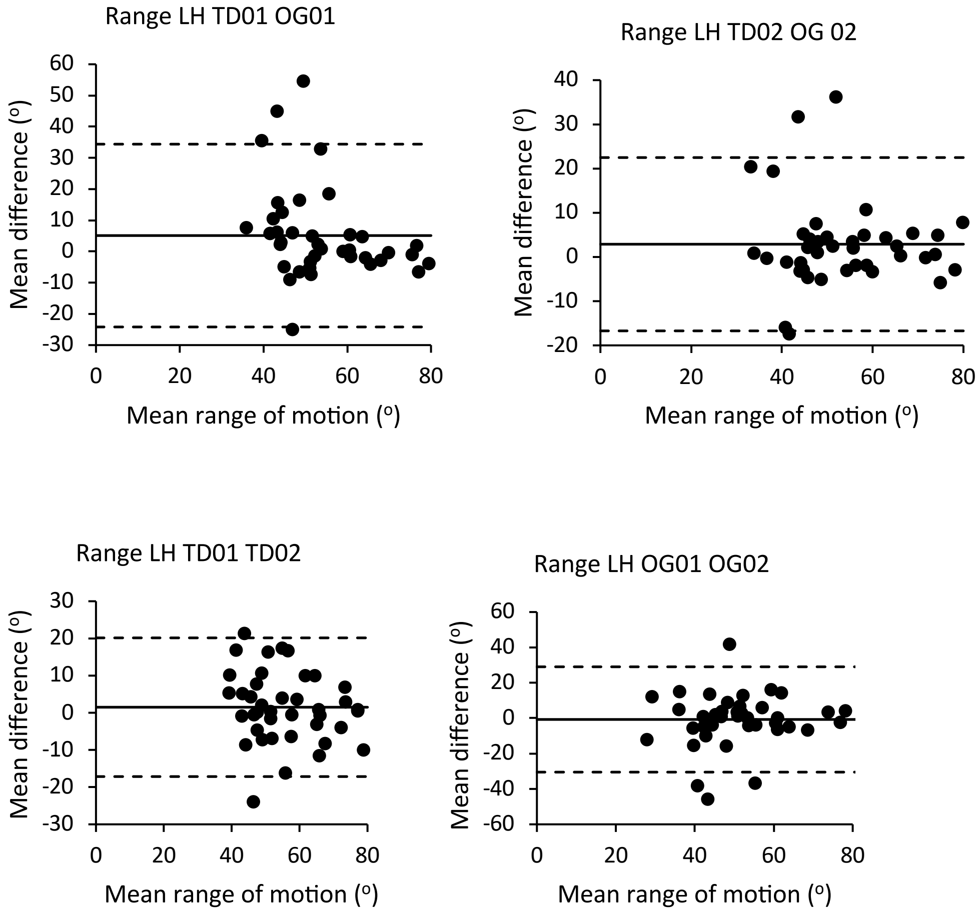
Figure 5.5 shows the 95% levels of agreement for the range of hip, knee and ankle angles from the left and right side for overground and treadmill running.

(A)

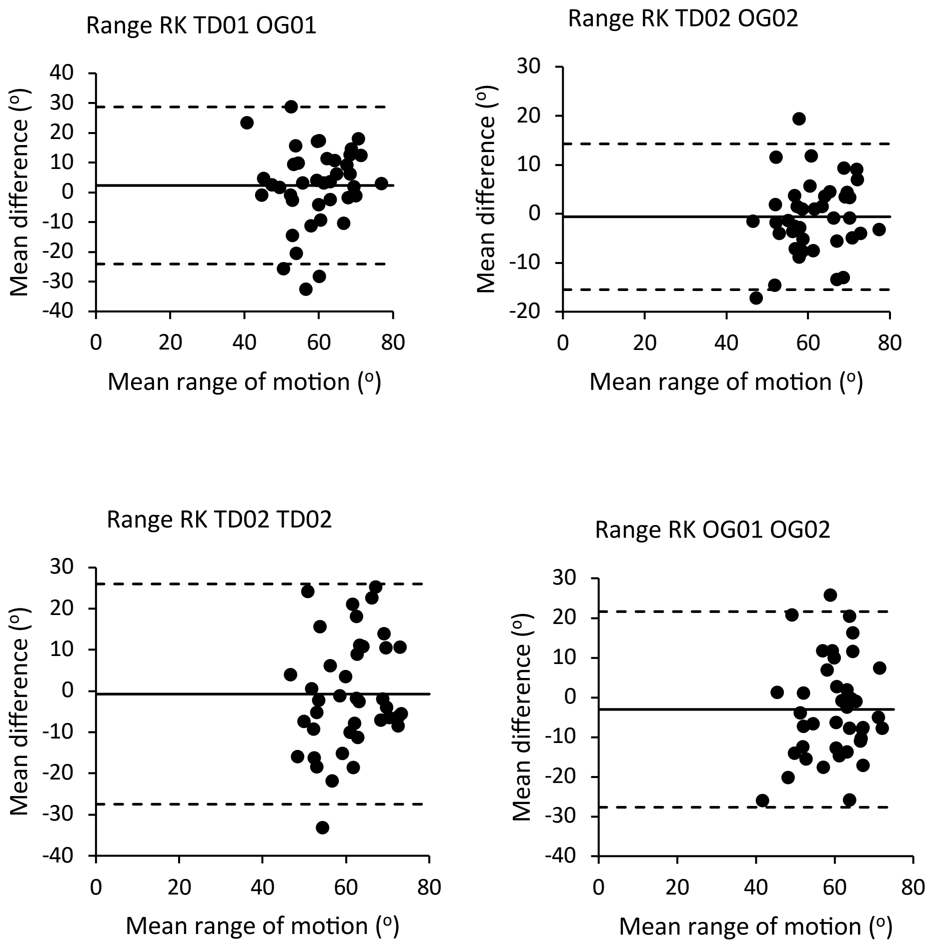



Range RH TD01 TD02
Mean difference (°)
Mean range of motion (°)
Range RH OG01 OG02
Mean difference (°)
Mean range of motion (°)

(B)

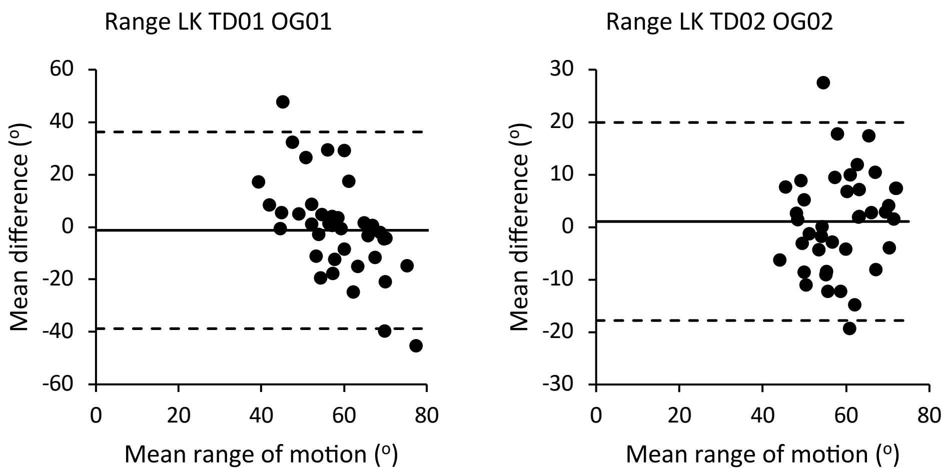

Range LH TD01 OG01
Mean difference (°)
Mean range of motion (°)
Range LH TD02 OG 02
Mean difference (°)
Mean range of motion (°)
Range LH TD01 TD02
Mean difference (°)
Mean range of motion (°)
Range LH OG01 OG02
Mean difference (°)
Mean range of motion (°)

(C)

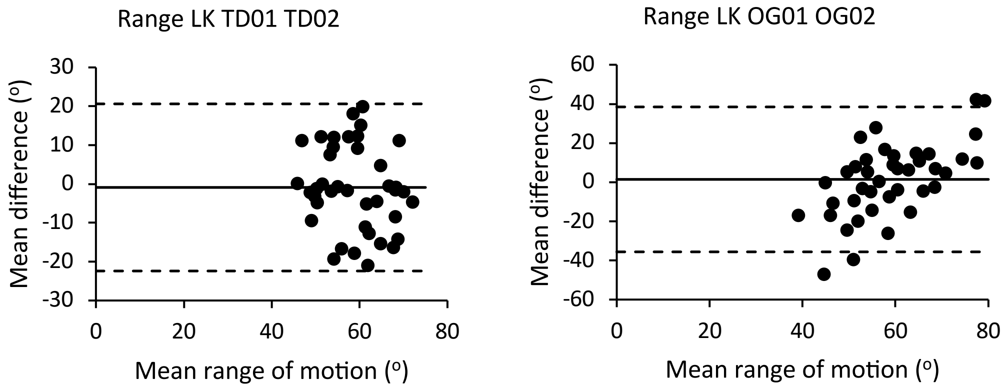


Range RK TD01 OG01
Range RK TD02 OG02
Range RK TD02 TD02
Range RK OG01 OG02
Mean difference (°)
Mean range of motion (°)

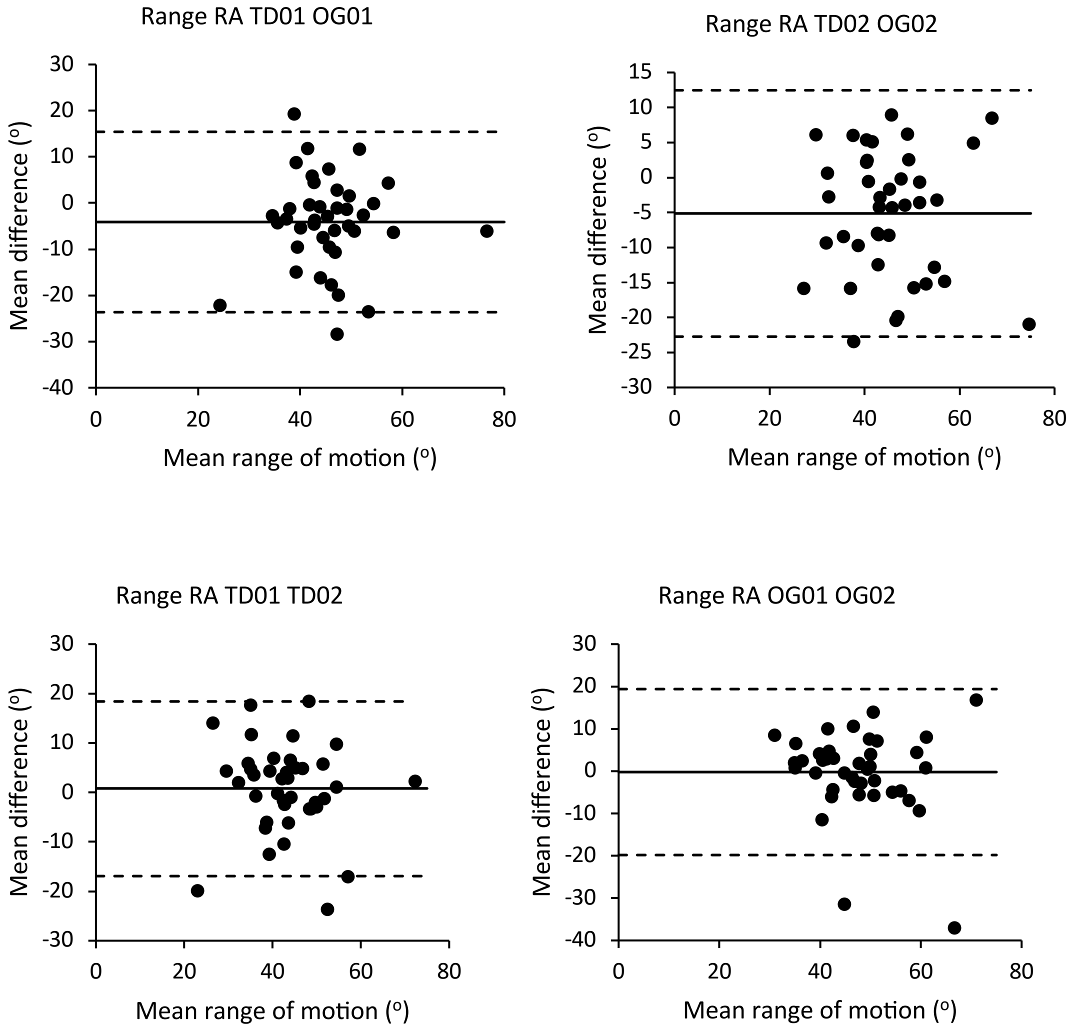
(D)



Range LK TD01 OG01
Range LK TD02 OG02
Mean difference (°)
Mean range of motion (°)


Range LK TD01 TD02
Mean difference (°)
Mean range of motion (°)
Range LK OG01 OG02
Mean difference (°)
Mean range of motion (°)

(E)


Range RA TD01 OG01
Mean difference (°)
Mean range of motion (°)
Range RA TD02 OG02
Mean difference (°)
Mean range of motion (°)
Range RA TD01 TD02
Mean difference (°)
Mean range of motion (°)
Range RA OG01 OG02
Mean difference (°)
Mean range of motion (°)

(F)

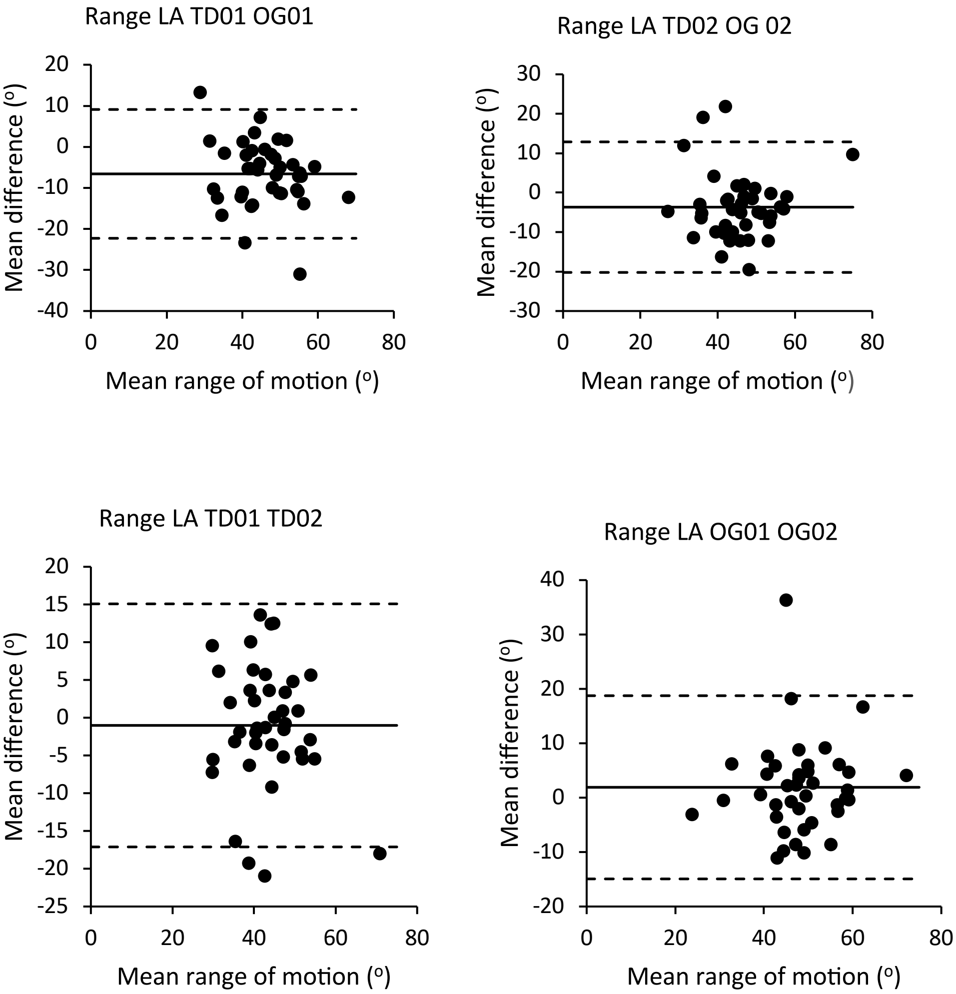


Figure 5.5: Bland Altman plots for range of movement for (A) right hip, (B) left hip, (C) right knee, (D) left knee, (E) right ankle and (F) left ankle angles. All measurements are taken during the final minute of each trial for 40 participants across each of the four trials. The y-axis is the mean difference (°) and the x-axis is the range of motion (°). The dashed lines denote the 95% limits of agreement and the solid line denotes the mean bias.

5.4 Discussion

5.4.1 General discussion

In all the areas examined, the parameters met the criteria to be accepted as reliable data. Centre of mass oscillation returned strong results in all trials with a low coefficient of variance (< 2%) across all measurements and a strong set of intra-class correlation results, ranging from 0.892 to 0.968. Similarly, for the stride related data, the coefficient of variance was comfortably within the acceptable parameters (< 4.5%), although the intra-class correlation was slightly low for the overground trials, apart from stride length (0.841) which is an area of particular interest. While there were some coefficient of variance measures that were outside the ideal 10% requirement, they were still within 20%, which is deemed to be acceptable (Reed, Lynn and Meade, 2002; Haff *et al.*, 2015; Murray, Beaven and Hébert-Losier, 2018). Additionally, when the coefficient of variance is considered alongside the intra-class correlation results, which all measure strongly above 0.89, it can be accepted that the testing procedures for measuring the biomechanical parameters in this trial are reliable, for both treadmill and overground running. Bland-Altman plots showed that there was a good level of agreement between the parameters. All the results indicate that the methods used were reliable and valid. The next few sections will examine the different parameters to compare treadmill running with overground running in this population.

5.4.2 Centre of mass oscillation

Prior to examining comparisons of results, an examination of the data identified a number of outliers in the range of displacement of centre of mass. It was investigated whether those that were either two or three standard deviations outside the mean should be removed. However, on closer examination, only two data points were found to be outside three standard deviations from the mean. Given that the impact on the group mean and standard deviation of removing these data points was nominal (see Figure 5.2), and that the anomalies occurred in different participants in different trials, it was not detrimental to the integrity of the data as a whole to keep these potential outliers in the data set. Having established this, the data could then be examined for reliability and agreement between the conditions and compare treadmill to overground.

Contrary to the findings of Pink *et al.* (1994) there was no difference in vertical oscillation between treadmill and overground running, with a consistent 0.08 m in each trial. However, a t-test suggested that there was some difference between overground and treadmill running ($p < 0.001$). However, the Pink *et al.* (1994) trial used a treadmill with no incline and the overground conditions were limited to a 15 m surface, which was inside the laboratory. It could be argued that neither of these conditions sufficiently replicate the outdoor overground running experience. There seems to be a section of work examining the varying impact of altering vertical oscillation on other aspects of running such as cadence and again on a treadmill (Watari *et al.*, 2016; Adams *et al.*, 2018), but little that examines the impact on running economy. Increasing vertical oscillation has been shown to significantly raise running economy from 46.1 ± 2.0 $ml.kg^{-1}.min^{-1}$ to 51.0 ± 2.5 $ml.kg^{-1}.min^{-1}$, when actively exaggerating movement on a treadmill (Tseh, Caputo and Morgan, 2008). However, this doesn't demonstrate whether a lower, more controlled displacement would benefit running economy or any indication whether the method used, hitting a target placed above the treadmill, could be replicated outside.

