A comparative study of muscle activation and oxygen uptake between stationary cycle ergometry and rollers.

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Declaration

No part of this thesis has been submitted of an application for any degree or other qualification of the University of Kent, or any other University or Institution of learning.

Signed: Harry J Doy

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List of abbreviations and symbols

Ag	Silver
AgCl	Silver chloride
ANOVA	Analysis of variance
ATP	Adenosine triphosphate
Bf	Breathing frequency
CO_2	Carbon dioxide
EMG	Electromyography
ETC	Electron transport chain
$FADH_2$	Flavin adenine dinucleotide
F_EO_2	Fraction of expire oxygen
F_ECO_2	Fraction of expired carbon dioxide
H+	Hydrogen ions
Hz	Hertz
HR	Heart rate
ICC	Intraclass correlation coefficients
Ln	Natural log
LT1	First lactate threshold
NADH	Nicotinamide adenine dinucleotide
Nm	Newton-metres
PO	Power output

PPO	Peak power output
Rad/s	Radians per second
RER	Respiratory exchange ratio
RMS	Root mean square
RPE	Rating of perceived exertion (Borg 6 – 20)
RPM	Revolutions per minute
SENIAM	Surface Electromyography for the Non-Invasive Assessment of Muscles
sEMG	Surface electromyography
TT	Time trial
$\dot{V}CO_2$	Carbon dioxide production (L/min)
VT1	First ventilatory threshold
$\dot{V}O_2$	Oxygen uptake (L/min)
$\dot{V}O_{2max}$	Maximal oxygen consumption (ml/kg/min)
$\dot{V}_E$	Pulmonary ventilation (L/min)
W	Watts
ω	Angular velocity

Abstract

This thesis aims to address two related challenges in indoor cycling research: 1) the validity of a pedal-based power measurement device when compared to laboratory standards, and 2) the physiological and biomechanical implications of cycling on two different indoor setups at matched workloads. Two studies were conducted to address these challenges. In study I, five participants completed 14 × 30 second bouts at progressively increasing intensities, beginning at 100 W and increasing in uniform 30 second increments up to 240 W using the Garmin Rally RK100 power pedals. In study II, nine participants completed 2 submaximal cycling trials (at power equivalent of ~VT1) on a stationary ergometer and on rollers, during which ventilatory measures ($\dot{V}O_2$, V_E and RER), upper body muscle activation (sEMG) and handlebar lateral movement were recorded. Bland-Altman analysis in study I revealed a systematic mean bias of -11.76 W between the Garmin Rally RK100 pedals and the Cyclus 2 ergometer, signifying an underestimation of power output by the pedal system. Results of study II showed no significant difference inactivation of the triceps brachii lateral head ($F_{(1,8)} = 2.678$, $p = 0.140$, $\eta p^2 = 0.251$), middle trapezius ($F_{(1,8)} = 0.464$, $p = 0.515$, $\eta p^2 = 0.055$), rectus abdominis ($F_{(1,8)} = 1.845$, $p = 0.211$, $\eta p^2 = 0.187$) and external obliques ($F_{(1,8)} = 1.137$, $p = 0.317$, $\eta p^2 = 0.124$)., as well as comparable ventilatory responses across conditions ($\dot{V}O_2$: $F_{(1,8)} = .208$, $p = .660$, $\eta p^2 = .025$; RER: $F_{(1,8)} = .000$, $p = .990$, $\eta p^2 = .000$; V_E: $F_{(1,8)} = .043$, $p = .840$, $\eta p^2 = .005$). However, cycling on rollers elicited 162.63% greater lateral handlebar movement than the Cyclus2, reflecting the higher stability demands of roller riding.

Overall, these findings demonstrate that while pedal-based power meters exhibit sufficient accuracy for general use, the presence of systematic bias demands greater caution when employed in research environments. Furthermore, the increased lateral handlebar movement observed during roller cycling, with an absence of difference in ventilatory responses,

suggests that rollers impose a greater stability demand while maintaining a similar metabolic cost. This highlights their potential utility as an indoor modality that more closely reflects the demands of outdoor cycling.

Chapter 1 – General Introduction

Laboratory-based cycling protocols have advanced our understanding of physiological performance, yet their ecological validity remains contested. Fixed cycle ergometers, which convenient and often highly accurate, fail to replicate the dynamic demands of real-world cycling. Research shows that cycling on an unstable platform (e.g. Rollers) increases oxygen uptake ($\dot{V}O_2$) despite equal mechanical output, implicating that increased postural control demand increases metabolic cost (Miller et al., 2013).

Technological advancements have broadened the landscape of indoor cycling measurement. While traditional stationary ergometers remain gold standard in laboratory environments due to their precise control over power output/ resistance, the development of commercially available power meters has altered data collection in applied environments (typically integrated into cranks, pedals or hubs). These portable systems offer immediate feedback and seamless integration into training platforms (e.g. TrainingPeaks and Strava). However, questions could be raised about the measurement validity and reliability. Therefore, ensuring these devices produce data comparable to laboratory-grade systems is essential for bridging the gap between laboratory testing and field-based performance monitoring.

Simultaneously with the expansion of power measurement devices, the range of indoor cycling modalities have also diversified. Stationary ergometers, which fix the bicycle in place, allow for high reproducibility but differ in stability demands compared to road cycling. Rollers, in contrast, allow natural lateral bike movement which may better replicate outdoor cycling conditions, but their physiological implications remain mostly unknown. Understanding these differences is crucial for both training prescription and accurately integrating laboratory-based data into training.

This thesis addresses two related challenges in indoor cycling research: 1) the validity of a pedal-based power measurement device when compared to laboratory standards, and 2) the physiological and biomechanical implications of cycling on two different indoor setups at matched workloads. Study 1 investigates the agreement between the Garmin Rally RK100 power pedals across a range of workloads, Study 2 assessing the differences ventilatory response, upper body muscle activation and handlebar movement between cycling on a fixed ergometer (Cyclus2) and rollers. Together, these investigations provide a more complete picture of methodological considerations in cycling research.

By validating a commercial power meter against a laboratory standard and assessing the ecological validity of different indoor modalities, therefore this thesis bridges the gap between controlled laboratory testing and real-world cycling.

2.1.1 Cycle Ergometry and Power Measurement

The use of cycle ergometry is common in performance laboratories as the more restricted movement of the upper body and the fixed position of the bike allows researchers to collect more invasive measurements than they would otherwise in field-based cycling testing (Maclaren et al., 1999; Atkinson et al., 2003). It is also frequently used rehabilitation in physiotherapy clinics for a battery of purposes: cardiac rehabilitation (Balsam et al., 2013; Gerlach et al., 2020; Gama Lordello et al., 2020), pulmonary rehabilitation (Ries 1994; Mahler, 1998; Altindag et al, 2021) and muscle, tendon and ligament injury/ surgery rehabilitation due to its low impact nature (Wright et al., 2008; Milandri & Sivarasu, 2021). Ergometry's physiological versatility i.e. stresses multiple physiological systems, allows it to be used in an array of contexts.

Two common types of cycle ergometer used in physiology laboratories are electromagnetically braked ergometers and friction-loaded ergometers. Electromagnetically braked ergometers use a flywheel which passes through a magnetic field generated by an electric current. By varying the strength of the current passing through the electromagnet, the strength of the magnetic field changes, thus altering the resistance applied to the flywheel. Unlike friction-loaded systems, electromagnetic braking is independent of the rider's pedalling cadence, which allows precise control over workload (W). While fixed ergometers provide convenience and accurate power measurement, they lack a crucial element inherent to road cycling which is balance. Real-world cycling is a complex motor task involving not just lower-limb force production, cyclists also constantly engage in subtle muscle activity to maintain stability.

Rollers offer a laboratory compromise, as they allow cyclists to use their own bikes which they are comfortable with, require them to remain balance like outdoor cycling, whilst allows staying stationary. Unlike ergometers, rollers require the cyclist to actively engage balance, maintain coordination and stability, closely mimicking real-world cycling conditions. This increase in neuromuscular demand improves ecological validity as it replicates the several dynamic elements intrinsic to cycling (Faria et al., 2005). Previous research has suggested that cycling on rollers requires greater engagement of the upper body stabiliser muscles (Miller et al., 2013), reflected by an increase in metabolic cost. While this enhances ecological validity in laboratory conditions, it introduces challenges for workload measurement precision. Small variations in posture, balance or pedalling technique can affect power delivery (Harnish et al., 2007; Fennell et al., 2020), making it more difficult to achieve tighter control of workloads compared with stationary ergometers. Particularly electromagnetically controlled ergometers which can alter resistance depending on cadence allowing for more precise power control.

The development of on-bike power measurement devices, particularly crank and pedal-based systems, has expanded opportunities for both applied and scientific research. These technologies provide quantification of power output during training and competition, thereby allowing data collection in more ecologically valid contexts. Pedal-based systems have become increasingly popular due to their portability, ease of use, price and compatibility with online training platforms (Hutchinson et al., 2017; Dickenson & Wright, 2021). Due to their increasing use by athletes and coaches, there is now a growing body of research for accuracy of pedal-based power meters, although research is still limited. Nevertheless, despite their practical and monetary advantages, laboratory ergometers such as the Cyclus2 and the Monark cycle ergometer, as well as crank-based power meters (SRM) remain widely used as gold standard in modern research. This is due to their high precision, repeatability and

stability (Reiser et al., 2000; Wooles & Robinson, 2005; Lunn & Axtell, 2021). Pedal-based power meters therefore present a potential bridge between laboratory and field-based, however more research should be done to assess the accuracy of these devices compared to the laboratory standard.

A key challenge in incorporating portable power meters into scientific research is ensuring consistency in workloads across devices. Multiple studies have identified systematic discrepancies between portable power meters and gold standard cycle ergometers (Hutchinson et al., 2017; Dickenson & Wright, 2021). However, it is important to note that although power is more robust measurement than physiological metrics which can change from day to day and be influenced by even small adjustments in body position. Jobson et al., (2008) conducted a study comparing different physiological variables across a 40.23km TT (mean HR, $\dot{V}O_2$, V_E, RER and Bf). Participants completed 3 separate TTs in 3 different conditions (in a randomised order), one in the aerodynamic position outdoors, another in the aerodynamic position indoors on an ergometer (a Kingcycle), and the other in an upright position indoors. The data displayed in the study showed that V_E and breathing frequency (Bf) were significantly lower than that of the outdoors condition. HR was also higher however this was deemed statistically insignificant; this may be due to the small sample size used (n=9). Certain adjustments can be made to improve the ecological validity of laboratory-based testing, for example using turbo trainers to allow participants to use their own bike which they would be suited to. It was also found that there was no significant increase in $\dot{V}O_2$ across the different conditions (Jobson et al. 2008). However, Gnehm et al., (1997) assessed different riding positions whilst measuring EMG and $\dot{V}O_2$. They found that there was an increase in $\dot{V}O_2$ when cycling in a more aerodynamic position compared to an upright position, which accounted for a decrease of 9 W in the 'aero' position. Jobson et al., (2008) found a similar decrease in power in their study between body positions also. Both studies

suggested that an increase in upper body muscle activation especially the arms and upper back.

This interpretation is further supported by the findings of McDaniel et al. (2005), who directly manipulated trunk stability using a torso stabilisation device aiming to reduce the metabolic cost of producing submaximal cycling power. Their main finding was that the device significantly reduced metabolic cost (1%). Metabolic cost was based on the thermal equivalent of O_2 for nonprotein respiratory equivalent. Metabolic cost (kJ/min) = 4.187 × (1.2341 × RER × $\dot{V}$O2 + 3.8124). This study was sufficiently powered (β =0.81). Collectively, these studies demonstrate that an increase in muscle activation causes an increase in metabolic demand.

2.2.2 Oxygen Uptake ($\dot{V}O_2$) in Cycling

Oxygen uptake ($\dot{V}O_2$) is an imperative variable in exercise physiology, representing the rate at which oxygen (O_2) is consumed by the body during physical activity (Poole & Richardson, 1997; Xu & Rhodes, 1999). O_2 is crucial to human life primarily due to its role in the biochemical process by which cells generate energy in the form of adenosine triphosphate (ATP), otherwise known as cellular respiration. O_2 serves as the final electron acceptor in the mitochondrial electron transport chain (ETC), which enables the efficient production of ATP via oxidative phosphorylation. This process accounts for the majority of ATP generation in aerobic organisms and relies on the continuous flow of electrons through the ETC. O_2's role in the ETC begins with the donation of electrons and hydrogen ions (H+)/ protons from cofactors such as NADH and $FADH_2$. This results in O_2 combining with electrons from cytochrome c (Chandel et al., 1996), and H+ ions (protons), ultimately forming water which is imperative to maintaining the proton gradient (Blomberg, 2016). This reaction is facilitated by an enzyme called cytochrome c oxidase which also is responsible for a process called

‘proton pumping’. Proton pumping involves transferring protons across the inner mitochondrial membrane, thus creating an electrochemical gradient that drives ATP synthesis through ATP synthase (Brand, 2000). In the absence of oxygen, this gradient cannot be maintained, halting oxidative phosphorylation and forcing cells to rely more on anaerobic glycolysis and the ATP phosphocreatine system, which yields far less ATP and contributes to lactate accumulation and acidosis (Hochachka & Somero, 2002).

$\dot{V}O_2$ is widely used to measure metabolic demand during cycling, as it reflects whole-body O_2 utilisation and provides a direct indicator of aerobic energy expenditure. As $\dot{V}O_2$ responds to changes in exercise intensity (Hettinga et al., 2009), however the relationship between intensity is not strictly linear. Physiological thresholds such as the ventilatory thresholds and lactate thresholds represent transition periods where the metabolic and ventilatory responses change disproportionately to the increase in workload. This suggests that even small discrepancies in workload for example ± 5 or 10 W could position an individual on either side of these thresholds, causing large in ventilatory response and metabolic cost (Jones et al., 2010). Knowing the sensitivity of $\dot{V}O_2$, it is important to take this into account when matching intensities.

2.2.3 Indirect Calorimetry

Given O_2’s essential role in aerobic metabolism, accurately measuring $\dot{V}O_2$ provides critical insight into integrative performance of the pulmonary, cardiovascular and muscular systems. Indirect calorimetry is considered the reference standard for measuring energy expenditure and substrate utilisation by analysing respiratory gas exchange (Haugen et al., 2007; Mtaweh et al., 2018). Using $\dot{V}O_2$, carbon dioxide production ($\dot{V}CO_2$), and respiratory exchange ratio (RER), indirect calorimetry allows the quantification of metabolic rate, substrate use, and aerobic capacity during rest and exercise (Carter & Jeukendrup, 2002; Robergs et al., 2010).

Gas analysis thus serves as a non-invasive, real-time window into the interplay between O_2 delivery and utilisation.

The gold standard of indirect calorimetry devices is Douglas bags and the metabolic cart (Macfarlane, 2001; Haugen et al., 2007). Douglas bags are one of the oldest methods of sampling expired gas; they involve collecting expired air in an airtight bag over a set period and analysing the collected gas sample (Shepard, 2017). Participants breathe through a two-way valve that directs inspired air from the ambient environment and expired air into the Douglas bag. By combining the volume of gas inside the bag and its composition, the rate of $\dot{V}O_2$ and $\dot{V}CO_2$ can be calculated by multiplying the total volume of air expired (V_E) by the fractional concentrations of O_2 (FeO_2) and CO_2 ($FeCO_2$), which are determined when a sample of the expired air is drawn from the bag and composition is analysed. Overall, Douglas bags are an excellent method for gas analysis, but they still have their distinct disadvantages (Carter & Jeukendrup, 2002). The most prominent limitation is that they can only be used for averaged data and not breath by breath, meaning that they are unable to detect temporal changes in volumes/concentrations. Another limitation of Douglas bags is that they require practitioners to time collections perfectly to maintain validity (Haugen et al., 2007).

Modern metabolic carts (more specifically open circuit) typically include a flow censor, gas analysers, and data acquisition software allowing for real-time analysis of respiratory gases. Metabolic carts have become more prevalent in present research due to their operational efficiency, immediate data processing, and user convenience. Multiple validation studies have shown that breath-by-breath metabolic carts produce $\dot{V}O_2$ and $\dot{V}CO_2$ values nearly identical to the Douglas bag method with mean error margins within 2-3% during both sub-maximal and maximal exercise (Jensen et al. 2002; Rosdahl et al. 2010; Macfarlane & Wong, 2012). Metabolic carts have also been found to display low coefficients of variation (~1.8 – 2.4%)

similar to that of Douglas bags. While Douglas bags are lower cost and robust, they hinder practicality in high-throughput settings and require extensive post-test processing, whereas metabolic carts eliminate many of the manual steps associated with Douglas bags. While some research has shown that metabolic carts elicit a subtly higher breathing resistance compared to Douglas bags (Ainegreen et al. 2018), this rarely outweighs the benefits of their use making them a frequent choice in physiological research.

Amongst the choices of metabolic carts, the Cortex Metalyzer 3B is regarded as an economical and valid choice for conducting indirect calorimetry. Its performance has been evaluated in several studies; in both healthy participants and athletes, test-retest reliability is exceedingly high. For example, Meyer et al. (2001) reported intraclass correlation coefficients (ICC) of ~0.97 for $\dot{V}O2$, 0.96 for $\dot{V}CO_2$ and 0.95 for V_E in repeated ramp tests. The Metalyzer 3B showed minimal drift over hours of continuous use, measured values changing 2% across a 3-hour test (Macfarlane & Wong, 2012). Macfarlane & Wong (2012) and Meyer et al. (2001) deemed the Metalyzer 3b reliable when calibrated carefully.

2.2.4 Muscle Activation and surface EMG use

Muscle activation refers to the process by which the nervous system stimulates the muscle fibres to contract, enabling movement and force production. This process begins when an action potential is generated in the motor cortex and travels down the spinal cord, thus resulting in the generation of tension in the muscle (Huxley, 1974). When a muscle is activated by neural input, electrical potentials are generated by depolarizing motor units and can be detected on the skin's surface using electrodes. Surface Electromyography (sEMG) is a non-invasive method of measuring the summation of motor unit action potentials during skeletal muscle contraction. It involves placing an electrode with most commonly Ag/AgCl sensors on the surface of the skin of the muscle of interest to detect their electrical activity

(Dideriksen et al., 2011). The use of sEMG allows researchers to examine how different muscles contribute to movement; how recruitment patterns change with varying loads or fatigue, and how increased activity may lead to and increased metabolic cost. At the cellular level this activation triggers a chain of events described by the sliding filament theory, which explains how force is produced through the cyclical interaction of actin and myosin filaments within the sarcomere (Powers et al., 2021). Each cross-bridge cycle (where myosin heads attach to actin, perform a power stroke and then detach) requires the hydrolysis of ATP. This causes an increase in muscle activation (i.e. higher rates of cross-bridge cycling) and thus increases metabolic cost. This relationship between optimal motor unit recruitment and metabolic cost has practical implications for exercise efficiency; greater or prolonged muscle activation measured by sEMG, may reflect increased energy expenditure.