5.4.3 Step count, stride rate, stride length and cycle time

All four of the spatiotemporal parameters were recorded and analysed, but as they are all related, the discussion will focus on stride length and stride rate. In particular because it is known that these parameters are modifiable in a recreational running population (Quinn *et al.*, 2021; Sellés-Pérez *et al.*, 2022). It is typical to see a stride length of somewhere between 1.15 and 1.17 times the height of the person, which for the participants in this thesis, with a mean height of 1.70 m, would predict a stride length of 1.96 to 1.99 m (Elliott and Blanksby, 1979). The average stride length across all four trials ranged from 2.21 m to 2.24 m, which, although slightly longer than predicted, compares well with previous studies that recorded stride lengths of 2.01 m to 2.38 m (Squadrone *et al.*, 2015; Zimmermann and van Valderen, 2021).

The results from this study showed no statistically significant differences in stride length, stride rate or cycle time between treadmill and overground running ($p > 0.05$), however, it is suggested that there is a change in the stride cycle pattern. In particular, there is a decrease in the variability of the stride cycle demonstrated on a treadmill, possibly due to the rhythmic pattern of the treadmill acting like a pacemaker. This adds weight to the argument that overground trials have more ecological validity than treadmill running when translating the findings into overground distance running for recreational runners.

5.4.4 Hip, knee and ankle angles

Turning to the angles at the hip, knee and ankle, the results showed that for the hip and knee there was no difference between the treadmill and overground running conditions ($p > 0.05$). However, there was a difference in the maximum ankle angle and the range of motion in the ankle ($p = 0.03$, $p = 0.009$). The maximum overground being 26.52^{o} ±

8.17 ^{o}, compared to 23.70 ^{o} ± 9.12 ^{o} on the treadmill, and an overground range of 47.27 ^{o} ± 9.51^{o} compared to 43.60 ^{o} ± 9.60^{o}.

5.5 Conclusion

This chapter set out to examine the reliability and validity of the potentially modifiable biomechanical factors investigated and to compare the performance on the treadmill with that overground. In line with the previous chapter, which was concerned with running economy, it has now been established that testing participants overground in their habitual running environment is an ecologically valid and reliable method when examining biomechanical variables. Further, similarly to Chapter 4, r-values (all $p < 0.05$) showed that there was concurrent validity. The null hypotheses identified in Chapter 2 and restated in the introduction can be rejected. This adds further weight to the evidence from the previous chapter to support the case for studying recreational runners in a field environment. Further, there were significant differences between the range of vertical oscillation between treadmill 2 and overground 2 ($p < 0.001$), and also the range and minimum ankle angles ($p = 0.03$ and $p = 0.009$). These results suggest participants slightly adapt some of their biomechanical features when running on a treadmill compared with overground, reinforcing the ecological validity of running overground for this cohort of runners and confirming, alongside the running economy findings, that future testing should take place outside, overground.

The next chapter will examine which of the biomechanical factors assessed have the strongest relationship with running economy and subsequently the potential for helping to improve running economy.

Chapter 6: Determining the impact of biomechanical variables on running economy

6.1 Introduction

The aims of the previous two chapters were manifold. Initially, the data was assessed to determine whether the findings were reliable and valid for both the physiological and the biomechanical data. Comparisons were then made to establish whether it was reasonable to focus future testing to only an outdoor, overground setting instead of indoors using the treadmill, for this cohort of runners. The motivation behind this was that, as has been discussed in Chapter 2, most recreational runners habitually run overground outdoors rather than on an indoor treadmill and so testing outside would be a more ecologically valid experience. The results found indicate that for future research, testing recreational runners outside is an acceptable experimental method, meaning that the results are reliable when compared to the established testing method of treadmill running. Therefore, the next phase of the research and the aim of this chapter, as outlined in Chapter 2, is to examine all the biomechanical factors measured to isolate the one(s) that have the strongest relationship to running economy, focussing on the results from the outdoor, overground trials. The purpose of this is to enable the researcher to be able to recommend an adaptation to a runner's biomechanical performance that will improve running economy, therefore enabling them to run further, faster of for longer for the same metabolic cost.

The intrinsic biomechanical factors examined as part of this study can be categorised as spatiotemporal, the parameters concerned with vertical oscillation and aspects of the gait cycle, namely stride length, stride rate and cycle time; and kinematic, the factors that describe the movement patterns, such as joint angles at the ankle, knee and hip.

Vertical oscillation has been the subject of a number of studies, given that it is a modifiable factor, which has been successfully demonstrated using both visual and auditory cues (Eriksson, Halvorsen and Gullstrand, 2011). Research suggests that female runners tend to have a lower range of vertical oscillation than males, although it is unclear as to whether this also means they have a more economical running pattern (Bransford and Howley, 1977; Williams, Cavanagh and Ziff, 1987; Helgerud, Støren and

Hoff, 2010). Halvorsen, Eriksson and Gullstrand (2012) reported a lowering in running economy with a decrease in centre of mass displacement. However, the population consisted of 16 male runners who compete at a national level, with a running test carried out on a treadmill at a speed of 16 $km.h^{-1}$, which is beyond the running speed of most recreational runners, so it cannot be assumed that the results from this study would translate is directly to the recreational running population. Additionally, recreational runners are more accustomed to running on road conditions and will not have had access to coaching that high-level competitive athletes will have had. Several other studies have investigated centre of mass displacement, but not in an extensive cohort of recreational runners or overground.

As with vertical oscillation, stride length and stride rate are also modifiable factors. Initially, runners are believed to naturally adopt a stride length and rate that optimises running economy known as self-optimisation (Moore, Jones and Dixon, 2012). However, this seems to settle after an early period when the runner is learning their craft. Previous research has shown that adjusting stride length up to 3% can have some effect on running economy and shortening by 3% leads to an improvement, while changes greater than 6% can have a negative impact (Moore, Jones and Dixon, 2012; Craighead, Lehecka and King, 2014; de Ruiter *et al.*, 2014b). Further, it was found that the correlation with running economy was 0.444 ($p < 0.001$), so shortening the stride length potentially reduces the running economy (Folland *et al.*, 2017). The relationship with stride length and stride rate is such that to maintain a steady speed, as stride length decreases, the stride rate must increase. It has been shown that altering the stride rate can be done, for example using music with a fixed number of beats per minute, which is possibly easier for someone to adapt than stride length which can be difficult to notice when running (Sellés-Pérez *et al.*, 2022).

The final area of consideration was joint angles at the hip, knee and ankle, although most studies have focussed on the knee and to a lesser extent the ankle (Moore, 2016). Some studies suggest that there is a strong connection with improved running economy when there is less extension in the leg at toe-off, through either a reduced plantarflexion or reduced knee extension, or a combination of the two. The reasoning for this being that if the leg is already slightly flexed, less energy will be required to then flex the leg during the swing phase (Williams and Cavanagh, 1987; Moore, Jones and Dixon, 2012). Of studies that have looked at hip angles, it was found that better running economy was found when the maximal angle of the thigh during hip extension was greater and alongside more acute knee angles when in the swing phase (Barnes and Kilding, 2015). However, it is worth noting that the participants in these studies were all elite or good runners, with small numbers of participants.

To summarise, the aim of this chapter is to isolate, using linear regression, the modifiable, measurable biomechanical variable(s) that have a significant impact on running economy.

6.2 Method

6.2.1 Participants

Following ethical approval from the University of East London Ethics and Integrity Sub-committee, 40 recreational runners (male=19, female=21) were recruited for the study from local running clubs and the university. Table 6:1 contains the summary details for the participants.

Table 6:1: Anthropometric data as mean ± SD with 95% CI

	Mean ± SD	95% CI
Age (years)	37.45 ± 10.86	(34.09, 40.81)
Mass (kg)	66.86 ± 12.69	(62.93, 70.79)
Height (cm)	170.90 ± 8.41	(168.29, 173.51)

All participants had been running for a minimum of 6 months and were accustomed to running 5 km. They provided written, informed consent and completed a BASES health questionnaire (see Appendices 2 and 3).

6.2.2 Procedure

The data used for analysis in this chapter was that collected during the previous research chapters using methods outlined in the methods chapter. To summarise the process, participants attended the University of East London Docklands campus on two separate occasions not less than a week apart. They were asked to refrain from intense exercise for 24 hours prior to attending, not to eat for 3 hours before and arrive fully hydrated wearing suitable clothing and the same footwear on both occasions. To try to limit any differences that could be the result of circadian rhythms, the tests were conducted as close to the same time of day as possible (Drust *et al.*, 2005).

On the first visit, anthropometric measurements were taken, mass using a standard weighing scale, height with a portable stadiometer (Seca, Birmingham, UK) and additional measurements with a segmometer (MVN SegoMeter, Xsens, Enschede, The Netherlands). The Cosmed K5 and the MTw Awinda motion trackers (Xsens, Enschede, The Netherlands) were then placed on the participant on the sites as outlined in the general methods chapter (Chapter 3).

Participants then performed a 5-minute warm-up at a self-selected pace on a treadmill (Mercury, h/p/cosmos, Nussdorf-Traunstein, Germany), set at 1% incline to compensate for the wind resistance that would be experienced outside (Jones and Doust, 1996), and 5 minutes of self-selected stretching.

A coin toss was used to randomly allocate whether they ran on the treadmill or overground first, with a 15-minute recovery period between the two trials, the order was reversed on their return visit. They ran for 5 minutes in each of the conditions at the same self-selected usual 5 km pace to enable the runners to reach steady state (Saunders *et al.*, 2004a; Barnes *et al.*, 2013; Boone, Deprez and Bourgois, 2014; Barnes and Kilding, 2015a). The chosen speed was programmed into the treadmill and replicated outside by using a cyclist as a pace setter, maintaining the same steady pace with the aid of a speedometer (YS-Sports, Shenzhen, China).

6.2.3 Data analysis

The results from the separate chapters for the physiological and biomechanical data analysis (Chapters 4 and 5) showed that it was reliable and valid to consider only overground data for this cohort of runners. Further, the analysis in Chapter 5 showed that there was no significant difference between the data for the left and right side of the body for the angles measured. Therefore, a linear regression analysis was performed on the data from the overground trials initially, using the left side data only where applicable. The aim of the regression analysis was to determine the effect (positive or negative) and size of the contribution each of the biomechanical variables being measured had on running economy.

Analysis was carried out using SPSS software (IBM SPSS Statistics, Rel. 28.0, 2021, SPSS Inc, Chicago, IL USA) and Excel (Microsoft Corporation, v16.33, Redmond, WA, USA). Linear regression was performed on the data recorded in both the first and second overground trials, then additionally with all the overground data as a complete set. This was done to determine whether the regression analysis showed that the same biomechanical factor was the largest contributor to running economy for all three sets of data analysis.

6.3 Results

The first set of results are for the findings of the whole group and all parameters measured for both trial 1, 2 and the combined results. Subsequent further analysis with smaller, specific groups, results are only presented for the combined trial data.

6.3.1 Overground trial 1

The ANVOA test, $F (12,39) = 3.570$, $p < 0.003$, show that this model is a good fit. The adjusted R^2 value of 0.442, means that the variables account for 44.2% of the variation in running economy. The regression analysis showed that in the first overground trial, only stride length has a statistically significant impact on running economy. Isolating the variable for stride length gives $F (1,39) = 35.850$, $p < 0.001$, with an adjusted R^2 value of 0.472, suggesting that stride length alone accounts for 47.2% of the variation in running economy.

Table 6:2: Correlations between biomechanical variables and running economy for trial 1

	Correlation	Significance
OG01_CoM_min	-0.041	0.401
OG01_CoM_max	0.055	0.368
OG01_CoM_range	0.391	0.006
OG01_LA_min	-0.189	0.121
OG01_LA_max	0.278	0.041
OG01_LA_range	0.397	0.006
OG01_LK_angle_min	-0.089	0.293
OG01_LK_angle_max	0.008	0.480
OG01_LK_angle_range	0.112	0.245
OG01_LH_min	-0.425	0.003
OG01_LH_max	-0.010	0.475
OG01_LH_range	0.437	0.002
OG01_steps_per_minute	-0.032	0.423

OG01_Stride_Length	0.697	0.000
OG01_Stride_rate	-0.031	0.426
OG01_Cycle_time	0.038	0.408

Table 6:3: Linear regression in overground trial 1 with running economy as the dependent variable

	Unstandardised Coefficients		Standardised Coefficients			Collinearity Statistics
	B	Std. Error	Beta	t	Sig.	VIF
(Constant)	6.315	99.279		0.064	0.950	
OG01_CoM_min	-5.246	12.736	-0.063	-0.412	0.684	1.639
OG01_CoM_range	-51.091	73.356	-0.149	-0.696	0.492	3.178
OG01_LA_min	0.300	0.240	0.198	1.252	0.221	1.749
OG01_LA_range	0.105	0.142	0.138	0.740	0.466	2.440
OG01_LK_angle_max	-0.053	0.071	-0.133	-0.747	0.461	2.203
OG01_LK_angle_range	0.013	0.061	0.030	0.215	0.831	1.336
OG01_LH_min	-0.143	0.105	-0.297	-1.359	0.185	3.336
OG01_LH_max	0.066	0.100	0.112	0.654	0.518	2.038
OG01_steps_per_minute	-1.025	2.439	-2.495	-0.420	0.678	2463.774
OG01_Stride_Length	13.798	3.909	0.761	3.529	0.002	3.249
OG01_Stride_rate	133.313	287.463	2.720	0.464	0.647	2403.113
OG01_Cycle_time	-7.477	79.586	-0.060	-0.094	0.926	28.675

6.3.2 Overground trial 2

In this case, the model F (13,39) = 5.226, $p < 0.001$ is also a good fit. Adjusted R^2 value of 0.585, meaning the variables account for 58.5% of the variation in running economy. Similarly to overground trial 1, the regression analysis showed that in the second overground trial, only stride length has a statistically significant impact on running economy. Isolating the variable for stride length gives F (1,39) = 33.919, $p < 0.001$, with an adjusted R^2 value of 0.458, therefore accounting for 45.8% of the variation in running economy.

Table 6:4: Correlations between biomechanical variables and running economy for trial 2

	Correlation	Significance
OG02_CoM_min	0.206	0.101
OG02_CoM_max	0.351	0.013
OG02_CoM_range	0.513	0.000
OG02_LA_min	-0.339	0.016
OG02_LA_max	0.141	0.192
OG02_LA_range	0.316	0.023
OG02_LK_angle_min	0.085	0.301
OG02_LK_angle_max	0.408	0.005
OG02_LK_angle_range	0.423	0.003
OG02_LH_min	-0.425	0.003
OG02_LH_max	0.171	0.146

OG02_LH_range	0.536	0.000
OG02_steps_per_minute	0.025	0.439
OG02_Stride_Length	0.687	0.000
OG02_Stride_rate	0.028	0.432
OG02_Cycle_time	-0.028	0.433

Table 6:5: Linear regression in overground trial 2 with running economy as the dependent variable

	Unstandardised Coefficients		Standardised Coefficients			Collinearity Statistics
	B	Std. Error	Beta	t	Sig.	VIF
(Constant)	54.240	85.608		0.634	0.532	
OG02_CoM_min	1800.537	1794.500	9.028	1.003	0.325	7604.937
OG02_CoM_max	-1826.051	1795.177	-10.485	-1.017	0.318	9980.742
OG02_CoM_range	2005.362	1804.364	3.846	1.111	0.277	1124.875
OG02_LA_min	-0.109	0.220	-0.068	-0.497	0.623	1.772
OG02_LA_max	-0.047	0.154	-0.044	-0.306	0.762	1.945
OG02_LK_angle_min	0.051	0.182	0.046	0.283	0.779	2.465
OG02_LK_angle_range	0.109	0.122	0.107	0.888	0.383	1.354
OG02_LH_min	0.052	0.125	0.080	0.413	0.683	3.504
OG02_LH_max	-0.086	0.122	-0.101	-0.707	0.486	1.918
OG02_steps_per_minute	0.267	2.419	0.624	0.110	0.913	2998.599
OG02_Stride_Length	15.559	3.879	0.792	4.011	<.001	3.663
OG02_Stride_rate	-34.719	284.532	-0.677	-0.122	0.904	2891.466
OG02_Cycle_time	-53.447	65.156	-0.441	-0.820	0.420	27.182

6.3.3 Combining overground trials 1 and 2

In this case, the model $F (12,79) = 8.846$, $p < 0.001$ is also a good fit. The adjusted R^2 value of 0.544, indicates that the variables account for 54.4% of the variation in running economy. Echoing the findings of overground trials 1 and 2, the regression analysis showed that when combining the two overground trials, again only stride length has a statistically significant impact on running economy ($p < 0.001$). Isolating the variable for stride length gives $F (1,79) = 71.310$, $p < 0.001$ and an adjusted R^2 of 0.471, indicating that stride length accounts for 47.1% of the variation in running economy.

Table 6:6: Correlations between biomechanical variables and running economy for combined overground trials 1 and 2

	Correlation	Significance
OG_CoM_min_total	0.032	0.389
OG_CoM_max_total	0.148	0.095
OG_CoM_range_total	0.072	0.264
OG_LA_min_total	-0.273	0.007
OG_LA_max_total	0.203	0.036
OG_LA_range_total	0.346	0.001
OG_LK_min_total	-0.017	0.441
OG_LK_max_total	0.159	0.079

OG_LK_range_total	0.203	0.035
OG_LH_min_total	-0.419	0.000
OG_LH_max_total	0.075	0.253
OG_LH_range_total	0.485	0.000
OG_Steps_per_min_total	-0.002	0.491
OG_Stride_length_total	0.691	0.000
OG_Stride_rate_total	0.000	0.500
OG_Cycle_time_total	0.004	0.487

Table 6:7: Linear regression in both overground trials with running economy as the dependent variable

	Unstandardised Coefficients		Standardised Coefficients			Collinearity Statistics
	B	Std. Error	Beta	t	Sig.	VIF
(Constant)	11.616	58.327		0.199	0.843	
OG_CoM_min_total	-3.427	9.684	-0.031	-0.354	0.725	1.291
OG_CoM_range_total	41.853	47.144	0.100	0.888	0.378	2.216
OG_Steps_per_min_total	-0.625	1.540	-1.486	-0.406	0.686	2322.260
OG_LA_max_total	0.079	0.084	0.094	0.947	0.347	1.698
OG_LA_min_total	0.065	0.151	0.041	0.428	0.670	1.622
OG_LK_max_total	0.025	0.054	0.047	0.455	0.650	1.877
OG_LK_range_total	0.003	0.053	0.004	0.050	0.960	1.359
OG_LH_max_total	-0.015	0.071	-0.021	-0.205	0.838	1.790
OG_LH_min_total	-0.020	0.070	-0.036	-0.287	0.775	2.753
OG_Stride_length_total	14.754	2.400	0.778	6.147	<.001	2.777
OG_Stride_rate_total	83.508	181.291	1.661	0.461	0.647	2250.412
OG_Cycle_time_total	-27.668	46.177	-0.226	-0.599	0.551	24.654

6.3.4 Comparing female and male data

Both the female only and male only data were found to be that consistent with the results of the whole population. The models, $F(12,41) = 3.834$, $p = 0.001$ and $F(12,37) = 4.017$, $p = 0.002$ respectively, were shown to be a good fit. The adjusted R^2 value for the female only data of 0.453, indicates that the variables account for 45.3% of the variation in running economy. The male only data produced an adjusted R^2 value of 0.495, showing that the variables account for 49.5% of the variation in running economy. Stride length is shown to have a statistically significant impact on running economy for both the female only and male only data ($p = 0.02$ and $p < 0.001$ respectively), echoing the results for the whole population. However, there is also a statistically significant contribution from stride rate and steps per minute ($p = 0.04$ and $p = 0.048$ respectively) in the female population.

Isolating the variable for stride length in the male contingent returns a model of gives $F(1,37) = 44.974$, $p < 0.001$ and an adjusted R^2 of 0.543, indicating that stride length accounts for 54.3% of the variation in running economy.

For the female data, isolating the stride rate, stride length and steps per minute variables returns a model of F (3,41) = 8.047, $p < 0.001$ and an adjusted R^2 of 0.340, indicating that stride rate, stride length and steps per minute account for 34.0% of the variation in running economy. Isolating for solely the stride length variable returns a model of F (1,41) = 5.781, p = 0.021 and an adjusted R^2 of 0.104, indicating that stride length accounts for 10.4% of the variation in running economy.

Table 6:8: Linear regression with female only data in both overground trials with running economy as the dependent variable

	Unstandardised Coefficients		Standardised Coefficients			Collinearity Statistics
	B	Std. Error	Beta	t	Sig.	VIF
(Constant)	36.097	71.723		0.503	0.619	
OG_CoM_max_total	7.576	13.913	0.077	0.545	0.590	1.494
OG_CoM_range_total	114.624	58.395	0.313	1.963	0.059	1.910
OG_Steps_per_min_total	-3.861	1.869	-12.138	-2.066	0.048	2589.438
OG_LA_min_total	0.358	0.177	0.288	2.025	0.052	1.512
OG_LA_range_total	0.054	0.139	0.062	0.389	0.700	1.926
OG_LK_min_total	-0.021	0.080	-0.041	-0.264	0.794	1.847
OG_LK_range_total	-0.100	0.068	-0.185	-1.461	0.155	1.198
OG_LH_max_total	0.004	0.065	0.008	0.054	0.957	1.469
OG_LH_range_total	0.102	0.089	0.197	1.154	0.258	2.190
OG_Stride_length_total	10.767	4.380	0.504	2.458	0.020	3.150
OG_Stride_rate_total	465.660	217.024	12.189	2.146	0.040	2420.367
OG_Cycle_time_total	-52.200	56.724	-0.576	-0.920	0.365	29.348

Table 6:9: Linear regression with male only data in both overground trials with running economy as the dependent variable

	Unstandardised Coefficients		Standardised Coefficients			Collinearity Statistics
	B	Std. Error	Beta	t	Sig.	VIF
(Constant)	37.939	111.329		0.341	0.736	
OG_CoM_min_total	-19.485	17.01	-0.162	-1.146	0.263	1.466
OG_CoM_range_total	-65.94	79.342	-0.166	-0.831	0.414	2.931
OG_Steps_per_min_total	1.659	2.805	3.761	0.592	0.559	2957.535
OG_LA_max_total	0.122	0.129	0.16	0.948	0.352	2.087
OG_LA_min_total	0	0.264	0	-0.002	0.999	1.962
OG_LK_max_total	0.048	0.088	0.094	0.55	0.588	2.156
OG_LK_range_total	0.084	0.074	0.152	1.136	0.267	1.307
OG_LH_max_total	-0.085	0.18	-0.094	-0.472	0.641	2.901
OG_LH_range_total	0.06	0.138	0.113	0.435	0.667	4.959
OG_Stride_length_total	13.544	3.61	0.729	3.752	<.001	2.76
OG_Stride_rate_total	-197.819	337.646	-3.764	-0.586	0.563	3021.456
OG_Cycle_time_total	-24.199	87.115	-0.182	-0.278	0.783	31.544

6.3.5 Comparing the twenty fastest runners with the twenty slowest runners

Looking at the twenty fastest runners (running at speed > 11.3 km.h^{-1}, up to 16 km.h^{-1}), the model F (13,59) = 5.824, $p < 0.001$ is a good fit. The adjusted R^2 value of 0.486, indicates that the variables account for 48.6% of the variation in running economy. Echoing the findings of the whole group, analysis showed that only stride length has a statistically significant impact on running economy ($p < 0.001$). Isolating the variable for stride length gives F (1,59) = 40.173, $p < 0.001$ and an adjusted R^2 of 0.399, indicating that stride length accounts for 39.9% of the variation in running economy.

Table 6:10: Linear regression with the 20 fastest runners in both overground trials with running economy as the dependent variable

	Unstandardised Coefficients		Standardised Coefficients			Collinearity Statistics
	B	Std. Error	Beta	t	Sig.	VIF
(Constant)	16.984	71.455		0.238	0.813	
OG_CoM_max_total	23.513	59.132	0.162	0.398	0.693	18.988
OG_CoM_min_total	-35.668	57.333	-0.225	-0.622	0.537	15.035
OG_CoM_range_total	3.238	2.379	0.16	1.361	0.180	1.577
OG_Steps_per_min_total	1.263	2.244	3.138	0.563	0.576	3565.219
OG_LA_max_total	0.15	0.112	0.169	1.337	0.188	1.825
OG_LA_min_total	0.026	0.197	0.016	0.131	0.897	1.677
OG_LK_min_total	-0.014	0.075	-0.026	-0.186	0.853	2.192
OG_LK_range_total	0.055	0.077	0.085	0.709	0.482	1.664
OG_LH_max_total	-0.033	0.095	-0.041	-0.35	0.728	1.548
OG_LH_min_total	-0.079	0.092	-0.128	-0.855	0.397	2.58
OG_Stride_length_total	16.071	3.318	0.813	4.843	<.001	3.233
OG_Stride_rate_total	-142.512	265.888	-2.96	-0.536	0.595	3498.432
OG_Cycle_time_total	-37.213	57.007	-0.31	-0.653	0.517	25.797

For the twenty slowest runners (running at speed ≥ 8 km.h^{-1} and ≤ 11 km.h^{-1}), the model F (13,59) = 8.500, $p < 0.001$ is a good fit. The adjusted R^2 value of 0.623, indicates that the variables account for 62.3% of the variation in running economy. Again, the results echoed the findings of the whole group, with analysis showing that stride length has a statistically significant impact on running economy ($p < 0.001$). However, centre of mass maximum and centre of mass minimum were also shown to have a statistically significant impact, $p = 0.014$ and 0.011 respectively.

Repeating the analysis with the centre of mass maximum, centre of mass minimum and stride length parameters returns the model F (3,59) = 23.178, $p < 0.001$ and an adjusted R^2 of 0.530, indicating that stride length accounts for 53% of the variation in running economy.

Isolating the variable for stride length gives F (1,59) = 63.165, $p < 0.001$ and an adjusted R^2 of 0.513, indicating that stride length accounts for 51.3% of the variation in running economy.

Table 6:11: Linear regression with 20 slower runners in both overground trials with running economy as the dependent variable

	Unstandardised Coefficients		Standardised Coefficients			Collinearity Statistics
	B	Std. Error	Beta	t	Sig.	VIF
(Constant)	27.172	65.021		0.418	0.678	
OG_CoM_max_total	140.465	55.19	1.323	2.545	0.014	42.287
OG_CoM_min_total	-143.79	53.931	-1.372	-2.666	0.011	41.416
OG_CoM_range_total	-1.611	1.788	-0.091	-0.901	0.372	1.591
OG_Steps_per_min_total	-1.162	1.541	-2.663	-0.754	0.454	1949.844
OG_LA_max_total	-0.03	0.099	-0.033	-0.303	0.763	1.896
OG_LA_min_total	0.054	0.146	0.037	0.371	0.712	1.527
OG_LK_min_total	0.093	0.078	0.134	1.192	0.239	1.991
OG_LK_range_total	0.056	0.07	0.076	0.795	0.430	1.410
OG_LH_max_total	-0.103	0.084	-0.156	-1.229	0.225	2.520
OG_LH_min_total	0.089	0.086	0.163	1.04	0.304	3.863
OG_Stride_length_total	16.428	2.858	0.869	5.749	<.001	3.573
OG_Stride_rate_total	142.773	180.958	2.73	0.789	0.434	1873.628
OG_Cycle_time_total	-44.695	50.692	-0.374	-0.882	0.383	28.102

6.3.6 Comparing the differences between runners at a range of speeds

For the slowest running group (8 $km.h^{-1}$ to < 10 $km.h^{-1}$, n=12), the model $F(13,51) = 7.455$, $p < 0.001$ is a good fit. The adjusted R^2 value of 0.622, indicates that the variables account for 62.2% of the variation in running economy. Again, the results echoed the findings of the whole group, with analysis showing that stride length has a statistically significant impact on running economy ($p < 0.001$). However, similarly to the slowest 20 runners, centre of mass maximum and centre of mass minimum were also shown to have a statistically significant impact, $p = 0.024$ and 0.016 respectively.

Conducting an analysis with just the centre of mass maximum, centre of mass minimum and stride length parameters returns the model $F(3,51) = 20.435$, $p < 0.001$ and an adjusted R^2 of 0.533, indicating that stride length accounts for 53.3% of the variation in running economy.

Isolating the variable for stride length gives $F(1,51) = 55.135$, $p < 0.001$ and an adjusted R^2 of 0.515, indicating that stride length accounts for 51.5% of the variation in running economy.

Table 6:12: Linear regression runners at a pace of 8 $km.h^{-1}$ to < 10 $km.h^{-1}$ in both overground trials with running economy as the dependent variable

	Unstandardised Coefficients		Standardised Coefficients			Collinearity Statistics
	B	Std. Error	Beta	t	Sig.	VIF
(Constant)	33.882	71.76		0.472	0.64	
OG_CoM_max_total	150.514	63.824	1.409	2.358	0.024	48.14
OG_CoM_min_total	-157.296	62.306	-1.487	-2.525	0.016	46.789
OG_CoM_range_total	-3.233	2.318	-0.154	-1.395	0.171	1.649
OG_Steps_per_min_total	-0.482	1.808	-1.085	-0.267	0.791	2229.917
OG_LA_max_total	-0.019	0.121	-0.019	-0.159	0.875	1.861
OG_LA_min_total	0.081	0.162	0.053	0.499	0.621	1.495
OG_LK_min_total	0.11	0.094	0.153	1.162	0.253	2.34
OG_LK_range_total	0.057	0.094	0.069	0.614	0.543	1.691
OG_LH_max_total	-0.034	0.083	-0.044	-0.412	0.683	1.564
OG_LH_range_total	-0.061	0.098	-0.097	-0.624	0.536	3.276
OG_Stride_length_total	16.742	3.19	0.883	5.248	<.001	3.819
OG_Stride_rate_total	60.149	211.92	1.129	0.284	0.778	2133.098
OG_Cycle_time_total	-48.421	55.865	-0.393	-0.867	0.392	27.712

For the middle-paced running group (≤ 10 km.h^{-1} to ≤ 12 km.h^{-1}, n=18), the model F (13,57) = 5.420, $p < 0.001$ is a good fit. The adjusted R^2 value of 0.502, indicates that the variables account for 50.2% of the variation in running economy. Again, the results echoed the findings of the whole group, with analysis showing that only stride length has a statistically significant impact on running economy ($p < 0.001$).

Isolating the variable for stride length gives F (1,57) = 31.365, $p < 0.001$ and an adjusted R^2 of 0.348, indicating that stride length accounts for 34.8% of the variation in running economy.

Table 6:13: Linear regression runners at a pace of 10 km.h^{-1} to < 12 km.h^{-1} in both overground trials with running economy as the dependent variable

	Unstandardised Coefficients		Standardised Coefficients			Collinearity Statistics
	B	Std. Error	Beta	t	Sig.	VIF
(Constant)	17.305	64.35		0.269	0.789	
OG_CoM_max_total	120.67	64.342	0.704	1.875	0.067	16.151
OG_CoM_min_total	-114.318	68.01	-0.589	-1.681	0.1	14.044
OG_CoM_range_total	3.925	2.148	0.205	1.828	0.074	1.438
OG_Steps_per_min_total	1.038	2.127	2.823	0.488	0.628	3829.929
OG_LA_max_total	0.045	0.117	0.052	0.381	0.705	2.164
OG_LA_min_total	0.149	0.189	0.095	0.789	0.434	1.666
OG_LK_min_total	-0.057	0.081	-0.085	-0.701	0.487	1.686
OG_LK_range_total	0.051	0.077	0.073	0.668	0.508	1.368
OG_LH_max_total	-0.059	0.077	-0.086	-0.764	0.449	1.451
OG_LH_range_total	0.102	0.081	0.175	1.263	0.213	2.192
OG_Stride_length_total	13.239	3.37	0.65	3.928	<.001	3.135
OG_Stride_rate_total	-121.933	251.184	-2.773	-0.485	0.63	3735.321
OG_Cycle_time_total	-47.937	52.27	-0.438	-0.917	0.364	26.069

For the fast-paced running group (< 12 km.h^{-1} to ≤ 16 km.h^{-1}, n=10), the model F (13,49) = 6.178, $p < 0.001$ is a good fit. The adjusted R^2 value of 0.579, indicates that the variables account for 57.9% of the variation in running economy. Again, the results echoed the findings of the whole group, with analysis showing that only stride length has a statistically significant impact on running economy ($p < 0.001$).

Isolating the variable for stride length gives $F(1,49) = 31.365$, $p < 0.001$ and an adjusted R^2 of 0.503, indicating that stride length accounts for 50.3% of the variation in running economy.

Table 6:14: Linear regression runners at a pace of < 12 km.h^{-1} to ≤ 16 km.h^{-1} in both overground trials with running economy as the dependent variable

	Unstandardised Coefficients		Standardised Coefficients			Collinearity Statistics
	B	Std. Error	Beta	t	Sig.	VIF
(Constant)	37.779	83.45		0.453	0.653	
OG_CoM_max_total	62.866	63.948	0.451	0.983	0.332	24.525
OG_CoM_min_total	-80.663	62.673	-0.536	-1.287	0.206	20.141
OG_CoM_range_total	-0.078	3.19	-0.003	-0.025	0.981	2.038
OG_Steps_per_min_total	0.162	2.278	0.345	0.071	0.944	2744.571
OG_LA_max_total	0.051	0.111	0.053	0.457	0.65	1.589
OG_LA_min_total	-0.121	0.19	-0.076	-0.639	0.527	1.658
OG_LK_max_total	0.084	0.101	0.139	0.835	0.409	3.224
OG_LK_range_total	0.01	0.09	0.015	0.111	0.912	1.996
OG_LH_max_total	-0.154	0.106	-0.176	-1.46	0.153	1.685
OG_LH_min_total	0.102	0.111	0.16	0.917	0.365	3.522
OG_Stride_length_total	17.495	3.256	0.921	5.374	<.001	3.419
OG_Stride_rate_total	-15.03	268.121	-0.268	-0.056	0.956	2649.639
OG_Cycle_time_total	-47.593	65.517	-0.363	-0.726	0.472	28.966

6.4 Discussion

Results from the first overground trial point to a positive correlation between running economy and the range of centre of mass oscillation, ($p = 0.006$), the maximum angle of the ankle ($p = 0.041$), range of motion in the ankle ($p = 0.006$), range of motion in the hip ($p = 0.002$) and stride length ($p < 0.001$). This indicates that as each of these parameters increases, so does running economy, which is detrimental to the runner's performance. However, the reverse is also true, so that a reduction in each of these parameters could potentially lead to a reduction in running economy, and subsequently an improvement in performance. This supports previous work that demonstrated an improved running economy accompanied a decrease in centre of mass displacement (Halvorsen, Eriksson and Gullstrand, 2012) and a shorter stride length (Folland *et al.*, 2017).

However, a strong correlation is considered to be a result greater than 0.7, and stride length was the only one that came close to this at 0.697. This strong relationship is borne out when examining the results of the regression analysis, showing that stride length accounts for 47% of the variation in running economy. In fact, adding in additional factors suggests that the impact on running economy is reduced. This further strengthens the findings of Folland *et al.* (2017) who reported a correlation of 0.444 ($p< 0.001$) with running economy, noting that a slightly shorter stride length and a higher stride rate showed a better fit with running economy.

The findings from the second trial and combined trials show similar results for the strength of relationship between stride length and running economy with a correlation of 0.687 and 0.691 respectively and a contribution to the variation in running economy of 46% and 47%.

It needs to be noted that there are contributing factors to stride length that cannot be influenced or trained, specifically limb length. It has been reported that there is a relationship between stride length, stride rate and lower limb length, with the correlation between stride length and limb length increasing as velocity increases, from 0.53 at 2.5 $m.s^{-1}$ to 0.70 at 5.5 $m.s^{-1}$ in men and 0.69 to 0.74 in women (Elliott and Blanksby, 1979). However, these results should be taken with caution as all tests were completed on a treadmill, which by the nature of it means that there is little variation in stride length as it is, to a degree, controlled by the apparatus.

6.5 Conclusion

The aim of this chapter was to isolate the modifiable, measurable biomechanical variables that have a significant impact on running economy. The results indicate that there is a strong relationship between stride length and running economy. This suggests that reducing stride length, potentially by increasing stride frequency at the same pace, would lead to a reduction in running economy.

Chapter 7: Proposed method for experiment to explore impact of changing a single biomechanical variable on running economy

7.1 Introduction

The purpose of this chapter of research is to take the findings from the regression analysis performed in Chapter 6, which identified stride length as being the strongest influence on running economy, and determine whether manipulating the variable, stride length, improves running economy in a recreational running cohort in the field. This study aims to answer the main question of this thesis, to discover if a biomechanical approach can be taken to improve running economy in the field.

The regression analysis carried out in Chapter 6 identified stride length as having the most significant relationship with running economy in the recreational running group studied ($p < 0.001$). Stride length and running economy were shown to have a positive correlation, so this implies that a reduction in stride length may lead to a decrease in oxygen cost and an improvement in running economy at the individual runner's chosen 5 km pace overground.

However, stride length can be difficult for a runner to judge while they are running overground in an unmarked environment. Given that velocity is a product of stride length and stride rate, if maintaining velocity, an increase in stride rate would lead to a corresponding decrease in stride length. It has been shown that stride rate is a variable that can be manipulated in runners using music (Sellés-Pérez *et al.*, 2022). For ease of use, stride rate will be converted into step rate (stride rate doubled), so each individual footfall will be on the beat of the music. It is important that the user has a choice of music as it has been shown that whether the user prefers the music or not has an influence on the physiological response to exercise (Ballmann, 2021). While the choice of musical genre is selected by the individual, the tempo of the track is dictated by the step rate (calculated from the stride rate) that the runner is aiming for in order to attain the corresponding change in stride length. Each individual will have their personal target stride length calculated for them, which will be 3% less than their current rate, which has been shown to be achievable in previous studies (Cavanagh and Williams, 1982; Connick and Li, 2014; de Ruiter *et al.*, 2014a), this is then converted into step rate.

Since stride length, and by association stride rate, is the only biomechanical variable that is being measured in this study, it makes experimental sense to use a single inertial measurement unit (IMU) on each leg, comprising an accelerometer, gyroscope and magnetometer, to capture stride length and rate data rather than the full biomechanical data capture system, MTw Awinda motion trackers (Xsens, Enschede, The Netherlands), used in the biomechanical data analysis conducted in Chapter 5. Using IMUs placed on the tibia of each leg has been shown to be a reliable place to capture stride data (Horsley *et al.*, 2021). The ViPerform v5 (DorsaVi, Melbourne, Australia) has been shown to have excellent reliability when considering both between strides and between trials (ICC of 0.877, 95% CI 0.825–0.917) (Raper *et al.*, 2018).