During cycling, the propulsion is primarily generated by the coordinated work of the lower limb muscles. The quadriceps, particularly the vastus lateralis and vastus medialis, are strongly activated during the downstroke to extend the knee and generate the majority of crank torque (Jorge & Hull, 1986; Hug & Dorel, 2009). The rectus femoris contributes across the whole stroke due to its biarticular role in hip flexion and knee extension (Jorge & Hull, 1986; Hug & Dorel, 2009). The hamstrings, particularly the biceps femoris activating towards the end of the downstroke, assisting in hip extension and knee flexion (Da Silva et al., 2016). Although these prime movers provide most of the propulsive force, stabilising muscles of the trunk, hip flexors, and upper body may also contribute by maintaining posture, balance, and effective force transmission through the pedal cycle.

Theoretically, as stationary ergometers in upright positions provide extra stability due to their rigid designs, they may reduce reliance on the trunk and upper body stabiliser muscles (McDaniel et al., 2005). Rollers on the other hand, increase postural demands, which is

thought to cause greater activation in the upper back and stabilising muscles in the trunk (Asplund & Ross, 2010; Miller et al., 2013).

2.2.5 Electrode Placement

Table 1. Literature search for the standards of electrode placement for the triceps brachii lateral head, trapezius, rectus abdominis and external obliques.

Study title	Authors	Muscle(s)	Description of placement	Study protocol
A systematic review on fatigue analysis in triceps brachii analysis using surface electromyography	Hussain et al., (2018)	triceps brachii lateral head	Midpoint of the muscle belly in line with the fibres	Systematic review of relevant sEMG literature related to the triceps brachii
Comparison Between Pre-Exhaustion and Traditional Exercise Order on Muscle Activation and Performance in Trained Men	Soares et al., (2016)	triceps brachii lateral head	50% of the acromion–olecranon line (2 cm lateral)	Examined sEMG of the triceps brachii and pectoralis major in bench press and tricep pushdown exercises
Standards for surface electromyography: the European project "Surface EMG for non-invasive assessment of muscles (SENIAM)"	Hermens et al., (2000); Stegeman & Hermens, (2007)	Triceps brachii lateral head	50 % on the line between the posterior crista of the acromion and the olecranon at 2 finger widths lateral to the line.	Review of the SENIAM books and guidelines

Shoulder-Abduction Angle and Trapezius Muscle Activity During Scapular-Retraction Exercise	Kara et al., (2021)	All trapezius heads	For Middle Trap: The middle of the medial side of the scapula and the third thoracic vertebra	Measuring trapezius activation at different angles of shoulder abduction (0°, 45°, 90°, 120°)
Standards for surface electromyography: the European project "Surface EMG for non-invasive assessment of muscles (SENIAM)"	Hermens et al., (2000); Stegeman & Hermens, (2007)	Trapezius transversalis (middle)	50% between the medial border of the scapula and the spine, at the level of T3	Review of the SENIAM books and guidelines
Surface Electromyographic Activity of the Rectus Abdominis and External Oblique during Isometric and Dynamic Exercises	Mandroukas et al., (2022)	Upper and Lower rectus abdominis and external obliques	For lower rectus abdominis: 6cm above the umbilicus and 2cm lateral. For external obliques: placed diagonally in line with fibres	Measuring muscle activity of rectus abdominis and external obliques during 11 different isometric and dynamic exercises.

2.2.6 Relationship between EMG and $\dot{V}O_2$

The relationship between $\dot{V}O_2$ and EMG activity offers valuable insights into the integration of metabolic and neuromuscular response during physical exercise. During incremental exercise both $\dot{V}O_2$ and EMG amplitude have previously been assumed to increase simultaneously (Bearden & Moffatt, 2001), indicating that greater metabolic demands are met with increased neuromuscular output (particularly during submaximal workloads where increased force production), as the recruitment of additional motor units and/ or firing rates in turn elevates $\dot{V}O_2$ as more energy is required to sustain muscular activity. Understanding the link between electrical activity and metabolic demand is critical for evaluating performance, optimising movement strategies, and testing specificity. However, at higher intensities (approaching VT1) the relationship between $\dot{V}O_2$ and EMG becomes less proportionate, and EMG increases more rapidly than $\dot{V}O_2$ (Hug et al., 2003). This divergence can be attributed to the recruitment of type II muscle fibres which are less metabolically efficient than type I fibres and rely more heavily on anaerobic energy systems (Feher 2017).

A study conducted by Hug et al. (2004) previously examined the relationship between sEMG and oxygen uptake ($\dot{V}O_2$) during cycling in trained and untrained subjects. They found that sEMG RMS (Root mean square) showed a non-linear increase in $\dot{V}O_2$ with untrained participants, and a linear increase in RMS in trained cyclists during incremental exercise (the incremental exercise consisted of a standard step test starting at 0 W and increasing 20 W/min). The authors of this study concluded that sEMG can be a useful indicator of oxygen uptake changes during cycling in well-trained cyclists, as neuromuscular factors can affect the sEMG – $\dot{V}O_2$ relationship in untrained individuals. They stated that the non-linear increase in RMS in untrained participants was likely due to differences in neuromuscular transmission of the two populations as indicated by M-wave changes. Arnaud et al. (1997); Jammes et al. (1997) & Jammes et al. (1998) all previously reported that M-wave alterations

were positively correlated with anaerobic metabolism. Adeel et al. (2022) conducted a similar study analysing the relationship between sEMG and $\dot{V}O_2$ during moderate level strength training exercises. The authors also found that sEMG RMS was a useful predictor of $\dot{V}O_2$ in participants. However, despite the theoretical rationale, the relationship between muscle activity and $\dot{V}O_2$ is not consistently supported across the literature. Although EMG provides a measure of electrical activity in the muscle, it does not directly quantify the mechanical force produced or the metabolic cost of the muscle contraction (Hug & Dorel, 2009). As signal amplitude can be influenced by numerous factors such as electrode placement, site preparation and cross talk from adjacent muscles (Hug & Dorel, 2009), it is imperative that sEMG electrode placement and site preparation are appropriate to minimise risk of equipment-based errors.

Simultaneous analysis of $\dot{V}O_2$ and EMG offers a more comprehensive understanding of physiological demand. For example, comparing these variables concurrently using stationary cycling and rollers could reveal differences in EMG, as the requirement for balance may cause an increase in upper body stabiliser muscle activation. Specifically, greater EMG activity may be observed in the external obliques and rectus abdominis, which contribute to trunk stability and lateral balance as well as the triceps brachii (lateral head) and trapezius musculature which are contributors to maintaining posture and stabilising the shoulder girdle.

Multiple studies have outlined the need for future EMG research focusing on the upper body stabiliser muscles (Tseh et al., 2017; Miller et al., 2013). This gap is particularly significant given that stabiliser recruitment may elevate metabolic cost without being reflected in conventional lower-limb EMG recordings, thereby contributing to discrepancies in $\dot{V}O_2$ across cycling modalities. Addressing this gap would clarify whether 1) there is an increase in upper body stabiliser muscles, 2) if there is an increase, does this contribute to a higher metabolic cost.

Study I

Validity of the Garmin RallyRK100 Power Pedals.

Chapter 3 – Introduction

Accurate and reliable power measurement is essential for high-quality cycling research and performance training (Bouillod et al., 2022). Power, defined as the rate at which work is performed (expressed in watts, W). Power expresses the amount of work done (measured in joules, J) per second (s) and serves as a direct and objective indicator of mechanical output on the bike. Unlike physiological metrics such as heart rate (HR) and oxygen uptake ($\dot{V}O_2$), which are susceptible to external factors like hydration status, fatigue, and ambient temperature; power provides a consistent and immediate measure of performance.

Various power measurement technologies exist, each with unique advantages and limitations. Power meters can be integrated at various points along the drivetrain, such as the crankset, hub, or pedals (Bouillod et al., 2022). Crank-based systems (e.g., SRM, Rotor) have traditionally been regarded as the gold standard in laboratory settings due to their accuracy and stable sampling rates (Passfield et al., 2017). However, pedal-based systems such as the Garmin Rally series (Garmin Rally RK100, Olathe, Kansas, USA) have gained popularity due to their portability, ease of installation, and compatibility across multiple bicycles. In contrast, crank-based systems require more complex installation and calibration, limiting their flexibility in field-based settings.

Despite differences in design and hardware location, most power meters operate on a common principle: the calculation of power as the product of torque and angular velocity. Typically, strain gauges detect minute torsional deformations in the spindle or crank arm. These micro deformations cause changes in electrical resistance, allowing accurate measurement of applied force. Torque (measured in Newton-metres, Nm) is then multiplied by angular velocity (in radians per second, rad/s) to determine power output, using the equation: (Power (W)=Torque (Nm)×Angular Velocity (rad/s)).