Previous research has shown that after a period of six months, no change will be seen to a runner's running economy without any additional intervention or changes to the training pattern (Nakayama, Kudo and Ohtsuki, 2010). To check that this is the case, a control group will be tested alongside the experimental group. In line with findings of Chapters 4 and 5, which determined that running overground was a reliable test and ecologically valid to the experience of recreational runners, all testing, training and post-intervention / control group assessments will take place overground.

7.2 Method

7.2.1 Introduction

Some of the methods used in this study are covered in the general methods (Chapter 3), this section will outline additional methods, notably those involved in the intervention phase of the study.

7.2.2 Participants

Ahead of any experimental work, an application for ethical approval will be submitted to the University of East London Research Ethics committee. A power analysis using G*Power 3.1.9.6, with an α of 0.05 and a power of 0.80 indicated a sample size of 52 participants, 26 in each of the experimental and control groups. However, to allow for attrition which is estimated at 11% (Cramer *et al.*, 2016), a total of 58 participants will be required, 29 in each of the experimental and control groups. Recreational runners will be recruited from local running clubs and the University of East London.

The participants will be required to have been running for a minimum of 6 months, as after this length of time, any adaptions to cardiovascular and musculoskeletal properties and a stable and consistent running gait will have been established (Nakayama, Kudo and Ohtsuki, 2010) and so any changes from the baseline measure can be attributed to the intervention. They will also be accustomed to running 5 km overground and habitually listen to music on their own device whilst they run, so that they are already comfortable with listening to music whilst running. It is noted that the requirement to be accustomed to listening to music will exclude some members of the recreational running community, this will be revisited in Chapter 9. All participants will be asked to provide written, informed consent and complete a BASES health questionnaire.

7.2.3 Procedure

7.2.3.1 Initial baseline measurement

All participants will be required to make an initial visit to the University of East London for a baseline assessment. In line with the previous experimental studies as detailed in Chapter 3, for standardisation, they will be asked to refrain from intense exercise for 24 hours prior to attending, not to eat for 3 hours before and arrive fully hydrated wearing suitable clothing and the same footwear on both occasions as it is known that running shoes can impact running economy (Fuller *et al.*, 2015).

Anthropometric measurements will be taken, mass using a standard weighing scale and height with a portable stadiometer (Seca, Birmingham, UK). Measurements will be recorded to the nearest 0.5 kg and 0.1 cm respectively.

The participants will be fitted with a K5 portable metabolic cart (COSMED, Rome, Italy). To measure the stride frequency, the ViPerform v5 (DorsaVi, Melbourne, Australia) comprising an accelerometer, gyroscope and magnetometer will be attached to the medial border on the tibia of each leg. The data from this will be sent wirelessly from the device captured using the ViPerform software on a PC.

They will then perform a 5-minute warm-up at a self-selected pace on a treadmill (Mercury, h/p/cosmos, Nussdorf-Traunstein, Germany), set at 1% incline to compensate for the wind resistance that would be experienced outside (Jones and Doust, 1996), and 5 minutes of self-selected stretching as outlined in Chapter 3.

Results from the previous chapters have shown that for a cohort of recreational runners it is ecologically valid and reliable to conduct research overground. A paved, flat (see Appendix 5) area alongside the Royal Albert Dock will be used as the testing site. Participants will be required to run at their identified 5 km pace for 5 minutes, to achieve steady state (Saunders *et al.*, 2004; Barnes *et al.*, 2013; Boone, Deprez and Bourgois, 2014; Barnes and Kilding, 2015a). To ensure that a steady pace is maintained at the chosen speed, a cyclist will be used as a pace setter, maintaining the same steady pace with the aid of a speedometer (YS-Sports, Shenzhen, China). At the end of the 5 minutes, the recording on the K5 will be checked to ensure that the participant has achieved steady state, indicated by a rising O_2 intake, followed by no increase in demand, indicated by a plateau when the data is graphed (Saunders *et al.*, 2004; Barnes *et al.*, 2013; Boone, Deprez and Bourgois, 2014; Barnes and Kilding, 2015a).

To be consistent with the previous studies in this thesis, running economy will then be determined from the last minute of the recorded data as this is when the runner will have reached steady state and to coincide with the running economy data, the average stride length of the final minute will be taken from from ViPerform v5 (Quinn *et al.*, 2021).

After completing the baseline test, participants will be pair matched according to their running economy and one from each pair will be allocated to the control group and one to the intervention group, using a coin toss, to ensure that there is a balance of running economy levels in each group.

7.2.3.2 Intervention stage

The initial stage is to determine what the revised stride rate, and therefore step rate, will be for each participant so that it is equivalent to a 3% reduction in stride length, calculated for the pace at which they ran. The corresponding stride rate would be calculated using the equation:

$$\text{Stride rate (Hz)} = \frac{\text{Velocity (m.s}^{-1}\text{)}}{\text{Stride length (m)}}$$

This stride rate is then converted into a step per minute count for each individual so that each footfall will coincide with a beat of the music:

$$\text{Steps.min}^{-1} = \text{Stride rate (Hz)} \times 120$$

Participants will then select music with a tempo to match their required steps.min^{-1}. Websites such as https://getsongbpm.com allow the user to input the required beats per minute (bpm) which is the same as their steps per minute. The site then enables the user to select a genre they would like to listen to and from a particular time period. Alternatively, the user can input the specific bpm, and the site will list all tracks at that speed from which the user can select the tracks they would be happy to run to. It is important that the runner chooses their own music according to their taste, as there is much evidence to support that premise that preference has a great influence on the ergogenic potential of music as well as the physiological response (Ballmann, 2021).

Having selected their personal playlist, the participants will use a listening device of their choosing and run at their usual 5 km pace (that which was identified for the baseline visit to UEL) following their usual running timetable so that any changes can't be attributed to running more, or less frequently, matching their step rate to the beat of the music. This pattern will be repeated consistently over the following eight weeks (Craighead, Lehecka and King, 2014; Doyle *et al.*, 2022).

During the intervention stage, the participants allocated to the control group will continue to run in their usual training pattern and be asked not to change anything within their usual training regime.

7.2.3.3 Final visit

After the intervention period is concluded, the participants will return to the University of East London for an evaluation run. Again, for standardisation, they will be asked to refrain from intense exercise for 24 hours prior to attending, not to eat for 3 hours before and arrive fully hydrated wearing suitable clothing and the same footwear on both occasions as it is known that running shoes can impact running economy (Fuller *et al.*, 2015). They will also be asked to return at a time of day as close to the initial assessment as possible for standardisation and to try to limit any differences that could be the result of circadian rhythms (Drust *et al.*, 2005).

The same protocols and procedure for equipment and running as per the baseline level initial visit will be conducted, running at the same 5 km with the cyclist as a pacer, for 5 minutes. Running economy will then be determined for the last minute, having checked that steady state was achieved, and stride length information extracted from the ViPerform v5.

7.2.3.4 Data analysis

Data will be check for normality using the Kolomogrov-Smirnov test as $n > 50$. Paired sample t-tests will be used to determine whether there are differences between the pre- and post-intervention for both the control and experimental groups, and, the crux of the research, whether there is a difference between the control and experimental group using a combination of Excel (Microsoft Corporation, v16.33, Redmond, WA, USA) and SPSS (IBM SPSS Statistics, Rel. 28.0, 2021, SPSS Inc, Chicago, IL USA). The statistical significance level will be set at $p < 0.05$.

Chapter 8: General discussion

8.1 Introduction

The fundamental aim of this thesis was to identify whether there are any modifiable biomechanical factors that would improve the running economy in recreational endurance runners. The motivation for undertaking this area of research came from the fact that there is a large, and seemingly ever-increasing, population of recreational runners who are able to and regularly run distances considered to be endurance runs. This can be in part attributed to the popularity of the Couch to 5k app, which is available to be downloaded for free to a mobile device, and parkrun, a free, weekly timed event that happens in more than 20 countries across the globe. This cohort of recreational runners is largely under-investigated due to previous studies focussing on elite performers. However, the prospect of seeing running economy improved in this population has the potential to see them run further, faster or for longer for the same energy cost. The potential value of this is that if a runner can see improvements in their running performance, no matter how small the gains, it will help with exercise adherence (McAuley *et al.*, 2000; Rodrigues *et al.*, 2020). Continuing with some level of physical activity is considered vital for people's physical and mental health and well-being, with the Government outlining recommended guidelines for participation. The UK's Chief Medical Officer currently advises 150 minutes of moderate or 75 minutes of vigorous exercise per week. The majority of recreational runners can achieve this by committing to running 5 km just twice a week.

The first experimental chapters, Chapter 4 and Chapter 5, considered the reliability and ecological validity from a physiological and biomechanical perspective respectively. The main purpose of this was to establish whether or not testing recreational endurance runners outside overground could be used as standard experimental practice rather than inviting participants into a laboratory setting. The motivation for investigating this was because it is most common for recreational runners to run outside, overground and they may only use a treadmill when there are adverse weather conditions that prevent them from doing so, if at all, therefore, testing on a treadmill has little ecological validity for this population. Further, if treadmill running were to prove significantly different to overground running in this cohort, the scientific usefulness, could be questioned, as the results from testing on a treadmill and any subsequent changes seen on the treadmill, would not reflect how these runners run in their usual running context, so making and measuring changes on a treadmill will not truly reflect what is actually happening ,in terms of running technique, with recreational runners. Finally, it could be argued that testing recreational runners on a treadmill, where they do not habitually run, is not completely ethical as the research process should not be testing participants in situations that are not relevant to the research question being asked.

Chapter 4 concentrated on running economy to investigate the reliability and validity of testing and whether there were any significant differences between overground and treadmill running. Previous research, albeit with more highly trained runners, suggested the oxygen demand for treadmill and overground running was similar at velocities less than 15.48 km.h^{-1} ($0.1 < p < 0.25$) (van Ingen Schenau, 1980; Bassett *et al.*, 1985; Ceci and Hassmén, 1991; Oliveira *et al.*, 2016). However, within the recreational running population tested here, there was a statistically significant difference between overground and treadmill running across both trials, $p < 0.001$ in both cases and an effect size of $0.35 < x > 0.5$ (Cohen's d) indicating a small effect between the two. The differences in the physiological responses between the treadmill and overground running were also reflected in the measurements for heart rate, rating of perceived exertion and metabolic equivalents. With the exception of heart rate when comparing the first treadmill and first overground trial which showed no significant difference ($p > 0.05$), all other measurements (HR, RPE, METs) were found to be significantly different ($p < 0.05$) when comparing treadmill to overground running in all trials.

Turning to reliability and validity, the results showed that the testing was reliable and valid. The coefficient of variation between the two treadmill and two overground trials was 8.09% and 7.31% respectively, below the 10% acceptable threshold. Additionally, the intra-class correlation was recorded as 0.462 and 0.535 for treadmill and overground, which meets the fair to good level of reliability. The final checks were the Bland Altman levels of agreement, most of the results were found to be within the 95% level of agreement. The conclusion from this chapter was that testing overground was a reliable and valid means of assessing recreational runners. That there was a difference in the running economy recorded, suggests that if the aim to look for changes in running economy in recreational runners, it would make more ecological sense to test overground.

Having established in Chapter 4 that testing overground is a reliable and ecologically valid experimental design in terms of the physiological response, Chapter 5 then looked at the data from a biomechanical perspective. The aim of this chapter was to compare the way the participants run on a treadmill compared to overground, then identify whether there were any differences between the two conditions and determine if the method described for testing for biomechanical date in this cohort of runners was reliable and ecologically valid in this instant. All the parameters met the criteria set for reliability and validity, with coefficient of variation ranging from 1.15% to 18.70%, with all but three parameters having a value < 10%. Similarly, the levels for intra-class correlations fell within acceptable boundaries and the Bland Altman plots showed acceptable levels of agreement across between overground and treadmill conditions for all the biomechanical parameters measured. There were no significant differences identified between the treadmill and overground running parameters.

To summarise so far, the results from both Chapters 4 and 5 gave sufficient statistical weight to support the case for testing participants outside overground, providing confidence that any further testing could be carried out exclusively overground when studying a recreational endurance running population.

Having established the reliability and validity of the testing process, the final experimental chapter, Chapter 6, examined which of the parameters has the strongest relationship with running economy. Across all trials, the strongest relationship with running economy was shown to be stride length, with this accounting for 47.2%, 45.8% and 47.1% in the first, second and combined trials. Previous studies have demonstrated that stride length can be manipulated with a short-term intervention with a resultant improvement in running economy (Quinn *et al.*, 2021; Sellés-Pérez *et al.*, 2022). However, this previous work has been carried out with smaller numbers of trained participants. A novel aspect of this thesis was the ability to study a large number of recreational runners and gather the data from overground running where they habitually run.

8.2 Limitations

One possible limitation is that it could be argued that the participants who took part in the research were not a completely random set of recreational runners. They were mostly parkrunners and club members who expressed an interest in taking part in the research. Most were particularly keen to don the kit required for the testing process which requires a person to run wearing it and feel comfortable doing so. This group of runners were open to methods to improve their running, others may not be. However, given that the research required volunteers, there is always going to be an element of self-selection in the type of person who will participate. In mitigation, the volunteers were not a totally homogenous group so could be argued to represent the general recreational running community.

It could be considered a limitation that all the overground testing took place on a flat, paved surface, which is not where all runners necessarily run. Further testing would need to be done to see if the same finding or similar would be reported if the runner typically chose to run, for example, on a different surface, such as grass, or if the path was steep or undulating.

Although the equipment used for testing has been deemed reliable by previous studies (Zhang *et al.*, 2013; Winkert *et al.*, 2020; DeBlois, White and Barreira, 2021), it is possible that a limitation could arise due to some interference that impacted on the quality of the recordings, such as magnetic forces or the strength of the Bluetooth signal.

While an aim of the research undertaken was to identify a biomechanical trait that can be adjusted to improve the running economy of a recreational runner, to apply this to a wider population, it is limited by the fact that a participant would need to be tested before and after by a sports scientist, using a metabolic data system and the Xsens movement capture technology. However, the need for specialist equipment and an experienced researcher makes these testing processes less readily available to the majority of recreational runners. As a guide, if there has been a positive change, they should be able to recognise changes in their performance, notably that they find it more comfortable to run at the same pace or that they can run further or faster for the same perceived effort.

8.3 Potential areas of future research

8.3.1 Differences in running economy

The biomechanical differences tested (angles of hip, ankle and knee, vertical oscillation and stride length and rate) showed that there were no significant differences recorded between the two testing environments. However, there was a difference in running economy found comparing overground to treadmill running, although it was established in Chapter 4 that overground running was ecologically valid for recreational runners when looking at running economy. The question as to why there is a difference in running economy between the overground and treadmill conditions does not seem to be answered by the biomechanical parameters considered in this thesis. There were no significant differences between the indoor treadmill and outdoor overground running in any of the individual biomechanical factors studied. The environmental factors, as presented in Chapter 4 (Figure 4.2), between the two sets of trials were not significantly different, with trivial or small effect sizes (Appendix 6). Consideration was also given to the treadmill, which was set at a 1% incline to closer emulate the overground conditions (Jones and Doust, 1996). Jones and Doust (1996) investigated what, if any, adjustments should be made to ensure that treadmill running replicates overground running as faithfully as possible, in terms of energy expenditure. Many studies have faithfully used this method when comparing treadmill and overground running (Spencer and Gastin, 2001; Barnes and Kilding, 2015b). However, there are a few questions that might mean that setting the treadmill at a 1% gradient wasn't the most applicable method for this population.

The original testing by Jones and Doust (1996) examined nine male participants who were comfortable and familiar with treadmill running as well as overground running. They ran at speeds from 10.51 $km.h^{-1}$ to 18.0 $km.h^{-1}$, however, the running speed for the participants in this thesis ranged from 8.0 to 15.0 $km.h^{-1}$, with an average running speed of 11.26 $km.h^{-1}$. Although many of the runners fit in to the model proposed by Jones and Doust (1996), it might be that the lower speeds require less treadmill elevation, they did report that at the lowest velocities, $\dot{V}O_2$ during road running was not significantly different from treadmill running at 0% or 1% grade incline. While the incline on the treadmill might account for some difference in the $\dot{V}O_2$ seen between the overground and treadmill conditions, this becomes less important if testing is to be done exclusively outside, overground in future. Other suggested differences in the treadmill and overground conditions include the lack of visual cues when running in a static condition rather than changing surroundings (Dingwell *et al.*, 2001). To investigate whether the 1% incline of the treadmill was an issue for slower recreational runners, further study could be carried out testing the running economy of recreational runners whose speed falls in the range 8.0 km.h^{-1} up to 10 km.h^{-1} are studied, as these speeds are slower than the original Jones and Doust (1996) study. A range, from no incline on the treadmill to inclines of up to 1%, could be tested.

8.3.2 Testing findings from regression analysis

The findings of this thesis indicate that the biomechanical variable with the strongest relationship to running economy is stride length. However, due to the Covid 19 pandemic, the opportunity to conduct an experiment to introduce intervention to test this premise was denied. Therefore, the first line of inquiry would be to design and conduct such an intervention to demonstrate how these findings can be applied in the real world. Further, if stride length can be adjusted for participants in the recreational running population, it would be imperative to determine whether isolating and optimising this variable has an effect on other variables – for example whether altering the stride length will change the vertical oscillation pattern of a runner - and whether such changes would subsequently have a detrimental impact on running economy.

8.3.3 Identifying further modifiable parameters

The aim of this thesis was to isolate the modifiable biomechanical variable with the strongest relationship to running economy in a recreational running population, which was identified as stride length. It has been shown to be possible to change a runner's stride length (Sellés-Pérez *et al.*, 2022) and this thesis shows that this would subsequently improve the running economy in the cohort studied. Further investigation could be to determine if any additional manipulation of further variables could compound the improvement in running economy from adapting stride length.

8.3.4 Alternative lines of investigation

The Xsens MVN system enabled an extensive range of data to be collected across the four trials from all the participants. For the purposes of this thesis, the focus was on centre of mass oscillation and a number of gait cycle parameters, including stride length and joint angles at the hip and knee. There is still a variety of unused data which could potentially reveal other areas of interest. Analysis of upper body movement was limited to centre of mass vertical oscillation, but it would be possible to extract information on the lean of the torso, arm movements such as joint angles at elbow and shoulder as well as swing. There is the potential to see how these parameters interact with those examined in this thesis, and whether modifying upper body movement can improve any running economy gains from the changes identified here. There is evidence to suggest that arm swing aids stabilisation in the torso, but little work has been done to assess the impact on running economy (Arellano and Kram, 2012, 2014b).

A possible area of utilising the findings of this research is to tap into the potential provided by wearable technology. Runners who have used the Couch to 5k app, will be used to listening to a voice telling them to run or walk, while also offering words of encouragement. Including messages helping the runner to think about their stride length or rate could be incorporated into the technology. Today, some of the recent sports / smart watches are able to provide data on cadence and stride length among other things.

It is also commonly reported that people are not taught how to run, not as children and even less likely as adults (Protheroe *et al.*, 2012). Anyone can put on a pair of running shoes and head outside for a run. Using the key technical points identified here to think about the way you run from a young age - primarily at school - could help engender good habits to be continued into adulthood, as the repetitive movements practised by children, such as running, is known to hone their muscle memory and provide a blueprint for performing the same movement in the future without having to consciously think about it (Herrington, 2004; Eftestøl *et al.*, 2022).

8.4 The impact of Covid-19

It is not an exaggeration to say that the Covid-19 pandemic had a huge impact on the way this thesis developed. Early proposals and plans envisaged a final round of research, potentially involving an intervention, to test the modifiable biomechanical factors identified in Chapter 6 as being the most impactful on running economy in the recreational running population. Given the close contact necessary to perform any further research, it was not possible to gain ethical approval for any testing of this kind. Additionally, despite a number of mitigating procedures which could be put into place, several of the participants who had provisionally agreed to take part were no longer willing to be involved. Given that a power calculation for the proposed research reported that, allowing for attrition, a total of 58 participants were required, which is more that were recruited for the testing sessions in Chapters 4 and 5, recruiting sufficient new participants could prove problematic and therefore reduce the power of the study.

However, it is interesting to note that in the UK and across the globe, leisure centres and gyms were closed, so exercise could only be done at home or, in the UK, during the one hour a day people were permitted to be outside for exercise. That the people were encouraged to go outside for exercise was a positive indication from the UK Government on the value of exercising in open space. Given the limited options for exercise that were available to people in these circumstances, it is perhaps not surprising that there was a boom in the number of people who took up running for the first time or returned to running after a long absence. It is interesting to note that of those who started or returned to running, a significant proportion of them were committed to maintaining the habit and pledged that they would continue to do so once all restrictions were lifted (ASICS, 2020; Macmillan Cancer Support, 2021).

Given this further rise in the recreational running population, it seems even more relevant that this population should be the subject of research to understand their form and provide suggestions for improvements.

8.5 Conclusion

The overall aim of this thesis was to identify whether there are any modifiable biomechanical factors that would improve the running economy in recreational endurance runners. However, firstly, this thesis found that it is both reliable and ecologically valid to test recreational runners overground in a more natural environment rather than a laboratory treadmill from both a physiological and biomechanical aspect, suggesting that future research with recreational runners be carried out in the field. Addressing the original aim of the thesis, it is possible to identify stride length as a modifiable parameter that can potentially lead to an improvement in running economy.

Chapter 9: Practical implications and applications

9.1 Introduction

The purpose of this chapter is to consider the results from the experimental chapters and identify ways that these findings can be applied by recreational distance runners to improve their running and any other implications that result from the research. The initial findings from the first two experimental chapters (Chapters 4 and 5) showed that it is ecologically valid and reliable to test for running economy and gait information overground when studying recreational distance runners. The subsequent chapter (Chapter 6) identified stride length as being the parameter that would have the biggest impact on running economy.

9.2 Implications for future testing with recreational runners

As stated above, this thesis found that from both a physiological and a biomechanical perspective, a research method that specifies collecting data from overground running when studying recreational distance runners is a reliable and ecologically valid method of testing this cohort of participants. This potentially has a number of advantages over laboratory testing using a treadmill. Firstly, there is the opportunity for more flexibility of where and when runners are tested, as the research can potentially be conducted at a time and place suitable for the participants, as long as the procedure outlined in the method can be followed. Secondly, it removes the need to run on a treadmill, which is unfamiliar to many recreational runners who habitually tend to run overground (Hitchings and Latham, 2016). Testing outside, overground, for recreational runners could be applied to all research going forward, should the equipment be available to enable this to happen, as it has been shown, during the production of this thesis, to produce reliable and ecologically valid results in physiology and biomechanics for this cohort.

9.3 Practical applications for athletes and coaches

There are many fitness tracking apps and smart watches available that are often used by recreational runners to monitor their progress and log information about their runs. Among the information collected by several of these smart devices and apps is a step per minute rate which, as discussed in Chapter 7, it has been shown that altering the step rate will lead to a corresponding change in stride length. It is a decrease in stride length that this thesis identified as the parameter to have the most impact on improving running economy, with a decrease of 3% being the recommended scale of change. It is noted that while some smart devices may not be the most accurate when compared to more sophisticated scientific equipment, they are generally regarded as being consistent with themselves (Coutts and Duffield, 2010), so for a recreational runner who is looking to improve, this should be a reliable source to use as a baseline measure for their step rate. From here, they can determine the change they need to make from the calculation outlined in Chapter 7, choose the appropriate music and try the intervention.

9.4 Alternative and additional areas of research

The findings from this thesis suggest several other areas of interest that could be the subject of futures studies. Firstly, the intervention phase of this research included recreational distance runners who habitually listen to music. The logic behind this was that using music has been previously shown to help athletes adjust their stride length (Sellés-Pérez *et al.*, 2022) and it is relatively straightforward to obtain music of the tempo required for, and suitable for the taste of, each athlete, through various websites such as https://getsongbpm.com. If it is assumed that the piece of work as outlined in Chapter 7 found that shortening the stride length showed an improvement in running economy in recreational distance runners, then the method used for the research worked. The research excluded runners who don't listen to music for whatever reason or perhaps have a hearing impairment, so there is the opportunity to investigate other ways for the athlete to be aware of the required tempo. For instance, if a user feels a pulse or vibration from their smart phone or other device at the required tempo to adjust their stride length, does this have the same impact as hearing a musical beat?

If the intervention as proposed in Chapter 7 is successful, a next step in the research process could be to retest after a longer period, 6 or 12 months, to find out if the participant had been able to maintain the change in stride length and any associated change in running economy. This would take the form of the baseline protocol as outlined in Chapter 7.

Another area to consider could be the impact on injury prevention of altering a runner's stride length, while injury prevention was not within the remit of this thesis, it is something that could be investigated over a longer period of time. This could take the form of a longitudinal study, whereby participants keep record of any injuries pre- and post-intervention. Alongside a longitudinal study, research could also include the experience of the runners, specifically, whether an improved running economy led to a more enjoyable running experience, be that through improved times, distances run or another factor.

Further research could look at adapting one of the other biomechanical parameters, such as vertical oscillation, once the stride length has been adjusted, to determine whether if altering another biomechanical factor can further improve running economy.

9.5 Conclusion

To conclude, a useful finding from this thesis is that physiological and biomechanical testing on recreational distance runners can successfully and accurately be carried out in the field which is potentially useful for researchers. Additionally, a parameter has been identified, stride length, which can be manipulated through listening to music at a pre-determined tempo, which could improve running economy. The motivation for this was to improve the experience of recreational runners, with the potential benefit that an improved experience will lead to continued running and all the health and well-being benefits that brings (Biddle, Mutrie and Gorely, 2015; World Health Organisation, 2020).

Chapter 10: References

Abdi, H. (2010) 'Coefficient of variation', in N.J. Salkind (ed.) *Encyclopedia of research design*. Thousand Oaks, Calif: SAGE Publications, pp. 1–5.

Ache-Dias, J. *et al.* (2018) 'Effect of jump interval training on kinematics of the lower limbs and running economy', *Journal of Strength and Conditioning Research*, 32(2), pp. 416–422. Available at: https://doi.org/10.1519/JSC.0000000000002332.

Adams, D. *et al.* (2018) 'Altering cadence or vertical oscillation during running: effects on running related injury factors', *International Journal of Sports Physical Therapy*, 13(4), pp. 633–642. Available at: https://doi.org/10.26603/ijspt20180633.

Akobeng, A.K. (2005) 'Understanding randomised controlled trials', *Archives of Disease in Childhood*, 90(8), pp. 840–844. Available at: https://doi.org/10.1136/adc.2004.058222.

Alcaraz-Ibañez, M. and Rodríguez-Pérez, M. (2018) 'Effects of resistance training on performance in previously trained endurance runners: a systematic review', *Journal of Sports Sciences*, 36(6), pp. 613–629. Available at: https://doi.org/10.1080/02640414.2017.1326618.

Amann, M., Subudhi, A.W. and Foster, C. (2006) 'Predictive validity of ventilatory and lactate thresholds for cycling time trial performance', *Scandinavian Journal of Medicine and Science in Sports*, 16(1), pp. 27–34. Available at: https://doi.org/10.1111/j.1600-0838.2004.00424.x.

Anderson, T. (1996) 'Biomechanics and running economy', *Sports Medicine*, 22(2), pp. 76–89.

Arellano, C.J. and Kram, R. (2012) 'The energetic cost of maintaining lateral balance during human running', *Journal of Applied Physiology*, 112(3), pp. 427–434. Available at: https://doi.org/10.1152/japplphysiol.00554.2011.

Arellano, C.J. and Kram, R. (2014a) 'Partitioning the metabolic cost of human running: a task-by-task approach', *Integrative and Comparative Biology*, 54(6), pp. 1084–1098. Available at: https://doi.org/10.1093/icb/icu033.

Arellano, C.J. and Kram, R. (2014b) 'The metabolic cost of human running: is swinging the arms worth it?', *Journal of Experimental Biology*, 217(14), pp. 2456–2461. Available at: https://doi.org/10.1242/jeb.100420.

ASICS (2020) *New study explores the world's new-found love of running*. Available at: https://corp.asics.com/en/press/article/2020-06-09-1 (Accessed: 15 September 2022).

Aubry, R.L., Power, G.A. and Burr, J.F. (2018) 'An assessment of running power as a training metric for elite and recreational runners', *Journal of Strength and Conditioning Research*, 32(8), pp. 2258–2264. Available at: https://doi.org/10.1519/JSC.0000000000002650.

Badenes-Ribera, L. *et al.* (2016) 'Misconceptions of the p-value among Chilean and Italian academic psychologists', *Frontiers in Psychology*, 7. Available at: https://doi.org/10.3389/fpsyg.2016.01247.

Bailey, J., Mata, T. and Mercer, J.A. (2017) 'Is the relationship between stride length, frequency, and velocity influenced by running on a treadmill or overground?', *International Journal of Exercise Science*, 10(7), pp. 1067–1075.

Ballmann, C.G. (2021) 'The influence of music preference on exercise responses and performance: a review', *Journal of Functional Morphology and Kinesiology*, 6(2), p. 33. Available at: https://doi.org/10.3390/jfmk6020033.

Balsalobre-Fernández, C., Tejero-González, C.M. and Del Campo-Vecino, J. (2015) 'Seasonal strength performance and its relationship with training load on elite runners', *Journal of Sports Science & Medicine*, 14(1), pp. 9–15.

Barnes, K.R. *et al.* (2013) 'Effects of different uphill interval-training programs on running economy and performance', *International journal of sports physiology and performance*, 8(6), pp. 639–647. Available at: https://doi.org/10.1123/ijspp.8.6.639.

Barnes, K.R. and Kilding, A.E. (2015a) 'Running economy: measurement, norms, and determining factors', *Sports Medicine - Open*, 1(1), p. 8. Available at: https://doi.org/10.1186/s40798-015-0007-y.

Barnes, K.R. and Kilding, A.E. (2015b) 'Strategies to improve running economy', *Sports Medicine*, 45(1), pp. 37–56. Available at: https://doi.org/10.1007/s40279-014-0246-y.

Barnfield, A. (2016) 'Grasping physical exercise through recreational running and non-representational theory: a case study from Sofia, Bulgaria', *Sociology of Health & Illness*, 38(7), pp. 1121–1136. Available at: https://doi.org/10.1111/1467-9566.12434.

Bassett, D.R. *et al.* (1985) 'Aerobic requirements of overground versus treadmill running', *Medicine & Science in Sports & Exercise*, 17(4), pp. 477–481. Available at: https://doi.org/10.1249/00005768-198508000-00013.

Batterham, A.M. and George, K.P. (2003) 'Reliability in evidence-based clinical practice: a primer for allied health professionals', *Physical Therapy in Sport*, p. 7.

Biddle, S.J.H., Mutrie, N. and Gorely, T. (2015) *Psychology of physical activity determinants, well-being and interventions*. Hoboken: Taylor and Francis. Available at: http://Bangor.eblib.com/patron/FullRecord.aspx?p=1975219 (Accessed: 20 December 2021).

Bland, J.M. and Altman, D.G. (2010) 'Statistical methods for assessing agreement between two methods of clinical measurement', *International Journal of Nursing Studies*, p. 6.

Bonnaerens, S. *et al.* (2019) 'Grounded running reduces musculoskeletal loading', *Medicine & Science in Sports & Exercise*, 51(4), pp. 708–715. Available at: https://doi.org/10.1249/MSS.0000000000001846.

Boone, J., Deprez, D. and Bourgois, J. (2014) ‘Running economy in elite soccer and basketball players: differences among positions on the field’, *International Journal of Performance Analysis in Sport*, 14(3), pp. 775–787. Available at: https://doi.org/10.1080/24748668.2014.11868757.

Boone, T. (2014) *Introduction to exercise physiology*. Burlington, MA: Jones & Bartlett Learning.

Borg, G. (1998) *Borg’s perceived exertion and pain scales*. Champaign, Il: Human Kinetics.

Borgen, N.T. (2018) ‘Running performance, $\dot{V}O_{2max}$, and running economy: the widespread issue of endogenous selection bias’, *Sports Medicine*, 48(5), pp. 1049–1058. Available at: https://doi.org/10.1007/s40279-017-0789-9.

Bottenburg, M. van, Rijnen, B. and Sterkenburg, J. van (2005) *Sports participation in the European Union: trends and differences*. Nieuwegein: Arko Sports Media.

Bransford, D.R. and Howley, E.T. (1977) ‘Oxygen cost of running in trained and untrained men and women’, *Medicine and Science in Sports*, 9(1), pp. 41–44.

Breedveld, K., Scheerder, J. and Borgers, J. (2015) ‘England: The governance and history of running, the decision to run and trends in running participation’, in J. Scheerder, K. Breedveld, and J. Borgers (eds) *Running across Europe: the rise and size of one of the largest sport markets*. New York: Palgrave Macmillan, pp. 241–264.

Buman, M.P. *et al.* (2008) ‘Experiences and coping responses of “hitting the wall” for recreational marathon runners’, *Journal of Applied Sport Psychology*, 20(3), pp. 282–300. Available at: https://doi.org/10.1080/10413200802078267.

Cavanagh, P.R. and Williams, K.R. (1982) ‘The effect of stride length variation on oxygen uptake during distance running’, *Medicine & Science in Sports & Exercise*, 14(1), pp. 30–35. Available at: https://doi.org/10.1249/00005768-198201000-00006.

Ceci, R. and Hassmén, P. (1991) ‘Self-monitored exercise at three different RPE intensities in treadmill vs field running’:, *Medicine & Science in Sports & Exercise*, 23(6), pp. 732–738. Available at: https://doi.org/10.1249/00005768-199106000-00013.

Chambers, R. *et al.* (2015) ‘The use of wearable microsensors to quantify sport-specific movements’, *Sports Medicine*, 45(7), pp. 1065–1081. Available at: https://doi.org/10.1007/s40279-015-0332-9.

Chapman, A.R. *et al.* (2008) ‘Is running less skilled in triathletes than runners matched for running training history?’, *Medicine & Science in Sports & Exercise*, 40(3), pp. 557–565. Available at: https://doi.org/10.1249/MSS.0b013e31815e727a.

Clark, R.A. *et al.* (2019) ‘Three-dimensional cameras and skeleton pose tracking for physical function assessment: A review of uses, validity, current developments and Kinect alternatives’, *Gait & Posture*, 68, pp. 193–200. Available at: https://doi.org/10.1016/j.gaitpost.2018.11.029.

Colino, E. *et al.* (2020) ‘Mechanical properties of treadmill surfaces compared to other overground sport surfaces’, *Sensors (Basel, Switzerland)*, 20(14), p. 3822. Available at: https://doi.org/10.3390/s20143822.

Conley, D.L. and Krahenbuhl, G.S. (1980) ‘Running economy and distance running performance of highly trained athletes’, *Medicine & Science in Sports & Exercise*, 12(5), pp. 357–360. Available at: https://doi.org/10.1249/00005768-198025000-00010.

Connick, M.J. and Li, F.-X. (2014) ‘Changes in timing of muscle contractions and running economy with altered stride pattern during running’, *Gait & Posture*, 39(1), pp. 634–637. Available at: https://doi.org/10.1016/j.gaitpost.2013.07.112.

Cook, S., Shaw, J. and Simpson, P. (2016) ‘Jography: Exploring meanings, experiences and spatialities of recreational road-running’, *Mobilities*, 11(5), pp. 744–769. Available at: https://doi.org/10.1080/17450101.2015.1034455.

Coutts, A.J. and Duffield, R. (2010) ‘Validity and reliability of GPS devices for measuring movement demands of team sports’, *Journal of Science and Medicine in Sport*, 13(1), pp. 133–135. Available at: https://doi.org/10.1016/j.jsams.2008.09.015.

Craighead, D.H., Lehecka, N. and King, D.L. (2014) ‘A novel running mechanic’s class changes kinematics but not running economy’, *Journal of Strength and Conditioning Research*, 28(11), pp. 3137–3145. Available at: https://doi.org/10.1519/JSC.0000000000000500.

Cramer, H. *et al.* (2016) ‘A systematic review and meta-analysis estimating the expected dropout rates in randomized controlled trials on yoga interventions’, *Evidence-Based Complementary and Alternative Medicine*, 2016, pp. 1–7. Available at: https://doi.org/10.1155/2016/5859729.

Currell, K. and Jeukendrup, A.E. (2008) ‘Validity, reliability and sensitivity of measures of sporting performance’, *Sports Medicine*, 38(4), pp. 297–316. Available at: https://doi.org/10.2165/00007256-200838040-00003.

Daniels, J.T. (1985) ‘A physiologist’s view of running economy’, *Medicine and Science in Sports and Exercise*, 17(3), pp. 332–338.

De Asha, A.R., Robinson, M.A. and Barton, G.J. (2012) ‘A marker based kinematic method of identifying initial contact during gait suitable for use in real-time visual feedback applications’, *Gait & Posture*, 36(3), pp. 650–652. Available at: https://doi.org/10.1016/j.gaitpost.2012.04.016.

DeBlois, J.P., White, L.E. and Barreira, T.V. (2021) ‘Reliability and validity of the COSMED K5 portable metabolic system during walking’, *European Journal of Applied Physiology*, 121(1), pp. 209–217. Available at: https://doi.org/10.1007/s00421-020-04514-2.

Dellaserra, C.L., Gao, Y. and Ransdell, L. (2014) ‘Use of integrated technology in team sports: a review of opportunities, challenges, and future directions for athletes’, *Journal of Strength and Conditioning Research*, 28(2), pp. 556–573. Available at: https://doi.org/10.1519/JSC.0b013e3182a952fb.

Department of Health and Social Care (2023) *Millions of runs completed using Couch to 5k app*, *Gov.uk*. Available at: https://www.gov.uk/government/news/millions-of-runs-completed-using-couch-to-5k-app#:~:text=The%20app%20has%20been%20downloaded,get%20more%20active%20during%20lockdown (Accessed: 26 April 2023).

Dexheimer, J.D. *et al.* (2020) 'Predicting maximal oxygen uptake using the 3-minute all-out test in high-intensity functional training athletes', *Sports*, 8(12), p. 155. Available at: https://doi.org/10.3390/sports8120155.

Dingwell, J.B. *et al.* (2001) 'Local dynamic stability versus kinematic variability of continuous overground and treadmill walking', *Journal of Biomechanical Engineering*, 123(1), pp. 27–32. Available at: https://doi.org/10.1115/1.1336798.

Doyle, E. *et al.* (2022) 'The effectiveness of gait retraining on running kinematics, kinetics, performance, pain, and injury in distance runners: A systematic review with meta-analysis', *The Journal of Orthopaedic and Sports Physical Therapy*, 52(4), pp. 192-A5. Available at: https://doi.org/10.2519/jospt.2022.10585.

Drust, B. *et al.* (2005) 'Circadian rhythms in sports performance — an update', *Chronobiology International*, 22(1), pp. 21–44. Available at: https://doi.org/10.1081/CBI-200041039.