Cadence, used to calculate angular velocity (ω), is typically measured using internal accelerometers or gyroscopes calculated as $\omega = (2\pi \times \text{Cadence (RPM)})/60$. By combining torque with angular velocity power meters provide real-time estimates of mechanical power output.

While numerous studies have validated crank-based power meters under controlled laboratory conditions (Bini et al., 2014; Maier et al., 2017; Granier et al., 2020), there is limited research evaluating the validity and reliability of pedal-based systems. This gap is particularly relevant given the increasing prevalence of portable power meters in both recreational and elite training environments. The ability to use the same power measurement system across contexts enhances consistency in data collection and training prescription.

The Garmin Rally power pedals, launched in 2021, were designed to provide a practical, portable solution for measuring cycling power in applied training environments. Their ease of installation and ability to be quickly transferred between bikes make them especially appealing to athletes and coaches seeking consistent performance data across training contexts. However, before such devices can be confidently used in elite sport or research settings, their validity and reliability must be established against gold-standard laboratory equipment.

The Cyclus2 ergometer is a well-established tool in laboratory settings, offering highly accurate and repeatable power output measurements under tightly controlled conditions. The Cyclus2 has been used in numerous validation studies (Reiser et al., 2000; Rodger et al., 2016; Granier et al., 2020). As such, it provides a rigorous benchmark for evaluating the Garmin Rally pedals' suitability for use in real-world performance monitoring and athlete testing.

Given the increasing use of portable power meters in both recreational and elite cycling, and the limited peer-reviewed validation of novel pedal-based systems, there is a need to assess whether these devices provide accurate and reliable data when compared to laboratory-grade standards. Understanding how closely field-based systems like the Garmin Rally pedals align with established ergometers such as the Cyclus2 can help bridge the gap between lab-based testing and real-world performance monitoring. This study was therefore designed to evaluate the agreement between the Garmin Rally RK100 and the Cyclus 2 across a range of cycling intensities.

Aims and Hypotheses

The primary aim of this study was to assess the validity of the Garmin Rally power pedals by comparing their power output measurements with those obtained from the Cyclus2 ergometer. This comparison was used to evaluate whether the Garmin pedals could serve as an accurate alternative for field-based power monitoring and assess the accuracy of the roller system used in the second study of this thesis. It was hypothesised that the Garmin power pedals would demonstrate strong agreement with the Cyclus2 across a range of power outputs.

3.1 Methods

Ethics statement

The present study was carried out simultaneously with Study II and received ethical approval from the School of Sport and Exercise Sciences Research Ethics Advisory Group (Prop_65_2024) All participants were provided a participant information sheet outlining all planned procedures and provided their informed consent via a written consent form prior to their voluntary participation. All testing procedures were performed in accordance with the declaration of Helsinki.

Participants

Five recreationally trained males participated in this study. All participants provided written informed consent prior to participation. No formal power calculation was performed before as the study was a pilot. Eligibility was confirmed via a pre-screening health questionnaire, which excluded individuals with known cardiovascular, hepatic, renal, or neurological conditions (e.g., heart disease, liver or kidney disease, epilepsy, or any other chronic illness that could impact test safety or validity). Prior to each visit all participants were asked to refrain from any alcohol consumption for 48 hours and caffeine for 6 hours.

Table 2. Participant characteristics (Mean ± SD and Range)

	Mean ± SD	Range
Age (years)	23.6 ± 3.6	21 – 29
Height (cm)	177.7 ± 6.3	168.5 – 184
Body mass (kg)	78.1 ± 8.3	68.8 – 89.5
$\dot{V}O_{2max}$ (ml/kg/min)	55.1 ± 14.9	37.5 – 74.8
Power at $\dot{V}O_{2max}$ (W)	332.8 ± 102.5	262 – 501

Protocol

Participants completed two laboratory visits. The first visit involved an incremental ramp test to volitional exhaustion to determine maximal oxygen uptake ($\dot{V}O_{2max}$) and assess whether the participant could sustain a workload of at least 240 W for 30 seconds. The test was conducted on a Cyclus2 ergometer (Cyclus2, RBM elektronik-automation GmbH, Leipzig, DE) using a pre-programmed protocol. The protocol began with a 5-minute warmup at 60 W, followed immediately by the ramp phase. The ramp test began at 60 W and increased at a rate of 1 W every 2 seconds (i.e., 30 W·min⁻1) until exhaustion. The test was terminated once volitional exhaustion was reached, or cadence dropped below 60 RPM. Prior to this visit, each participant was fitted for optimal saddle height and position on the ergometer. The second visit comprised the main experimental trial. Participants cycled on a Cyclus2 ergometer (Cyclus2, RBM elektronik-automation GmbH, Leipzig, Germany) at a fixed cadence of 80 revolutions per minute (rpm). The protocol consisted of 14 × 30 – second bouts at progressively increasing intensities, beginning at 100 W and increasing in uniform 30 second increments up to 240 W. Participants used their own cycling shoes with Look Keo compatible cleats (9° float). Mean 10 second power was recorded from the Garmin pedals every 30 seconds before proceeding to the next PO.

Statistical analysis

All statistical analyses were conducted using IBM SPSS (Version 29.0.1.0, IBM SPSS software, IBM Corp., Armonk, NY) with statistical significance set to $P < 0.05$.

Agreement between the Garmin power pedals and the Cyclus2 ergometer was assessed using a Bland-Altman analysis (Bland & Altman, 1986), which included calculation of the mean bias and 95% limits of agreement. Prior to the Bland-Altman analysis, the normality of the differences was assessed using the Shapiro-Wilk test.

3.2 Results

A Bland-Altman analysis was performed to assess agreement between the Garmin power pedals and the Cyclus2 ergometer across a range of mean power outputs. Analysis revealed a mean bias of -11.76 W, indicating that the Garmin power pedals systematically underestimated power output compared to the Cyclus2. The 95% limits of agreement ranged from -14.14 W to -9.38 W, suggesting that in 95% of cases, the difference in power readings between the two devices fell within this range.

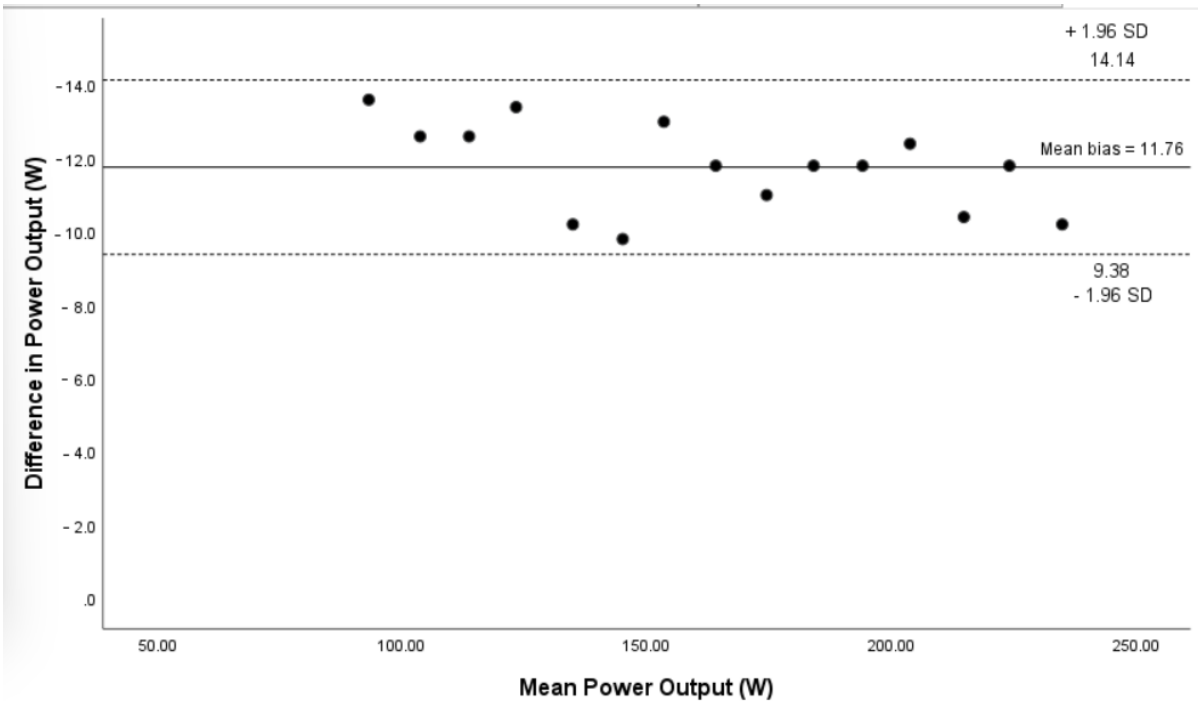

Figure 1. Bland-Altman plot showing the agreement between the difference in Power Output measurements from the Garmin power pedals and the Cyclus. Mean bias = 11.76 W (solid line). 95% limits of agreement (dotted lines).

3.3 Discussion

This study evaluated the agreement between a commercially available pedal-based power meter (Garmin RK100) and a laboratory-calibrated cycle ergometer (Cyclus 2) to assess the accuracy of pedal-based power measurement in controlled conditions. Bland-Altman analysis demonstrated a consistent systematic bias, with the Garmin pedals underestimating power output by an average of 11.76 W compared to the Cyclus 2. The 95% limits of agreement ranged from 9.38 W to 14.14 W, indicating that the underestimation was relatively stable across the range of measured power outputs. The normal distribution of differences, confirmed by Shapiro-Wilk testing, supports the reliability of this bias estimate. These results suggest that while the Garmin pedals produce consistent data, they systematically underestimate power relative to laboratory standards and therefore should not be considered interchangeable for applications requiring high measurement precision.