Dugan, S.A. and Bhat, K.P. (2005) 'Biomechanics and analysis of running gait', *Physical Medicine and Rehabilitation Clinics of North America*, 16(3), pp. 603–621. Available at: https://doi.org/10.1016/j.pmr.2005.02.007.

Eftestøl, E. *et al.* (2022) 'A juvenile climbing exercise establishes a muscle memory boosting the effects of exercise in adult rats', *Acta Physiologica*, 236(3), p. e13879. Available at: https://doi.org/10.1111/apha.13879.

Ekkekakis, P. (2009) 'Let them roam free?: Physiological and psychological evidence for the potential of self-selected exercise intensity in public health', *Sports Medicine*, 39(10), pp. 857–888. Available at: https://doi.org/10.2165/11315210-000000000-00000.

Elliott, B.C. and Blanksby, B.A. (1979) 'Optimal stride length considerations for male and female recreational runners', *British Journal of Sports Medicine*, 13(1), pp. 15–18. Available at: https://doi.org/10.1136/bjsm.13.1.15.

Eriksson, M., Halvorsen, K.A. and Gullstrand, L. (2011) 'Immediate effect of visual and auditory feedback to control the running mechanics of well-trained athletes', *Journal of Sports Sciences*, 29(3), pp. 253–262. Available at: https://doi.org/10.1080/02640414.2010.523088.

Farhan, S., Avalos, M.A. and Rosenblatt, N.J. (2023) 'Variability of spatiotemporal gait kinematics during treadmill walking: is there a Hawthorne effect?', *Journal of Applied Biomechanics*, 39(3), pp. 151–156. Available at: https://doi.org/10.1123/jab.2022-0185.

Ferrauti, A., Bergermann, M. and Fernandez-Fernandez, J. (2010) 'Effects of a concurrent strength and endurance training on running performance and running economy in recreational marathon runners', *Journal of Strength and Conditioning Research*, 24(10), pp. 2770–2778. Available at: https://doi.org/10.1519/JSC.0b013e3181d64e9c.

Finni, T. *et al.* (2003) 'Maximal but not submaximal performance is reduced by constant-speed 10-km run', *The Journal of Sports Medicine and Physical Fitness*, 43(4), pp. 411–417.

Fisher, D. *et al.* (2018) 'Three-dimensional kinematics of the thorax during over-ground running', *Journal of Bodywork and Movement Therapies*, 22(2), pp. 300–307. Available at: https://doi.org/10.1016/j.jbmt.2017.08.003.

Fletcher, J.R., Esau, S.P. and MacIntosh, B.R. (2010) 'Changes in tendon stiffness and running economy in highly trained distance runners', *European Journal of Applied Physiology*, 110(5), pp. 1037–1046. Available at: https://doi.org/10.1007/s00421-010-1582-8.

Folland, J.P. *et al.* (2017) 'Running technique is an important component of running economy and performance', *Medicine & Science in Sports & Exercise*, 49(7), pp. 1412–1423. Available at: https://doi.org/10.1249/MSS.0000000000001245.

Foster, C. and Lucia, A. (2007) 'Running economy: the forgotten factor in elite performance', *Sports Medicine*, 37(4), pp. 316–319. Available at: https://doi.org/10.2165/00007256-200737040-00011.

Frishberg, B.A. (1983) 'An analysis of overground and treadmill sprinting', *Medicine and Science in Sports and Exercise*, 15(6), pp. 478–485.

Fuller, J.T. *et al.* (2015) 'The effect of footwear on running performance and running economy in distance runners', *Sports Medicine*, 45(3), pp. 411–422. Available at: https://doi.org/10.1007/s40279-014-0283-6.

Fuller, J.T. *et al.* (2017) 'Six-week transition to minimalist shoes improves running economy and time-trial performance', *Journal of Science and Medicine in Sport*, 20(12), pp. 1117–1122. Available at: https://doi.org/10.1016/j.jsams.2017.04.013.

Futrell, E.E. *et al.* (2021) 'Exerted running results in altered impact mechanics and footstrike patterns following gait retraining', *Journal of Sports Sciences*, 39(11), pp. 1302–1311. Available at: https://doi.org/10.1080/02640414.2020.1868089.

García-Pérez, J.A. *et al.* (2013) 'Effect of overground vs treadmill running on plantar pressure: influence of fatigue', *Gait & Posture*, 38(4), pp. 929–933. Available at: https://doi.org/10.1016/j.gaitpost.2013.04.026.

George, K., Batterham, A. and Sullivan, I. (2003) 'Validity in clinical research: a review of basic concepts and definitions', *Physical Therapy in Sport*, p. 7.

González-Mohíno, F. *et al.* (2020) 'The effects of interval and continuous training on the oxygen cost of running in recreational runners: a systematic review and meta-analysis', *Sports Medicine*, 50(2), pp. 283–294. Available at: https://doi.org/10.1007/s40279-019-01201-x.

Haff, G.G. *et al.* (2015) ‘A comparison of methods for determining the rate of force development during isometric midthigh clean pulls’, *Journal of Strength and Conditioning Research*, 29(2), pp. 386–395. Available at: https://doi.org/10.1519/JSC.0000000000000705.

Halvorsen, K., Eriksson, M. and Gullstrand, L. (2012) ‘Acute effects of reducing vertical displacement and step frequency on running economy’, *Journal of Strength and Conditioning Research*, 26(8), pp. 2065–2070. Available at: https://doi.org/10.1519/JSC.0b013e318239f87f.

Handsaker, J.C. *et al.* (2016) ‘A kinematic algorithm to identify gait events during running at different speeds and with different footstrike types’, *Journal of Biomechanics*, 49(16), pp. 4128–4133. Available at: https://doi.org/10.1016/j.jbiomech.2016.10.013.

Hausswirth, C. and Lehénaff, D. (2001) ‘Physiological demands of running during long distance runs and triathlons’, *Sports Medicine*, 31(9), pp. 679–689. Available at: https://doi.org/10.2165/00007256-200131090-00004.

Hayes, P.R. and Walker, A. (2007) ‘Pre-exercise stretching does not impact upon running economy’, *Journal of Strength and Conditioning Research*, 21(4), pp. 1227–1232. Available at: https://doi.org/10.1519/R-19545.1.

Hefferon, K. and Mutrie, N. (2012) ‘Physical activity as a “stellar” positive psychology intervention’, in E.O. Acevedo (ed.) *The Oxford handbook of exercise psychology*. New York: Oxford University Press (Oxford library of psychology), pp. 117–128.

Heise, G.D. and Martin, P.E. (2001) ‘Are variations in running economy in humans associated with ground reaction force characteristics?’, *European Journal of Applied Physiology*, 84(5), pp. 438–442. Available at: https://doi.org/10.1007/s004210100394.

Helgerud, J., Støren, Ø. and Hoff, J. (2010) ‘Are there differences in running economy at different velocities for well-trained distance runners?’, *European Journal of Applied Physiology*, 108(6), pp. 1099–1105. Available at: https://doi.org/10.1007/s00421-009-1218-z.

Herrington, S. (2004) ‘Muscle memory: reflections on the North American schoolyard’, in H. Goelman, S. Marshall, and S. Ross (eds) *Multiple lenses, multiple images: perspectives on the child across time, space and disciplines*. Toronto: University of Toronto Press (Green College thematic lecture series), pp. 91–108.

Highton, J.M. *et al.* (2012) ‘The reliability and validity of short-distance sprint performance assessed on a nonmotorized treadmill’, *Journal of Strength and Conditioning Research*, 26(2), pp. 458–465. Available at: https://doi.org/10.1519/JSC.0b013e318225f384.

Hitchings, R. and Latham, A. (2016) ‘Indoor versus outdoor running: understanding how recreational exercise comes to inhabit environments through practitioner talk’, *Transactions of the Institute of British Geographers*, 41(4), pp. 503–514. Available at: https://doi.org/10.1111/tran.12138.

Hitchings, R. and Latham, A. (2017) 'How "social" is recreational running? Findings from a qualitative study in London and implications for public health promotion', *Health & Place*, 46, pp. 337–343. Available at: https://doi.org/10.1016/j.healthplace.2016.10.003.

Hollmann, W. (2001) '42 years ago - development of the concepts of ventilatory and lactate threshold', *Sports Medicine*, 31(5), pp. 315–320. Available at: https://doi.org/10.2165/00007256-200131050-00002.

Hoogkamer, W., Kram, R. and Arellano, C.J. (2017) 'How biomechanical improvements in running economy could break the 2-hour marathon barrier', *Sports Medicine*, 47(9), pp. 1739–1750. Available at: https://doi.org/10.1007/s40279-017-0708-0.

Hopkins, W.G. (2000) 'Measures of reliability in sports medicine and science', *Sports Med*, p. 15.

Hopkins, Will G. (2000) 'Measures of reliability in sports medicine and science', *Sports Medicine*, 30(1), pp. 1–15. Available at: https://doi.org/10.2165/00007256-200030010-00001.

Horsley, B.J. *et al.* (2021) 'Does site matter? Impact of inertial measurement unit placement on the validity and reliability of stride variables during running: a systematic review and meta-analysis', *Sports Medicine*, 51(7), pp. 1449–1489. Available at: https://doi.org/10.1007/s40279-021-01443-8.

Hung, K.-C. *et al.* (2019) 'Effects of 8-week core training on core endurance and running economy', *PLOS ONE*. Edited by S.E. Alway, 14(3), p. e0213158. Available at: https://doi.org/10.1371/journal.pone.0213158.

van Ingen Schenau, G.J. (1980) 'Some fundamental aspects of the biomechanics of overground versus treadmill locomotion', *Medicine and Science in Sports and Exercise*, 12(4), pp. 257–261.

Jakob, V. *et al.* (2021) 'Validation of a Sensor-Based Gait Analysis System with a Gold-Standard Motion Capture System in Patients with Parkinson's Disease', *Sensors*, 21(22), p. 7680. Available at: https://doi.org/10.3390/s21227680.

Johnston, R.E. *et al.* (1997) 'Strength training in female distance runners: impact on running economy', *Journal of Strength and Conditioning Research*, 11(4), pp. 224–229.

Jones, A.M. *et al.* (2021) 'Physiological demands of running at 2-hour marathon race pace', *Journal of Applied Physiology*, 130(2), pp. 369–379. Available at: https://doi.org/10.1152/japplphysiol.00647.2020.

Jones, A.M. and Carter, H. (2000) 'The effect of endurance training on parameters of aerobic fitness', *Sports Medicine*, 29(6), pp. 373–386. Available at: https://doi.org/10.2165/00007256-200029060-00001.

Jones, A.M. and Doust, J.H. (1996) 'A 1% treadmill grade most accurately reflects the energetic cost of outdoor running', *Journal of Sports Sciences*, 14(4), pp. 321–327. Available at: https://doi.org/10.1080/02640419608727717.

Jordan, K., Challis, J.H. and Newell, K.M. (2006) 'Long range correlations in the stride interval of running', *Gait & Posture*, 24(1), pp. 120–125. Available at: https://doi.org/10.1016/j.gaitpost.2005.08.003.

Joyner, M.J. and Coyle, E.F. (2008) 'Endurance exercise performance: the physiology of champions: factors that make champions', *The Journal of Physiology*, 586(1), pp. 35–44. Available at: https://doi.org/10.1113/jphysiol.2007.143834.

Kachouri, M. *et al.* (1996) 'Critical velocity of continuous and intermittent running exercise: An example of the limits of the critical power concept', *European Journal of Applied Physiology and Occupational Physiology*, 73(5), pp. 484–487. Available at: https://doi.org/10.1007/BF00334428.

Knechtle, B. (2014) 'Relationship of anthropometric and training characteristics with race performance in endurance and ultra-endurance athletes', *Asian Journal of Sports Medicine*, 5(2), pp. 73–90.

Kong, P.W. *et al.* (2012) 'Unmatched perception of speed when running overground and on a treadmill', *Gait & Posture*, 36(1), pp. 46–48. Available at: https://doi.org/10.1016/j.gaitpost.2012.01.001.

König, N. *et al.* (2014) 'Is gait variability reliable? An assessment of spatio-temporal parameters of gait variability during continuous overground walking', *Gait & Posture*, 39(1), pp. 615–617. Available at: https://doi.org/10.1016/j.gaitpost.2013.06.014.

Koo, T.K. and Li, M.Y. (2016) 'A guideline of selecting and reporting intraclass correlation coefficients for reliability research', *Journal of Chiropractic Medicine*, 15(2), pp. 155–163. Available at: https://doi.org/10.1016/j.jcm.2016.02.012.

LaCaille, R.A., Masters, K.S. and Heath, E.M. (2004) 'Effects of cognitive strategy and exercise setting on running performance, perceived exertion, affect, and satisfaction', *Psychology of Sport and Exercise*, 5(4), pp. 461–476. Available at: https://doi.org/10.1016/S1469-0292(03)00039-6.

Lam, K. *et al.* (2022) 'How effective and how expensive are interventions to reduce sedentary behavior? An umbrella review and meta-analysis', *Obesity Reviews*, 23(5). Available at: https://doi.org/10.1111/obr.13422.

Latham, A. (2015) 'The history of a habit: jogging as a palliative to sedentariness in 1960s America', *cultural geographies*, 22(1), pp. 103–126. Available at: https://doi.org/10.1177/1474474013491927.

Lees, A. (1999) 'Biomechanical assessment of individual sports for improved performance', *Sports Medicine*, 28(5), pp. 299–305. Available at: https://doi.org/10.2165/00007256-199928050-00001.

Lexell, J.E. and Downham, D.Y. (2005) ‘How to assess the reliability of measurements in rehabilitation’, *American Journal of Physical Medicine & Rehabilitation*, 84(9), pp. 719–723. Available at: https://doi.org/10.1097/01.phm.0000176452.17771.20.

López-Valenciano, A. *et al.* (2020) ‘Changes in sedentary behaviour in European Union adults between 2002 and 2017’, *BMC Public Health*, 20(1), p. 1206. Available at: https://doi.org/10.1186/s12889-020-09293-1.

Macmillan Cancer Support (2021) *Keep calm and jog on: millions turn to running to relieve lockdown stresses*. Available at: https://medium.com/macmillan-press-releases-and-statements/keep-calm-and-jog-on-millions-turn-to-running-to-relieve-lockdown-stresses-635746b8e37e (Accessed: 15 September 2022).

Magalhaes, F.A. de *et al.* (2015) ‘Wearable inertial sensors in swimming motion analysis: a systematic review’, *Journal of Sports Sciences*, 33(7), pp. 732–745. Available at: https://doi.org/10.1080/02640414.2014.962574.

McAuley, E. *et al.* (2000) ‘Physical activity, self-esteem, and self-efficacy relationships in older adults: A randomized controlled trial’, *Annals of Behavioral Medicine*, 22(2), pp. 131–139. Available at: https://doi.org/10.1007/BF02895777.

Miller, J.R. *et al.* (2019) ‘A systematic review and meta-analysis of crossover studies comparing physiological, perceptual and performance measures between treadmill and overground running’, *Sports Medicine*, 49(5), pp. 763–782. Available at: https://doi.org/10.1007/s40279-019-01087-9.

Millet, G.P. *et al.* (2002) ‘Effects of concurrent endurance and strength training on running economy and $\dot{V}O_{2max}$ kinetics’, *Medicine & Science in Sports & Exercise*, 34(8), pp. 1351–1359. Available at: https://doi.org/10.1097/00005768-200208000-00018.

Moore, I.S. (2016) ‘Is there an economical running technique? A review of modifiable biomechanical factors affecting running economy’, *Sports medicine (Auckland, N.Z.)*, 46(6), pp. 793–807. Available at: https://doi.org/10.1007/s40279-016-0474-4.

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

Morrow, J.R. *et al.* (2016) *Measurement and evaluation in human performance*. Fifth edition. Champaign, IL Windsor, ON Leeds: Human Kinetics.

Morrow, J.R. and Jackson, A. w. (1993) ‘How “significant” is your reliability?’, *Research Quarterly for Exercise and Sport*, 64(3), pp. 352–355. Available at: https://doi.org/10.1080/02701367.1993.10608821.

Murray, L., Beaven, C. and Hébert-Losier, K. (2018) ‘Reliability of overground running measures from 2D video analyses in a field environment’, *Sports*, 7(1), p. 8. Available at: https://doi.org/10.3390/sports7010008.

Nakayama, Y., Kudo, K. and Ohtsuki, T. (2010) 'Variability and fluctuation in running gait cycle of trained runners and non-runners', *Gait & Posture*, 31(3), pp. 331–335. Available at: https://doi.org/10.1016/j.gaitpost.2009.12.003.

Ng, S.W. and Popkin, B.M. (2012) 'Time use and physical activity: a shift away from movement across the globe: Declines in movement across the globe', *Obesity Reviews*, 13(8), pp. 659–680. Available at: https://doi.org/10.1111/j.1467-789X.2011.00982.x.

Nummela, A., Hämäläinen, I. and Rusko, H. (2007) 'Comparison of maximal anaerobic running tests on a treadmill and track', *Journal of Sports Sciences*, 25(1), pp. 87–96. Available at: https://doi.org/10.1080/02640410500497717.

Nummela, A., Keränen, T. and Mikkelsson, L. (2007) 'Factors Related to Top Running Speed and Economy', *International Journal of Sports Medicine*, 28(8), pp. 655–661. Available at: https://doi.org/10.1055/s-2007-964896.

Oliveira, A.S. *et al.* (2016) 'Modular Control of Treadmill vs Overground Running', *PLOS ONE*. Edited by D. Zhang, 11(4), p. e0153307. Available at: https://doi.org/10.1371/journal.pone.0153307.

Paavolainen, L. *et al.* (1999) 'Explosive-strength training improves 5-km running time by improving running economy and muscle power', *Journal of Applied Physiology*, 86(5), pp. 1527–1533. Available at: https://doi.org/10.1152/jappl.1999.86.5.1527.

Padulo, J. *et al.* (2019) 'Validity and reliability of a new specific parkour test: physiological and performance responses', *Frontiers in Physiology*, 10, p. 1362. Available at: https://doi.org/10.3389/fphys.2019.01362.

parkrun (2021) *home page*. Available at: https://www.parkrun.org.uk/ (Accessed: 20 December 2021).

Pauw, K.D. *et al.* (2013) 'Guidelines to Classify Subject Groups in Sport-Science Research', *International Journal of Sports Physiology and Performance*, 8(2), pp. 111–122. Available at: https://doi.org/10.1123/ijspp.8.2.111.

Perez-Suarez, I. *et al.* (2018) 'Accuracy and precision of the COSMED K5 portable analyser', *Frontiers in Physiology*, 9, p. 1764. Available at: https://doi.org/10.3389/fphys.2018.01764.

Peserico, C.S. and Machado, F.A. (2014) 'Comparison between running performance in time trials on track and treadmill', *Revista Brasileira de Cineantropometria e Desempenho Humano*, 16(4), p. 456. Available at: https://doi.org/10.5007/1980-0037.2014v16n4p456.

Pink, M. *et al.* (1994) 'Lower extremity range of motion in the recreational sport runner', *The American Journal of Sports Medicine*, 22(4), pp. 541–549. Available at: https://doi.org/10.1177/036354659402200418.

Pizzuto, F. *et al.* (2019) ‘Relationship Between Running Economy and Kinematic Parameters in Long-Distance Runners’, *Journal of Strength and Conditioning Research*, 33(7), pp. 1921–1928. Available at: https://doi.org/10.1519/JSC.0000000000003040.

Popovic, S. *et al.* (2013) ‘Body Height and Its Estimation Utilizing Arm Span Measurements in Serbian Adults’, *International Journal of Morphology*, 31(1), pp. 271–279. Available at: https://doi.org/10.4067/S0717-95022013000100043.