The observed underestimation in power output by the Garmin power pedals may be explained by several factors. A primary explanation lies in the location of power measurement. Pedal-based systems like the Garmin RK100 assess force at the pedal spindle, whereas the Cyclus 2 measures power downstream at the flywheel, including drivetrain losses (Bouillod et al., 2017; Bini & Hume, 2014). Consequently, pedal-based systems may report lower values, as they exclude mechanical inefficiencies between the pedals and the ergometer's output shaft.

In this study, a single-sided Garmin power pedal system was used (RK100) and not the double-sided version (RK200). The single sided version estimates total power by doubling the measurement from the left leg. This method assumes a perfectly symmetrical pedalling cycle, which may not reflect actual rider biomechanics. Even small degrees of leg asymmetry could introduce further error and may partially explain the consistent underestimation observed (Duc et al., 2007; Bini & Hume, 2014).

Additionally, individual differences in pedalling technique, torque application and cadence may influence power measurement accuracy in pedal-based systems. Strain gauges are sensitive to variations in angular velocity, pedal force orientation and the phase of torque application across the pedal stroke (Bouillod et al., 2022). Changes in cadence or inconsistencies in pedal force direction may affect how accurately the pedals sensors can capture real-time torque. As cadence was fixed for this study, such biomechanical variability was likely minimised. This is supported by the consistency of the mean bias and the narrow limits of agreement, suggesting that these factors would have only had minimal impact under the protocol used.

These findings are consistent with similar previously conducted validation studies of pedal-based systems. Bouillod et al. (2017) reported underestimations of 1-4% (with higher differences at higher power outputs) when compared to the SRM gold standard. Attributing these to the sensitivity of the strain gauges in each system and the individual systems processing (amplification, filtering, analogue-to-digital conversion).

Limitations

Several methodological limitations should be considered when interpreting these results. Firstly, this study only tested power outputs up to 240 W meaning that the bias may not represent the higher power outputs typically observed in training and competition, especially as previous research has found values to become more extreme at higher power outputs (Bouillod et la., 2017). Similarly, testing was only conducted at a fixed cadence of 80 rpm, meaning that other contexts, such as high torque-low power (steep climbs) or high torque-high cadence (sprinting) might not be as accurately represented. Additionally, the sample size was smaller than that required to achieve the desired statistical power, and the findings should therefore be interpreted as pilot data intended to inform future, adequately powered studies.

Conclusion

The Garmin Rally RK100 pedals consistently underestimated power output relative to the Cyclus2 by 11.76 W. This bias likely reflects both mechanical factors (drivetrain inefficiencies) and the limitations of single sided estimations. While not interchangeable with laboratory-grade systems, the RK100s may still offer utility in field-based performance monitoring, training prescription (providing users solely use the RK100 pedals for this).

Study II

A comparative study of muscle activation and oxygen uptake between stationary cycle ergometry and rollers.

Chapter 4 – Introduction

Cycling is a widely utilised form of exercise and a foundational component of both recreational and elite sports training. It is well recognised for improving cardiovascular fitness, muscular endurance, and overall physical health (Faria et al., 2005; Bassett et al., 2008). In controlled environments, indoor cycling modalities (particularly stationary ergometers and rollers) are commonly employed for training, research, and rehabilitation purposes (Kotler et al., 2016).

Stationary cycle ergometers offer a stable platform that facilitates the accurate and reproducible measurement of physiological variables such as oxygen uptake ($\dot{V}O_2$), heart rate, and power output. Their fixed nature eliminates the need for balance and coordination, allowing researchers and practitioners to isolate and monitor specific physiological responses (Miller et al., 2013). However, this mechanical stability may also limit ecological validity and contribute to reduced engagement or boredom due to the lack of sensory input or environmental variability.

In contrast, cycling on rollers requires the rider to maintain continuous balance and coordination, more closely simulating the dynamic demands of outdoor cycling (Cain et al., 2016; Tseh et al., 2017). As a result, rollers are often used by competitive cyclists for race warm-ups and offseason training. Despite their benefits, rollers introduce a steeper learning curve and potential safety concerns due to the need for active postural control and steering. Miller et al. (2013) found that roller cycling increased $\dot{V}O_2$ by 1.2 $mL \cdot kg^{-1} \cdot min^{-1}$ (2.5%) compared to stationary ergometry, (Monark ergometer) and a turbo trainer (CycleOps™ Supermagneto trainer), which was attributed to the greater activation of stabilising muscles. However, electromyographic (EMG) data were not collected in that study, leaving the

specific muscular contributions unverified. Also, the increase in $\dot{V}O_2$ could also be explained by the day-to-day variability naturally occurring in human participants.

While some studies have examined metabolic or kinematic differences between indoor cycling modalities, few have investigated the neuromuscular demands of rollers compared to stationary ergometers, particularly in terms of upper body and core muscle activation. The major muscle groups required to maintain optimal posture being those in the back (i.e. trapezius and erectors spinae) and those in the abdominal region (i.e. rectus abdominis and external obliques) (de Vey Mestdagh, 1998). This gap is important, as the dynamic nature of rollers introduce a greater requirement for balance and postural and stability, which is likely to increase the activation of the upper body and trunk stabiliser musculature. This compensatory muscle activation may in turn increase $\dot{V}O_2$ and ventilatory responses during otherwise equivalent workloads.

Comparing these two indoor cycling modalities is important for several reasons. Firstly, understanding the physiological and neuromuscular differences between them could inform researchers when choosing an appropriate testing setup, particularly when aiming for high ecological validity and specificity. Secondly, these insights can guide coaches and athletes in selecting the most effective training tools depending on their performance goals, for example, whether the goal is to isolate specific physiological metrics or to simulate real-world cycling demands. Finally, accurately comparing these two modalities helps ensure that training interventions, clinical assessments, and research findings based on one type of cycling setup are interpreted correctly and not mistakenly applied to the other, where physiological and neuromuscular demands may differ.

The present study aimed to address the gap in the literature by conducting a comparative analysis of muscle activation and oxygen uptake during roller and stationary ergometer

cycling. By examining both modalities at equal workloads, the study seeks to contribute to a more nuanced understanding of their respective physiological demands and practical applications.

Experimental aims and hypotheses

The aims of the study were:

(1) to identify whether there was a significant difference in the activation of the triceps brachii, trapezius, rectus abdominis, and external obliques muscles while cycling on rollers compared to a cycle ergometer, at the same fixed power output.

(2) to assess whether any differences in activation of these stabilising muscles are associated with a higher $\dot{V}O_2$, RER and VE.

(3) to reveal quantitative differences of lateral movement between rollers and the cycle ergometer.

(4) to investigate the relationship between lateral movement and VO_2.

It was hypothesised that, due to the increased potential for lateral movement on the rollers, there would be an increase in the activation of the external obliques, rectus abdominis, triceps brachii, and trapezius muscles (H1); an increase in $\dot{V}O_2$, RER and VE (H2); greater lateral movement of the centre point of the handlebars when riding on rollers (H3).

4.1 Methods

Ethics statement

This study received ethical approval from the School of Sport and Exercise Sciences Research Ethics Advisory Group (Prop_65_2024). All participants were provided a participant information sheet outlining all planned procedures and provided their informed consent via a written consent form prior to their voluntary participation. All experimental procedures were conducted in accordance with the declaration of Helsinki.

Participants

Eleven moderately active male participants with varying cycling abilities were recruited (anthropometric data in Table 1; some of whom also participated in study I). Nine participants completed all testing. No formal power calculation was performed prior to testing as the study was exploratory. Prior to testing all participants were given a participant information sheet outlining the requirements and prerequisites for each visit (*see appendix 1*). Inclusion criteria required participants to be competent riding a bike outdoors, a minimum of 3 hours of exercise per week and no history of illness or disease, as assessed by a pre-screening health questionnaire (e.g., cardiovascular, hepatic, renal, neurological, or chronic conditions that could affect participation). Participants were instructed to avoid alcohol, caffeine, and vigorous exercise for 24 hours prior to each visit, and to refrain from using analgesics (e.g., paracetamol, ibuprofen, aspirin) for 48 hours beforehand.

Table 3. Characteristics of the participants that completed all testing (Mean ± SD and Range)

Anthropometric Data		
	Mean ± SD	Range
Age (years)	29.1 ± 9.3	21 – 47
Height (cm)	180.7 ± 6.9	168.5 – 193.3
Body mass (kg)	79.5 ± 7.9	68.8 – 90.1
VO_{2max} (ml/kg/min)	51.2 ± 30.1	37.5 – 74.8
W at VO_{2max}	324.1 ± 75.5	262 – 501

Study Design

The present study required a total of 6 – 8 visits which were separated into two separate phases (A and B). Phase A was a 'learning' phase, where participants developed competency riding on rollers (see *"Phase A – Learning phase"*). Phase B was the 'experimental' phase which consisted of three visits, the first visit being a 'baseline' visit (see *"Phase B Visit 1"*) and visits 2 and 3 were similar visits that were conducted on different ergometers (see *"Phase B Visits 2 & 3"*) and adopted a randomised and counterbalanced design.

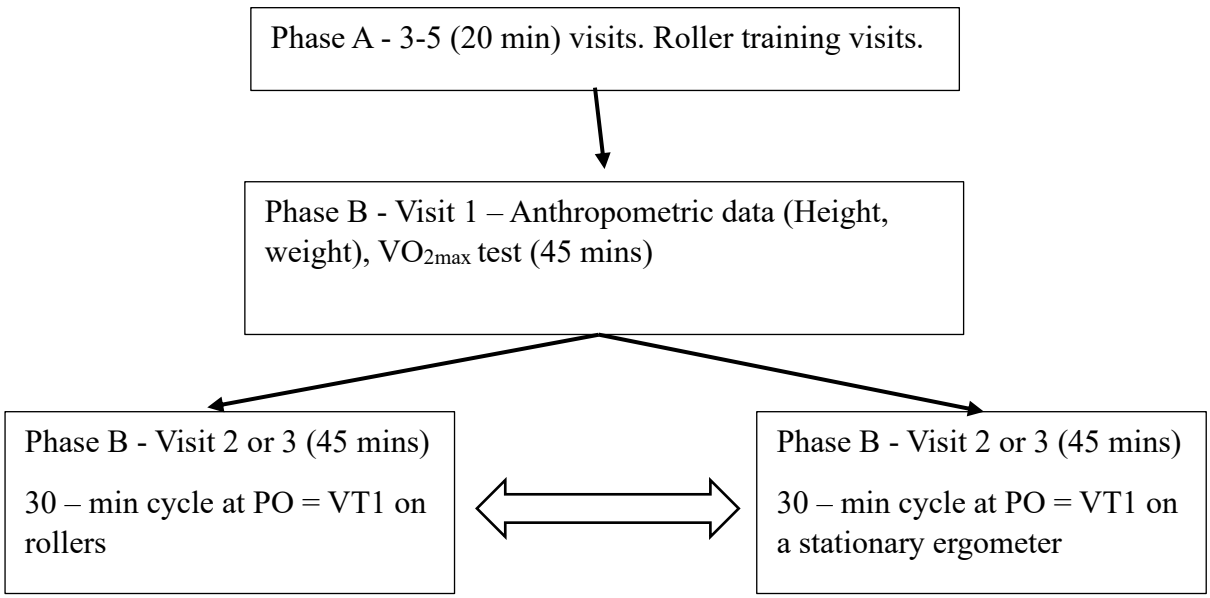

Figure 2. A schematic showing study design.

Phase A – Learning phase

The primary objective of this phase was to develop participant competency in roller cycling. Each participant attended between 2 and 5 familiarisation sessions, depending on individual aptitude. Sessions lasted approximately 30 minutes and participants were not permitted to proceed to Phase B until they demonstrated competency on rollers (Nero, Elite, Fontaniva, IT; *see "Figure 2"*). Competency was defined as the ability to ride continuously without contacting the surrounding safety cage for two separate 10-minute intervals. These bouts had to be completed across at least two different visits. Participants were allowed unlimited attempts per session. Failure to meet the competency criteria by the fifth visit resulted in exclusion from further testing.

Phase B – Experimental phase

Visit 1

During Visit 1, participants completed a ramp-incremental exercise test to volitional exhaustion to determine maximal oxygen uptake (V̇O2max), peak power output (PPO) and Ventilatory Threshold 1 (VT1) (see *cardiorespiratory measurements*). The test was conducted on a Cyclus2 ergometer (Cyclus2, RBM elektronik-automation GmbH, Leipzig, DE) using a pre-programmed protocol. The protocol began with a 5-minute warmup at 60 W, followed immediately by the ramp phase. The ramp test began at 60 W and increased at a rate of 1 W every 2 seconds (i.e., 30 $W \cdot min^{-1}$) until exhaustion. The test was terminated once volitional exhaustion was reached, or cadence dropped below 60 RPM. Respiratory gases were measured breath-by-breath using a calibrated metabolic cart (Metalyzer 3B, CORTEX Biophysik GmbH, Leipzig, Germany), Prior to each test, the Metalyzer 3B was calibrated using ambient air flow and known concentrations of O_2 (17%) and CO_2 (5%). A 3 L

calibration syringe (Series 5530, Hans Rudolph Inc, Shawnee, KS, USA) was used for volume and flow calibration of the bidirectional turbine to ensure accuracy.

Visits 2 & 3

Visits 2 and 3 both involved the use of the same SSES-owned laboratory racing bike, with one visit utilising a Cyclus setup and the other a roller setup. As this study employed a randomised and counterbalanced design 4 of the participants begun with the Cyclus setup and the other 5 started with rollers. Prior to commencing experimental procedures, surface electromyography (sEMG) electrodes were affixed to the participant (*see sEMG protocol)*. During each visit, participants completed a warm-up for a 10-minute duration at an effort corresponding to a Rating of Perceived Exertion (RPE) of 11(Borg, 6 – 20 scale) using the designated setup for that session (Cyclus or roller). This initial warm-up phase also served to acclimate participants to cycling while wearing the sEMG equipment.

Following the warm-up, participants performed a 30-minute cycling test at a fixed exercise intensity within the heavy intensity domain (a power output equivalent to VT1: group mean = 144.6 ± 30.3 W). Heavy intensity power outputs typically ranged from 39% to 48% of power at V̇O2max (dependant on the training status of the athlete) which had been determined during Visit 1. During this test, four key measurements were collected: (1) muscle activation via sEMG data, (2) breath-by-breath gas exchange analysis, recorded every 5 minutes and (3) lateral handlebar movement, captured using 3D motion capture.

Following the conclusion of the test, participants completed a 5-minute cooldown, cycling at a self-selected pace.

Figure 3. Shows the roller setup.

Physiological measurements

Online gas analysis was performed using the Metalyzer 3B Cortex, online breath-by-breath analyser (Metalyzer 3B, CORTEX Biophysik GmbH, Leipzig, Germany) to measure oxygen uptake ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), pulmonary ventilation (V_E), respiratory exchange ratio (RER), and breathing frequency (bf). The Metalyzer was calibrated prior to testing using ambient air flow and known concentrations of O2 (17%) and CO2 (5%). A 3 L syringe was used for volume and flow calibration of the bidirectional turbine to ensure accuracy.

To calculate VT1 a maximal incremental test was used, the data from this test (V_EVO_2, V_EVCO_2 and $PETO_2$) were then used to calculate VT1 (Lucia et al., 1999; Pallares et al., 2016; Cerezuela-Espejo et al., 2018)

Biomechanical measurements

sEMG protocol

Bipolar surface EMG was conducted using a wired surface EMG setup (Bioelettronica quattrocento, Torino, Italy) and in accordance with the SENIAM guidelines. Using a bipolar set up (two electrodes per muscle/ sensor) the electrodes (Ambu, 35mm, white sensor electrodes, Ballerup, Denmark) were placed with an inter electrode distance of 20 mm. The skin preparation for EMG involved ensuring sufficient electrode-skin contact, which was critical for obtaining higher-quality EMG recordings with minimal electrical interference and noise. The preparation process included shaving the desired area, cleaning the area with alcohol, and using an abrasive gel to remove dead skin and other contaminants to minimise impedance.

The muscles assessed included the triceps brachii (lateral head), trapezius transversalis, lower rectus abdominis, and external obliques. For the triceps brachii (lateral head), electrodes were placed midway along the line connecting the posterior crista of the acromion process and the olecranon process, positioned two finger widths lateral to this line. For the trapezius transversalis, electrodes were placed at 50% of the distance between the medial border of the scapula and the spine, at the level of T3, and oriented in the direction of the line connecting T5 and the acromion process. For the lower rectus abdominis, electrodes were positioned 3 cm lateral to the midline, near the midpoint between the umbilicus and the pubic symphysis. For the external obliques, electrodes were placed approximately two finger widths above the anterior iliac crest and aligned with the muscle fibres. Two reference electrodes were used; one placed on the lateral epicondyle and the other placed on the acromion.

For each target muscle, sEMG was captured at 2048 Hz over six 1-minute recording epochs (4-5 mins, 9-10 mins, 14-15 mins, 19-20 mins, 24-25 mins and 29-30 mins). Following

acquisition, all sEMG was band-pass filtered (10 - 200Hz) using a MATLAB script (*see appendix 4&5*). Once filtered and rectified, each individual's 6 epochs were combined to calculate a mean across the 30 minutes for each muscle. To account for inter-individual variability and allow for comparison across participants and conditions, EMG amplitudes were normalized to the higher mean value observed between the Cyclus 2 and roller trials. This value was defined as the peak dynamic contraction, and all EMG data were expressed as a percentage of this reference.