Pretty, J. *et al.* (2003) ‘Green exercise: complementary roles of nature, exercise and diet in physical and emotional well-being and implications for public health policy’, pp. 1–39.

Protheroe, C. *et al.* (2012) ‘Running: How is it Taught and Evaluated in British Columbian Schools?’, *Paediatrics & Child Health*, 17(suppl_A), pp. 26A-26A. Available at: https://doi.org/10.1093/pch/17.suppl_A.26A.

Pugh, L.G.C.E. (1970) ‘Oxygen intake in track and treadmill running with observations on the effect of air resistance’, *The Journal of Physiology*, 207(3), pp. 823–835. Available at: https://doi.org/10.1113/jphysiol.1970.sp009097.

Quinn, T.J. *et al.* (2021) ‘Step frequency training improves running economy in well-trained female runners’, *Journal of Strength and Conditioning Research*, 35(9), pp. 2511–2517. Available at: https://doi.org/10.1519/JSC.0000000000003206.

Raper, D.P. *et al.* (2018) ‘Use of a tibial accelerometer to measure ground reaction force in running: A reliability and validity comparison with force plates’, *Journal of Science and Medicine in Sport*, 21(1), pp. 84–88. Available at: https://doi.org/10.1016/j.jsams.2017.06.010.

Reed, G.F., Lynn, F. and Meade, B.D. (2002) ‘Use of coefficient of variation in assessing variability of quantitative assays’, *Clinical and Vaccine Immunology*, 9(6), pp. 1235–1239. Available at: https://doi.org/10.1128/CDLI.9.6.1235-1239.2002.

Reenalda, J. *et al.* (2016) ‘Continuous three dimensional analysis of running mechanics during a marathon by means of inertial magnetic measurement units to objectify changes in running mechanics’, *Journal of Biomechanics*, 49(14), pp. 3362–3367. Available at: https://doi.org/10.1016/j.jbiomech.2016.08.032.

Riley, P.O. *et al.* (2007) ‘A kinematic and kinetic comparison of overground and treadmill walking in healthy subjects’, *Gait & Posture*, 26(1), pp. 17–24. Available at: https://doi.org/10.1016/j.gaitpost.2006.07.003.

Riley, P.O. *et al.* (2008) ‘A kinematics and kinetic comparison of overground and treadmill running’, *Medicine & Science in Sports & Exercise*, 40(6), pp. 1093–1100. Available at: https://doi.org/10.1249/MSS.0b013e3181677530.

Rodrigues, F. *et al.* (2020) ‘The bright and dark sides of motivation as predictors of enjoyment, intention, and exercise persistence’, *Scandinavian Journal of Medicine & Science in Sports*, 30(4), pp. 787–800. Available at: https://doi.org/10.1111/sms.13617.

Roessler, K.K. and Muller, A.E. (2018) '"I don't need a flat tummy; I just want to run fast" – self-understanding and bodily identity of women in competitive and recreational sports', *BMC Women's Health*, 18(1), p. 146. Available at: https://doi.org/10.1186/s12905-018-0639-4.

Royal College of General Practitioners (2018) *parkrun UK teams up with RCGP to 'prescribe' active lifestyles to patients and practice staff*. Available at: https://www.rcgp.org.uk/about-us/news/2018/june/parkrun-uk-teams-up-with-rcgp-to-prescribe-active-lifestyles-to-patients-and-practice-staff.aspx (Accessed: 20 December 2021).

de Ruiter, C.J. *et al.* (2014a) 'Stride frequency in relation to oxygen consumption in experienced and novice runners', *European Journal of Sport Science*, 14(3), pp. 251–258. Available at: https://doi.org/10.1080/17461391.2013.783627.

de Ruiter, C.J. *et al.* (2014b) 'Stride frequency in relation to oxygen consumption in experienced and novice runners', *European Journal of Sport Science*, 14(3), pp. 251–258. Available at: https://doi.org/10.1080/17461391.2013.783627.

Saunders, Philo U *et al.* (2004) 'Factors Affecting Running Economy in Trained Distance Runners':, *Sports Medicine*, 34(7), pp. 465–485. Available at: https://doi.org/10.2165/00007256-200434070-00005.

Saunders, Philo U. *et al.* (2004a) 'Reliability and variability of running economy in elite distance runners', *Medicine & Science in Sports & Exercise*, 36(11), pp. 1972–1976. Available at: https://doi.org/10.1249/01.MSS.0000145468.17329.9F.

Saunders, Philo U. *et al.* (2004b) 'Reliability and variability of running economy in elite distance runners', *Medicine and Science in Sports and Exercise*, 36(11), pp. 1972–1976. Available at: https://doi.org/10.1249/01.mss.0000145468.17329.9f.

Scheerder, J., Breedveld, K. and Borgers, J. (eds) (2015) *Running across Europe: the rise and size of one of the largest sport markets*. New York: Palgrave Macmillan.

Sellés-Pérez, S. *et al.* (2022) 'Using musical feedback increases stride frequency in recreational runners', *International Journal of Environmental Research and Public Health*, 19(7), p. 3870. Available at: https://doi.org/10.3390/ijerph19073870.

Shaw, A.J. *et al.* (2013) 'The reliability of running economy expressed as oxygen cost and energy cost in trained distance runners', *Applied Physiology, Nutrition, and Metabolism*, 38(12), pp. 1268–1272. Available at: https://doi.org/10.1139/apnm-2013-0055.

Shaw, A.J., Ingham, S.A. and Folland, J.P. (2014) 'The valid measurement of running economy in runners', *Medicine & Science in Sports & Exercise*, 46(10), pp. 1968–1973. Available at: https://doi.org/10.1249/MSS.0000000000000311.

Shephard, R.J. (2017) 'Open-circuit respirometry: a brief historical review of the use of Douglas bags and chemical analyzers', *European Journal of Applied Physiology*, 117(3), pp. 381–387. Available at: https://doi.org/10.1007/s00421-017-3556-6.

Slawinski, J.S. and Billat, V.L. (2004) 'Difference in Mechanical and Energy Cost between Highly, Well, and Nontrained Runners':, *Medicine & Science in Sports & Exercise*, 36(8), pp. 1440–1446. Available at: https://doi.org/10.1249/01.MSS.0000135785.68760.96.

Smith, C.G.M. and Jones, A.M. (2001) 'The relationship between critical velocity, maximal lactate steady-state velocity and lactate turnpoint velocity in runners', *European Journal of Applied Physiology*, 85(1–2), pp. 19–26. Available at: https://doi.org/10.1007/s004210100384.

Spencer, M.R. and Gastin, P.B. (2001) 'Energy system contribution during 200- to 1500-m running in highly trained athletes':, *Medicine and Science in Sports and Exercise*, pp. 157–162. Available at: https://doi.org/10.1097/00005768-200101000-00024.

Spiers, A. *et al.* (2015) 'England: The governance and history of running, the decision to run and trends in running participation', in J. Scheerder, K. Breedveld, and J. Borgers (eds) *Running across Europe: the rise and size of one of the largest sport markets*. New York: Palgrave Macmillan, pp. 81–104.

Sport England (2022) *Active lives*. Available at: https://activelives.sportengland.org/Result?queryId=76156 (Accessed: 22 September 2022).

Spurrs, R.W., Murphy, A.J. and Watsford, M.L. (2003) 'The effect of plyometric training on distance running performance', *European Journal of Applied Physiology*, 89(1), pp. 1–7. Available at: https://doi.org/10.1007/s00421-002-0741-y.

Squadrone, R. *et al.* (2015) 'Acute effect of different minimalist shoes on foot strike pattern and kinematics in rearfoot strikers during running', *Journal of Sports Sciences*, 33(11), pp. 1196–1204. Available at: https://doi.org/10.1080/02640414.2014.989534.

Stevens, C. *et al.* (2015) 'The reliability of running performance in a 5 km time trial on a non-motorized treadmill', *International Journal of Sports Medicine*, 36(09), pp. 705–709. Available at: https://doi.org/10.1055/s-0034-1398680.

Szabo, A. and Ábrahám, J. (2013) 'The psychological benefits of recreational running: A field study', *Psychology, Health & Medicine*, 18(3), pp. 251–261. Available at: https://doi.org/10.1080/13548506.2012.701755.

Tam, E. *et al.* (2012) 'Energetics of running in top-level marathon runners from Kenya', *European Journal of Applied Physiology*, 112(11), pp. 3797–3806. Available at: https://doi.org/10.1007/s00421-012-2357-1.

Tartaruga, M.P. *et al.* (2014) 'Scale performance prediction in recreational and elite endurance runners', *International Journal of Sports Physiology and Performance*, 9(4), pp. 650–655. Available at: https://doi.org/10.1123/ijspp.2013-0165.

Taunton, J.E. (2003) 'A prospective study of running injuries: the Vancouver Sun Run "In Training" clinics', *British Journal of Sports Medicine*, 37(>3), pp. 239–244. Available at: https://doi.org/10.1136/bjsm.37.3.239.

Tawa, N. and Louw, Q. (2018) ‘Biomechanical factors associated with running economy and performance of elite Kenyan distance runners: A systematic review’, *Journal of Bodywork and Movement Therapies*, 22(1), pp. 1–10. Available at: https://doi.org/10.1016/j.jbmt.2017.11.004.

Teunissen, L.P.J., Grabowski, A. and Kram, R. (2007) ‘Effects of independently altering body weight and body mass on the metabolic cost of running’, *Journal of Experimental Biology*, 210(24), pp. 4418–4427. Available at: https://doi.org/10.1242/jeb.004481.

Tseh, W., Caputo, J.L. and Morgan, D.W. (2008) ‘Influence of gait manipulation on running economy in female distance runners’, *Journal of Sports Science & Medicine*, 7(1), pp. 91–95.

Turner, A.M., Owings, M. and Schwane, J.A. (2003) ‘Improvement in running economy after 6 weeks of plyometric training’, *Journal of Strength and Conditioning Research*, 17(1), pp. 60–67. Available at: https://doi.org/10.1519/1533-4287(2003)017<0060:iiream>2.0.co;2.

Van Caekenberghe, I. *et al.* (2013) ‘Joint kinematics and kinetics of overground accelerated running versus running on an accelerated treadmill’, *Journal of The Royal Society Interface*, 10(84), p. 20130222. Available at: https://doi.org/10.1098/rsif.2013.0222.

Van Hooren, B. *et al.* (2020) ‘Is motorized treadmill running biomechanically comparable to overground running? A systematic review and meta-analysis of cross-over studies’, *Sports Medicine*, 50(4), pp. 785–813. Available at: https://doi.org/10.1007/s40279-019-01237-z.

Vilas-Boas, M. do C. *et al.* (2019) ‘Full-body motion assessment: Concurrent validation of two body tracking depth sensors versus a gold standard system during gait’, *Journal of Biomechanics*, 87, pp. 189–196. Available at: https://doi.org/10.1016/j.jbiomech.2019.03.008.

Warne, J.P. and Warrington, G.D. (2014) ‘Four-week habituation to simulated barefoot running improves running economy when compared with shod running: Habituation to simulated barefoot running’, *Scandinavian Journal of Medicine & Science in Sports*, 24(3), pp. 563–568. Available at: https://doi.org/10.1111/sms.12032.

Wasserstein, R.L. and Lazar, N.A. (2016) ‘The ASA Statement on *p* -Values: Context, Process, and Purpose’, *The American Statistician*, 70(2), pp. 129–133. Available at: https://doi.org/10.1080/00031305.2016.1154108.

Watari, R. *et al.* (2016) ‘Validation of a Torso-Mounted Accelerometer for Measures of Vertical Oscillation and Ground Contact Time During Treadmill Running’, *Journal of Applied Biomechanics*, 32(3), pp. 306–310. Available at: https://doi.org/10.1123/jab.2015-0200.

Williams, K.R. and Cavanagh, P.R. (1987) ‘Relationship between distance running mechanics, running economy, and performance’, *Journal of Applied Physiology*, 63(3), pp. 1236–1245. Available at: https://doi.org/10.1152/jappl.1987.63.3.1236.

Williams, K.R., Cavanagh, P.R. and Ziff, J.L. (1987) 'Biomechanical studies of elite female distance runners', *International Journal of Sports Medicine*, 8 Suppl 2, pp. 107–118. Available at: https://doi.org/10.1055/s-2008-1025715.

Wills, E. (2021) 'Covid: Councils urged to allow England parkrun events to resume', *BBC news online*, 25 May. Available at: https://www.bbc.co.uk/news/uk-57235948 (Accessed: 20 July 2022).

Winkert, K. *et al.* (2020) 'The COSMED K5 in breath-by-breath and mixing chamber mode at low to high intensities', *Medicine and Science in Sports and Exercise*, 52(5), pp. 1153–1162. Available at: https://doi.org/10.1249/MSS.0000000000002241.

World Health Organisation (2020) *Physical activity*. Available at: https://www.who.int/news-room/fact-sheets/detail/physical-activity (Accessed: 20 December 2021).

Zhang, J.-T. *et al.* (2013) 'Concurrent validation of Xsens MVN measurement of lower limb joint angular kinematics', *Physiological Measurement*, 34(8), pp. N63–N69. Available at: https://doi.org/10.1088/0967-3334/34/8/N63.

Zimmermann, W. and van Valderen, N. (2021) 'The automatic strike-change phenomenon: when running barefoot patients change from a heel strike to a forefoot strike without any instruction', *International Journal of Sports Science and Physical Education*, 6(1), p. 1. Available at: https://doi.org/10.11648/j.ijsspe.20210601.11.

Appendix 1: Ethical Approval

University of East London

Pioneering Futures Since 1898

Dear Gill

Application ID: ETH1819-0020

Project title: The repeatability of indoor and outdoor running tests

Principal Investigator: Dr Andy Galbraith

Researcher: Ms Gill Macaskill

Your application to University Research Ethics Committee was considered on the 7th of November 2018.

The decision is: **Approved**

The Committee's response is based on the protocol described in the application form and supporting documentation.

Your project has received ethical approval for 2 years from the approval date.

If you have any questions regarding this application please contact your supervisor or the secretary for the University Research Ethics Committee.

Approval has been given for the submitted application only and the research must be conducted accordingly.

Should you wish to make any changes in connection with this research project you must complete 'An application for approval of an amendment to an existing application'.

The approval of the proposed research applies to the following research site.

Research site: The treadmill testing will take place in the sports testing laboratory at SportsDock in UEL Docklands campus and outdoor testing will be on the paved pedestrian route along the dockside at the UEL Docklands campus.

Principal Investigator / Local Collaborator: Ms Gill Macaskill

Approval is given on the understanding that the UEL Code of Practice for Research and the Code of Practice for Research Ethics is adhered to.

Any adverse events or reactions that occur in connection with this research project should be reported using the University's form for Reporting an Adverse/Serious Adverse Event/Reaction.

The University will periodically audit a random sample of approved applications for ethical approval, to ensure that the research projects are conducted in compliance with the consent given by the Research Ethics Committee and to the highest standards of rigour and integrity.

Please note, it is your responsibility to retain this letter for your records.

With the Committee's best wishes for the success of the project

Yours

Fernanda Silva

Administrative Officer for Research Governance

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University of East London

Pioneering Futures Since 1898

Dear Gill

Application ID: ETH1920-0158

Original application ID: ETH1819-0020

Project title: Performance in recreational distance runners: a biomechanical approach to improving running economy

Lead researcher: Ms Gill Macaskill

Your application to Health, Sport and Bioscience School Research Ethics Committee was considered on the 25th of February 2020.

The decision is: **Approved**

The Committee's response is based on the protocol described in the application form and supporting documentation.

Your project has received ethical approval for 2 years from the approval date.

If you have any questions regarding this application please contact your supervisor or the secretary for the Health, Sport and Bioscience School Research Ethics Committee.

Approval has been given for the submitted application only and the research must be conducted accordingly.

Should you wish to make any changes in connection with this research project you must complete 'An application for approval of an amendment to an existing application'.

The approval of the proposed research applies to the following research site.

Research site: The treadmill testing will take place in the sports testing laboratory at SportsDock in UEL Docklands campus and outdoor testing will be on the paved pedestrian route along the dockside at the UEL Docklands campus.

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Please note, it is your responsibility to retain this letter for your records.

With the Committee's best wishes for the success of the project

Yours sincerely

Fernanda Silva

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Appendix 2: Participant information and consent forms

University of East London

University Way, London, E16 2RD

Research Integrity

The University adheres to its responsibility to promote and support the highest standard of rigour and integrity in all aspects of research; observing the appropriate ethical, legal and professional frameworks. The University is committed to preserving your dignity, rights, safety and wellbeing and as such it is a mandatory requirement of the University that formal ethical approval, from the appropriate Research Ethics Committee, is granted before research with human participants or human data commences.

The Principal Investigator/Director of Studies

Dr. Andy Galbraith; a.j.galbraith@uel.ac.uk

University Way, London, E16 2RD

Student researcher

Gill Macaskill; u1418565@uel.ac.uk

University Way, London, E16 2RD

Consent to Participate in a Research Study

The purpose of this letter is to provide you with the information that you need to consider in deciding whether to participate in this study.

Project Title

The repeatability of indoor and outdoor running tests

Project Description

Most research in this area to date has been conducted using elite athletes. The purpose of the study is to determine the differences in physiology and running techniques between treadmill and outdoor running with the aim of adjusting a person's technique to improve their physiological response and their running experience. The research is aimed at recreational runners at any level of fitness.

You will be required to come into the UEL Docklands campus on two separate occasions, not less than a week apart. You will be required to refrain from intense exercise for 24 hours before the test and from eating for 3 hours before and wear suitable clothing and footwear, arriving fully hydrated. On each occasion, you will be fitted with the Cosmed K5 portable breathing system, which has an adjustable harness to improve comfort, and 17 sensors for the Xsens motion capture, which are attached using non-intrusive cloth straps. You will then do two trials, one on a treadmill in the laboratory for up to 5 minutes at your usual 5k running pace and the other run outside for up to 5 minutes at your usual 5k running pace, there will be a rest period between the two trials. In between the two visits, your normal training and diet will continue.

By taking part in this study, you will be helping further our understanding of the relationship between indoor and outdoor running. There are minor risks from trip hazards outside, but no more than a normal running activity. There is also the potential for muscle soreness, but this can be minimised by performing a warm-up and cool-down as directed.

Confidentiality of the Data

Your participation in this study and all information collected will be kept strictly confidential unless a disclosure is made that indicates that the participant or someone else is at serious risk of harm. Such disclosures may be reported to the relevant authority. Where necessary, information collected will be coded so that you cannot be recognised from it. The data will be stored safely on a password protected computer or in a locked filing cabinet.

The data generated in the course of the research will be retained in accordance with the University's Data Protection Policy. The results of this study will be reported as part of my degree programme and may be further disseminated for scientific benefit. The results will be available to you on request.

Location

Sports Dock, UEL, University Way, London, E16 2RD

Disclaimer

Your participation in this study is entirely voluntary, and you are free to withdraw at any time during the research. Should you choose to withdraw from the programme you may do so without disadvantage to yourself and without any obligation to give a reason. Please note that your data can be withdrawn up to the point of data analysis – after this point it may not be possible.

University Research Ethics Committee

If you have any concerns regarding the conduct of the research in which you are being asked to participate, please contact:

Catherine Hitchens, Research Integrity and Ethics Manager, Graduate School, EB 1.43

University of East London, Docklands Campus, London E16 2RD

(Telephone: 020 8223 6683, Email: researchethics@uel.ac.uk**)**

For general enquiries about the research please contact the Principal Investigator on the contact details at the top of this sheet.