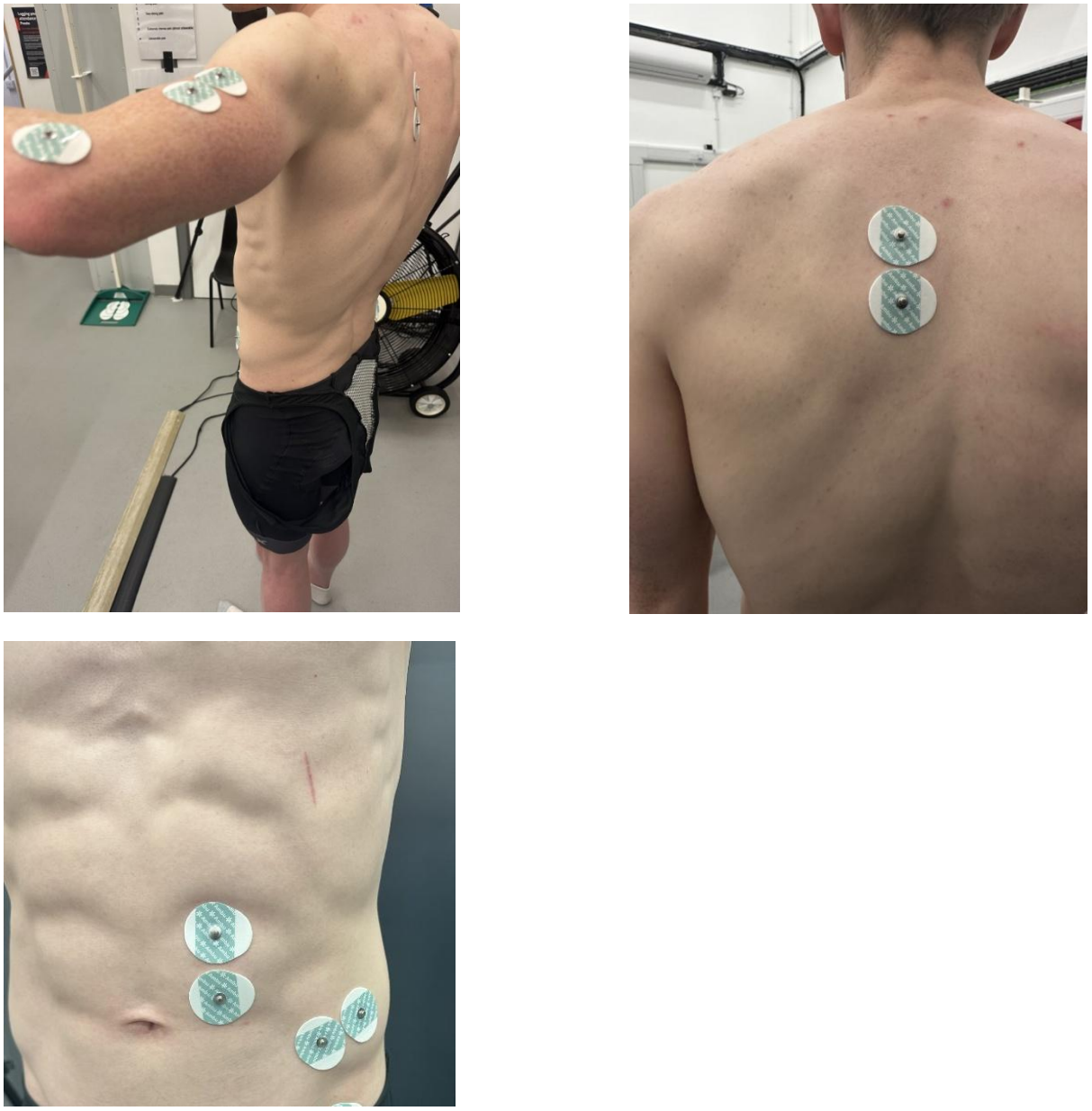

Figure 4. Shows electrode placement for each muscle site

3D motion capture

Three-dimensional lateral movement analysis was performed using a 3 Oqus camera system (Oqus 3, Qualisys, Gothenburg, Sweden) capturing at 100 Hz.

The calibration procedure of the Oqus 3 cameras used a T wand and a stationary L frame, the stationary L frame was placed adjacent to the area of interest. All 3D motion capture data were prepared for statistical analysis using MATLAB (*see appendix 6*).

Statistical analysis

Statistical analysis for this study was performed using IBM SPSS (IBM SPSS software, Armonk, NY). All data are presented as mean ± SD. All data were checked for normality with the Shapiro-Wilk test and sphericity with the Mauchly test. If normality was violated for a given variable, the entire dataset for that variable was natural log (ln) transformed prior to analysis (i.e. Trapezius and Obliques EMG data). If the sphericity assumption was violated, then a Greenhouse-Geisser correction was applied. The effect of condition (Rollers vs. Cyclus2) and time (6 time points) on all gas and EMG data were analysed using a two-way repeated measure ANOVA). Effect sizes for ANOVA outcomes were reported as partial eta squared (ηp^2). Effect size thresholds were interpreted as small ($\eta p^2 \geq 0.01$), medium ($\eta p^2 \geq 0.06$), and large ($\eta p^2 \geq 0.14$). The significance level was set at $P < 0.05$ in all cases. A Pearson correlation was also conducted to assess the relationship between mean $\dot{V}O_2$ and total lateral movement on the rollers, and to investigate the relationship between percentage of power at $\dot{V}O_2$ and total lateral movement on the rollers.

4.2 – Results

Muscle activation (sEMG)

A two-way repeated measures ANOVA of surface EMG data showed no statistically significant difference in activation between conditions of the triceps brachii lateral head ($F_{(1,8)} = 2.678$, $p = 0.140$, $\eta p^2 = 0.251$), middle trapezius ($F_{(1,8)} = 0.464$, $p = 0.515$, $\eta p^2 = 0.055$), rectus abdominis ($F_{(1,8)} = 1.845$, $p = 0.211$, $\eta p^2 = 0.187$) and external obliques ($F_{(1,8)} = 1.137$, $p = 0.317$, $\eta p^2 = 0.124$).

Table 4 sEMG statistics for time and interaction (condition x time) respectively i.e. P value, F value and ηp²

Measure		*P*	F	ηp²
Tricep	Significant difference detected	.002	$_{(5,40)}$ = 4.776	.374
Middle trapezius	No significant difference detected	.515	$_{(2.513.20.108)}$ = .746	.085
Rectus abdomninis	No significant difference detected	.719	$_{(1.569,12.551)}$ = .265	.032
External obliques	No significant difference detected	.749	$_{(1.762,14.100)}$ = .259	.031
Measure		*P*	F	ηp²
Tricep	No significant difference detected	.115	$_{(2.322,18.572)}$ = 2.369	.228
Middle trapezius	No significant difference detected	.253	$_{(2.794.22.350)}$ = 1.458	.154
Rectus abdomninis	No significant difference detected	.525	$_{(2.690,21.519)}$ = .741	.085
External obliques	No significant difference detected	.222	$_{(1.807,14.455)}$ = 1.673	.173

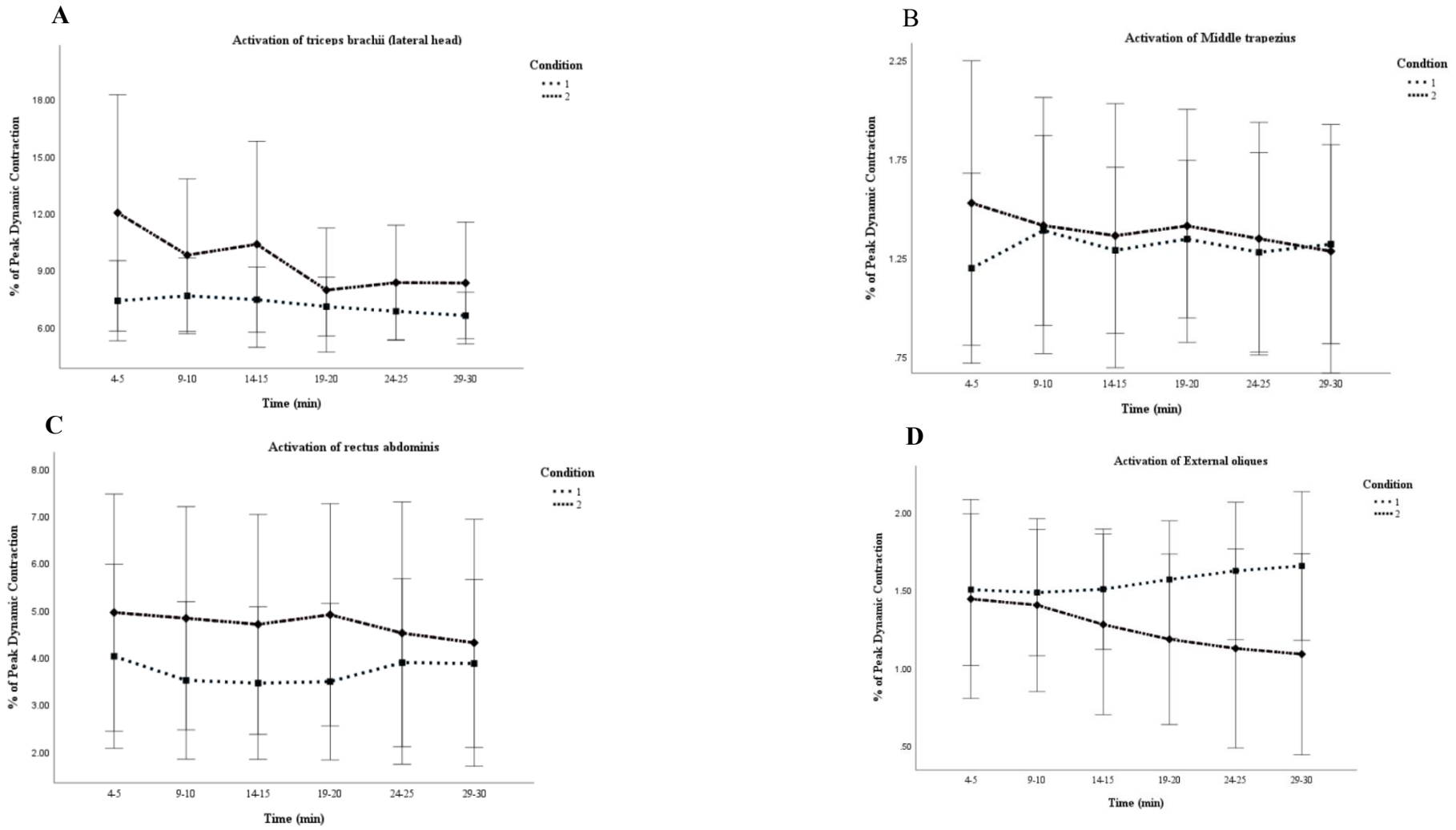

Figure 5. (A-D) Shows mean (Mean ± SD; Confidence interval: 95%) % of Peak Dynamic Contraction across 6 time points (Condition 1 = Rollers, Condition 2 = Cyclus2). A = Activation of triceps brachii lateral head, B = Activation of Middle trapezius, C = Activation of rectus abdominis, D = Activation of external obliques.