UNIVERSITY OF EAST LONDON

Consent to Participate in a Programme Involving the Use of Human Participants.

The repeatability of indoor and outdoor running tests

Researcher: Gill Macaskill

Please tick as appropriate:

	YES	NO
I have read the information leaflet relating to the above programme of research in which I have been asked to participate and have been given a copy to keep. The nature and purposes of the research have been explained to me, and I have had the opportunity to discuss the details and ask questions about this information. I understand what is being proposed and the procedures in which I will be involved have been explained to me.		
I understand that my involvement in this study, and particular data from this research, will remain strictly confidential as far as possible. Only the researchers involved in the study will have access to the data.		
I understand that maintaining strict confidentiality is subject to the following limitations: A disclosure is made that indicates that the participant or someone else is at serious risk of harm. Such disclosures may be reported to the relevant authority.		
I understand that the results will form part of the researcher's thesis and will be submitted to an appropriate scientific journal for publication.		
Would you be happy for the data to be used in future research studies?		
Would you be happy to be contacted for future research studies?		

It has been explained to me what will happen once the programme has been completed.		
I understand that my participation in this study is entirely voluntary, and I am free to withdraw at any time during the research without disadvantage to myself and without being obliged to give any reason. I understand that my data can be withdrawn up to the point of data analysis and that after this point it may not be possible.		
I hereby freely and fully consent to participate in the study which has been fully explained to me and for the information obtained to be used in relevant research publications.		

Participant’s Name (BLOCK CAPITALS) …………………………………………………………………….

Participant’s Signature ………………………………………………………………………………………..

Investigator’s Name (BLOCK CAPITALS) ……………………………………………………………………..

Investigator’s Signature ………………………………………………………………………………………

Date: ………………………….

Appendix 3: BASES questionnaire

BASES Pre-test Questionnaire

Name……………………………………………………………………………………
Date of Birth…………………………..
Age…………………………………….

As you are to be a client in this assessment, would you please complete the following questionnaire. Your co-operation in this greatly appreciated

* = Please circle to indicate response

ANY INFORMATION CONTAINED HEREIN WILL BE TREATED AS CONFIDENTIAL

1. How would you describe your present level of activity?

Sedentary/moderately active/ highly active*
Give an example of typical weeks exercise.

2. How would you describe your present level of fitness?

Very unfit/moderately fit/trained/highly trained*

3. How would you consider your present body weight?

Under weight/ideal weight/slightly overweight/very overweight*

4. Smoking Habits:

Currently non-smoker yes/no*
A previous smoker yes/no* of…..per day
If *previous smoker*, how long since stopping?………years
Regular smoker yes/no* of…..per day?
An occasional smoker yes/no* of…..per day?

5. Consumption of alcohol:

Do you drink alcoholic drinks? yes/no*

If *yes*, then do you:

Have the occasional drink? yes/no*
Have a drink every day? yes/no*
Have more than one drink a day? yes/no*

Please indicate the type of alcoholic beverage you consume i.e. beer, spirits, shandy

1. Have you had to consult your doctor within the last 6 months? yes/no*

If *yes*, please give relevant details to the test supervisor.

2. Are you presently taking any form of medication? yes/no*

If *yes*, please give relevant details to the test supervisor.

3. Do you suffer, or have you ever suffered, from

Asthma? yes/no*
Diabetes? yes/no*
Bronchitis? yes/no*
Epilepsy? yes/no*

4. Do you suffer, or have you ever suffered from, any form of heart complaint? yes/no*

5. Is there a history of heart disease in your family? yes/no*

6. Do you currently have any form of muscle or joint injury? yes/no*

7. Have you had any cause to suspend your normal training in the last two weeks? yes/no*

8. Is there anything to your knowledge that prevent you from successfully completing the tests that have been outlined to you? yes/no*

Signature of client…………………………………. Date……………………

Signature of test supervisor…………………………….

Appendix 4: Tests of normality

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
OG1_CoM_min	.247	40	<.001	.720	40	<.001
OG1_CoM_max	.232	40	<.001	.872	40	<.001
OG1_CoM_range	.172	40	.004	.917	40	.006
OG2_CoM_min	.077	40	.200*	.978	40	.608
OG2_CoM_max	.089	40	.200*	.977	40	.575
OG2_CoM_range	.150	40	.024	.927	40	.012
TD1_CoM_min	.190	40	<.001	.803	40	<.001
TD1_CoM_max	.224	40	<.001	.675	40	<.001
TD1_CoM_range	.293	40	<.001	.425	40	<.001
TD2_CoM_min	.108	40	.200*	.900	40	.002
TD2_CoM_max	.086	40	.200*	.974	40	.473
TD2_CoM_range	.111	40	.200*	.921	40	.008

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Step_count_TD01	.112	40	.200*	.977	40	.579
Step_count_TD02	.073	40	.200*	.987	40	.928
Step_count_OG01	.171	40	.005	.700	40	<.001
Step_count_OG02	.178	40	.003	.788	40	<.001
Step_count_TDALL	.081	40	.200*	.982	40	.767
Step_count_OGALL	.067	40	.200*	.982	40	.756
Stride_rate_TD01	.113	40	.200*	.976	40	.555
Stride_rate_TD02	.073	40	.200*	.987	40	.927
Stride_rate_OG01	.172	40	.005	.700	40	<.001
Stride_rate_OG02	.178	40	.003	.788	40	<.001
Stride_rate_TDALL	.074	40	.200*	.982	40	.752
Stride_rate_OGALL	.071	40	.200*	.982	40	.754
Stride_length_TD01	.115	40	.195	.951	40	.079
Stride_length_TD02	.126	40	.109	.945	40	.050
Stride_length_OG01	.095	40	.200*	.979	40	.658
Stride_length_OG02	.117	40	.184	.976	40	.558
Stride_length_TDALL	.118	40	.170	.945	40	.050
Stride_length_OGALL	.114	40	.200*	.964	40	.229
Cycle_time_TD01	.138	40	.052	.965	40	.251
Cycle_time_TD02	.098	40	.200*	.979	40	.641
Cycle_time_OG01	.108	40	.200*	.873	40	<.001
Cycle_time_OG02	.123	40	.130	.925	40	.011
Cycle_time_TDALL	.099	40	.200*	.971	40	.380
Cycle_time_OGALL	.079	40	.200*	.982	40	.750

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Range_LH_TD01	.116	40	.195	.961	40	.185
Range_LH_TD02	.094	40	.200*	.970	40	.372
Range_LH_OG01	.066	40	.200*	.980	40	.697
Range_LH_OG02	.077	40	.200*	.977	40	.587
Range_LH_TDALL	.133	40	.072	.937	40	.027
Range_LH_OGALL	.087	40	.200*	.967	40	.292
Max_LH_TD01	.121	40	.140	.967	40	.293
Max_LH_TD02	.130	40	.087	.929	40	.014
Max_LH_OG01	.113	40	.200*	.956	40	.126
Max_LH_OG02	.106	40	.200*	.968	40	.300
Max_LH_TDALL	.068	40	.200*	.981	40	.738
Max_LH_OGALL	.098	40	.200*	.950	40	.073
Min_LH_TD01	.102	40	.200*	.987	40	.918
Min_LH_TD02	.070	40	.200*	.981	40	.728
Min_LH_OG01	.089	40	.200*	.975	40	.516
Min_LH_OG02	.129	40	.094	.892	40	.001
Min_LH_TDALL	.082	40	.200*	.967	40	.284
Min_LH_OGALL	.080	40	.200*	.985	40	.864
Range_RH_TD01	.109	40	.200*	.928	40	.014
Range_RH_TD02	.123	40	.131	.956	40	.118
Range_RH_OG01	.146	40	.031	.963	40	.213
Range_RH_OG02	.090	40	.200*	.977	40	.564
Range_RH_TDALL	.106	40	.200*	.961	40	.175
Range_RH_OGALL	.113	40	.200*	.974	40	.463
Max_RH_TD01	.131	40	.083	.966	40	.258
Max_RH_TD02	.135	40	.066	.869	40	<.001
Max_RH_OG01	.090	40	.200*	.980	40	.699
Max_RH_OG02	.188	40	.001	.822	40	<.001
Max_RH_TDALL	.131	40	.083	.950	40	.075
Max_RH_OGALL	.106	40	.200*	.968	40	.315
Min_RH_TD01	.076	40	.200*	.984	40	.821
Min_RH_TD02	.098	40	.200*	.962	40	.194
Min_RH_OG01	.098	40	.200*	.976	40	.560
Min_RH_OG02	.060	40	.200*	.993	40	.996
Min_RH_TDALL	.090	40	.200*	.981	40	.722
Min_RH_OGALL	.109	40	.200*	.972	40	.421

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Range_LK_TD01	.089	40	.200*	.963	40	.212
Range_LK_TD02	.155	40	.016	.933	40	.020
Range_LK_OG01	.072	40	.200*	.986	40	.898
Range_LK_OG02	.098	40	.200*	.969	40	.325
Range_LK_TDALL	.090	40	.200*	.964	40	.222
Range_LK_OGALL	.089	40	.200*	.969	40	.341
Max_LK_TD01	.084	40	.200*	.971	40	.392
Max_LK_TD02	.147	40	.029	.947	40	.060
Max_LK_OG01	.132	40	.078	.933	40	.020
Max_LK_OG02	.102	40	.200*	.961	40	.183
Max_LK_TDALL	.069	40	.200*	.986	40	.898
Max_LK_OGALL	.077	40	.200*	.973	40	.434
Min_LK_TD01	.085	40	.200*	.966	40	.258
Min_LK_TD02	.106	40	.200*	.966	40	.264
Min_LK_OG01	.298	40	<.001	.620	40	<.001
Min_LK_OG02	.143	40	.038	.849	40	<.001
Min_LK_TDALL	.099	40	.200*	.967	40	.291
Min_LK_OGALL	.243	40	<.001	.773	40	<.001
Range_RK_TD01	.118	40	.169	.970	40	.347
Range_RK_TD02	.070	40	.200*	.977	40	.568
Range_RK_OG01	.133	40	.074	.961	40	.179
Range_RK_OG02	.069	40	.200*	.985	40	.877
Range_RK_TDALL	.110	40	.200*	.956	40	.118
Range_RK_OGALL	.121	40	.141	.960	40	.170
Max_RK_TD01	.144	40	.035	.942	40	.041
Max_RK_TD02	.146	40	.030	.742	40	<.001
Max_RK_OG01	.214	40	<.001	.742	40	<.001
Max_RK_OG02	.166	40	.007	.774	40	<.001
Max_RK_TDALL	.108	40	.200*	.955	40	.113
Max_RK_OGALL	.140	40	.047	.900	40	.002
Min_RK_TD01	.098	40	.200*	.953	40	.095
Min_RK_TD02	.309	40	<.001	.470	40	<.001
Min_RK_OG01	.216	40	<.001	.677	40	<.001
Min_RK_OG02	.309	40	<.001	.567	40	<.001
Min_RK_TDALL	.198	40	<.001	.730	40	<.001
Min_RK_OGALL	.199	40	<.001	.799	40	<.001

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

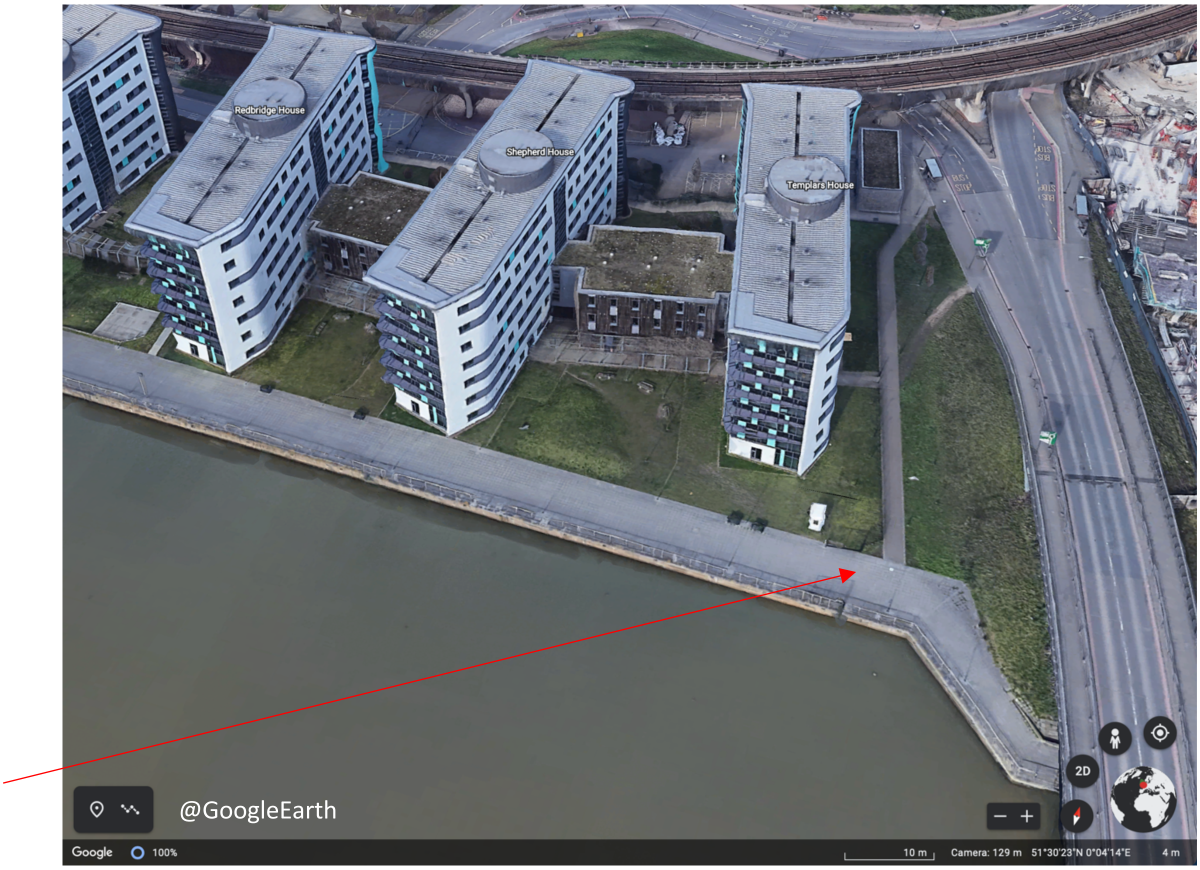
Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Range_LA_TD01	.076	40	.200*	.978	40	.630
Range_LA_TD02	.075	40	.200*	.928	40	.014
Range_LA_OG01	.067	40	.200*	.986	40	.900
Range_LA_OG02	.109	40	.200*	.968	40	.313
Range_LA_TDALL	.091	40	.200*	.946	40	.054
Range_LA_OGALL	.108	40	.200*	.966	40	.263
Max_LA_TD01	.096	40	.200*	.978	40	.607
Max_LA_TD02	.102	40	.200*	.919	40	.007
Max_LA_OG01	.076	40	.200*	.988	40	.939
Max_LA_OG02	.077	40	.200*	.985	40	.862
Max_LA_TDALL	.108	40	.200*	.952	40	.086
Max_LA_OGALL	.097	40	.200*	.987	40	.915
Min_LA_TD01	.086	40	.200*	.957	40	.134
Min_LA_TD02	.113	40	.200*	.968	40	.315
Min_LA_OG01	.079	40	.200*	.976	40	.547
Min_LA_OG02	.110	40	.200*	.973	40	.451
Min_LA_TDALL	.132	40	.077	.952	40	.090
Min_LA_OGALL	.116	40	.192	.981	40	.745
Range_RA_TD01	.099	40	.200*	.942	40	.039
Range_RA_TD02	.083	40	.200*	.970	40	.363
Range_RA_OG01	.092	40	.200*	.956	40	.121
Range_RA_OG02	.112	40	.200*	.951	40	.080
Range_RA_TDALL	.085	40	.200*	.968	40	.311
Range_RA_OGALL	.115	40	.196	.972	40	.407
Max_RA_TD01	.127	40	.101	.955	40	.116
Max_RA_TD02	.195	40	<.001	.843	40	<.001
Max_RA_OG01	.145	40	.034	.951	40	.085
Max_RA_OG02	.167	40	.006	.790	40	<.001
Max_RA_TDALL	.158	40	.013	.938	40	.029
Max_RA_OGALL	.108	40	.200*	.941	40	.036
Min_RA_TD01	.084	40	.200*	.973	40	.441
Min_RA_TD02	.148	40	.027	.845	40	<.001
Min_RA_OG01	.074	40	.200*	.977	40	.570
Min_RA_OG02	.119	40	.155	.917	40	.006
Min_RA_TDALL	.101	40	.200*	.980	40	.687
Min_RA_OGALL	.106	40	.200*	.968	40	.301

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Appendix 5: Elevation of overground running path



This first image, taken from Google Earth, shows the start of the overground running path along the dockside at the Royal Albert Dock, Newham, London. The red arrow indicates the starting point, at the gated entrance to University of East London property. The height above sea level at this point is 4 m, as indicated in the bottom right of the image.

The path was walked three times wearing a Garmin Forerunner 235 (Garmin International Inc, Olathe, Kansas, USA). Data collected by the device recorded an average total ascent of 0 m and an average total descent of 0 m.

This second image, again taken from Google Earth, shows the end of the overground running path along the dockside at the Royal Albert Dock, Newham, London. The red arrow indicates the end point, just before the London Design and Engineering building. The height above sea level at this point is 4 m, as indicated in the bottom right of the image.


London Design and Engineering UTC
Docklands Lbry
@GoogleEarth
2D
Google
100%
10 m
Camera: 129 m 51°30'25"N 0°03'40"E
4 m

Appendix 6: Environmental data from testing in Chapters 4 and 5

Effect size calculations between the treadmill trials and overground trials

		Pre-Test			Post-Test			Glass's	Cohen's	Hedges'
Condition 1	*Condition 2*	Mean	SD	*n*	Mean	SD	*n*	Δ	*d*	*g*
		Temp								
TM1	TM2	24.53	0.85	40	24.45	1.71	40	0.09	0.06	0.06
OG1	OG2	18.25	4.58	40	20.8	4.33	40	0.56	0.57	0.57
		Pressure								
TM1	TM2	1038.3	12.93	40	1042.98	7.41	40	0.36	0.44	0.44
OG1	OG2	1014.35	8.75	40	1014.9	6.58	40	0.06	0.07	0.07
		Humidity								
TM1	TM2	47.03	7.98	40	48.12	7.06	40	0.14	0.14	0.14
OG1	OG2	61.68	13.25	40	57.45	11.83	40	0.32	0.34	0.33

Magnitude	Effect Size
Trivial	0.0-0.2
Small	0.2-0.6
Moderate	0.6-1.2
Large	1.2-2.0
Very Large	2.0-4.0
Extremely Large	>4.0

Based on Hopkins et al., (2009)

Environmental data presented as mean ± SD.

	Humidity (%)	Pressure (mb)	Temp (°C)	Wind ($km.h^{-1}$)
Treadmill 1	47.03 ± 7.98	1038.30 ± 12.93	24.53 ± 0.85	N/A
Overground 1	61.68 ± 13.25	1014.35 ± 8.75	18.25 ± 4.58	12.35 ± 4.45
Treadmill 2	48.12 ± 7.06	1042.98 ± 7.41	24.45 ± 1.71	N/A
Overground 2	57.45 ± 11.83	1014.90 ± 6.58	20.80 ± 4.33	11.95 ± 4.16