$\dot{V}O_2$ and Ventilatory Responses

Mean $\dot{V}O_2$ during the roller trial was 2.35 L/min^{-1} compared to the Cyclus2 trial, which was 2.39 L/min^{-1}, a two-way repeated measures ANOVA revealed no statistically significant differences between the two conditions (see *Table 5*). A mean RER of 0.985 was observed for both conditions following a two-way repeated measures ANOVA. Mean V_E during the roller trial was 64.21 ± 5.43 L/min^{-1}, and 63.26 ± 4.12 L/min^{-1} for the Cyclus2 trial.

Table5. Ventilatory response statistics for condition i.e. P value, F value and ηp²

Measure		*P*	F	ηp²
$\dot{V}O_2$	No significant difference detected	.660	$_{(1,8)}$ = .208	.025
RER	No significant difference detected	.990	$_{(1.8)}$ = .000	.000
V_E	No significant difference detected	.840	$_{(1,8)}$ = .043	.005

Significant main effects of time were observed for all three variables with VO_2 increasing by 8.75% (VO_2: *P*<.001, F $_{(5,40)}$ = 8.646, ηp²= 0.519) and V_E increasing by 11.73% across the 30 minutes (V_E: *P*<.001, F $_{(5,40)}$ = 7.722, ηp²= 0.491). RER decreased by 3.19% (RER: *P*<.001, F $_{(5,40)}$ = 10.068, ηp²= 0.557). No significant interaction effects were detected in VO_2 (*p* = .137, F $_{(5,40)}$ = 1.792, ηp² = .183), V_E (*p* = .719, F $_{(5,40)}$ = .574, ηp² = .067), RER (*p* = .704, F $_{(5,40)}$ = .574, ηp² = .067).

Lateral Displacement

The summation of handlebar motion was significantly higher in the roller condition (128.48 ± 36.02 m) compared to the Cyclus2 (48.92 ± 15.08 m; $F_{(1,8)} = 32.84$, $p = < 0.001$, $\eta p^2 = 0.804$). Lateral handlebar movement was higher (by 162.63%) in the roller condition. A significant main effect of time was also detected, with a mean increase of movement over 30 minutes of 20.83%. ($F_{(5,40)} = 10.47$, $p = 0.005$, $\eta p^2 = 0.567$).

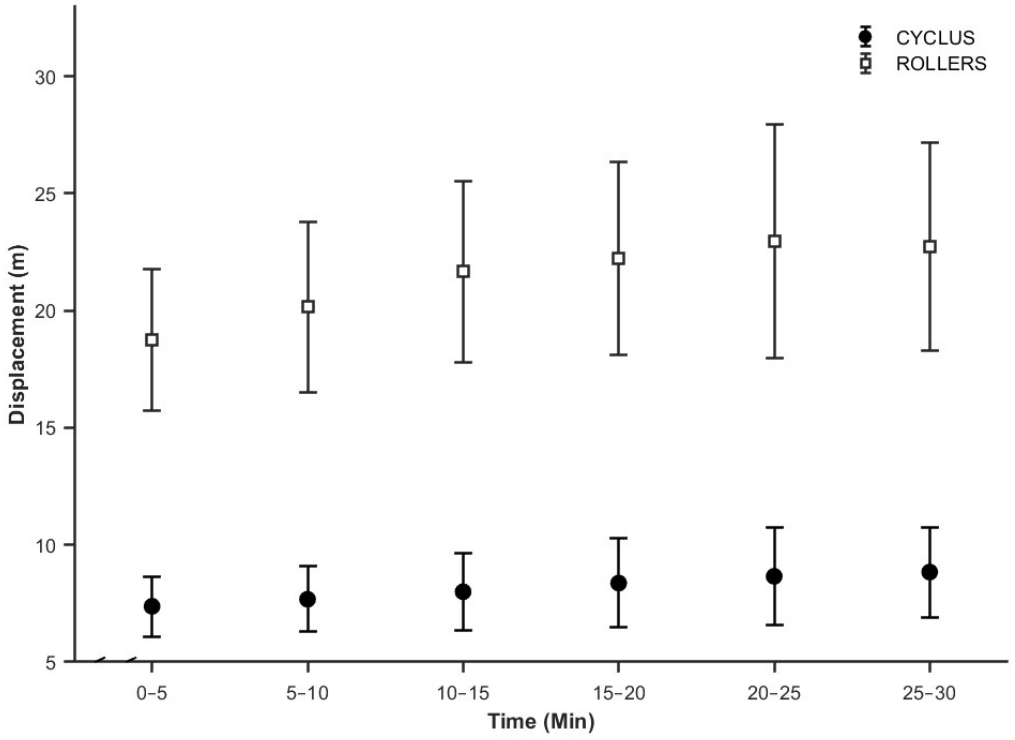

Figure 6. Shows mean displacement over 30 minutes across both conditions (Mean ± SD).

A Pearson correlation was conducted to assess the relationship between mean $\dot{V}O_2$ and total lateral movement on the rollers. As shown in Figure 7, this correlation was weak and non-significant (r = -.329, p = .387).

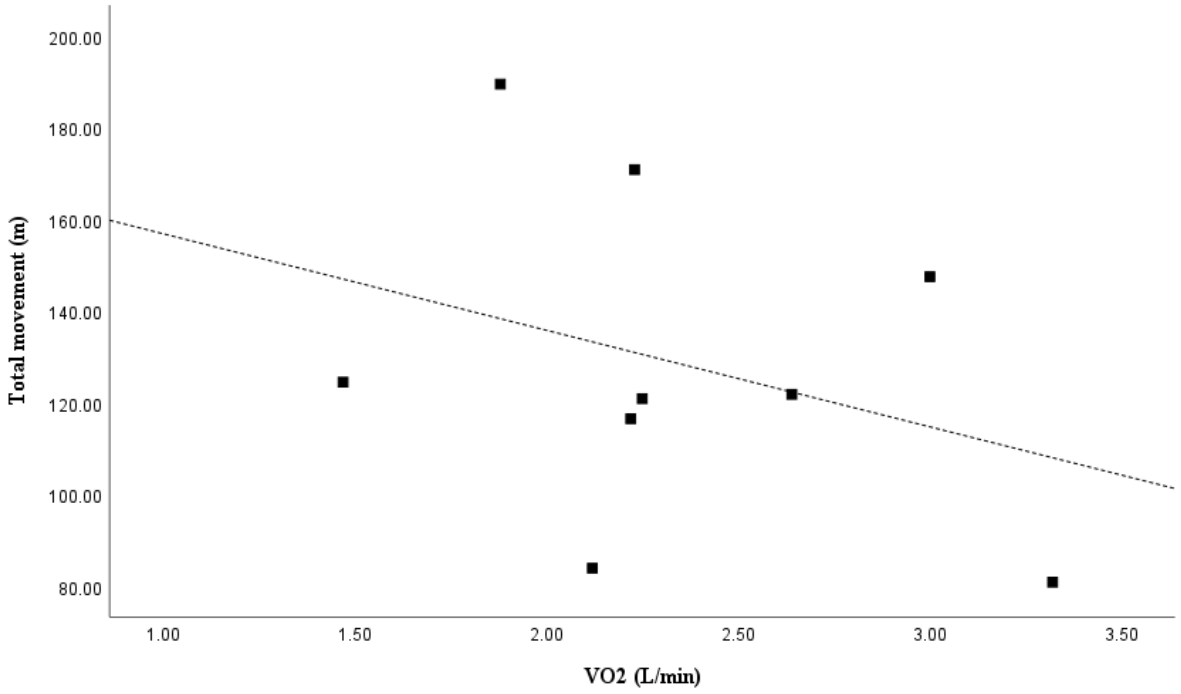

Figure 7. Scatterplot of oxygen uptake ($\dot{V}O_2$, $L \cdot min^{-1}$) versus total movement distance (m).

A Pearson correlation was also used to investigate the relationship between percentage of power at $\dot{V}O_2$ and total lateral movement on the rollers. As shown in Figure 8, this correlation was weak and non-significant (r = -.403, p = .282).

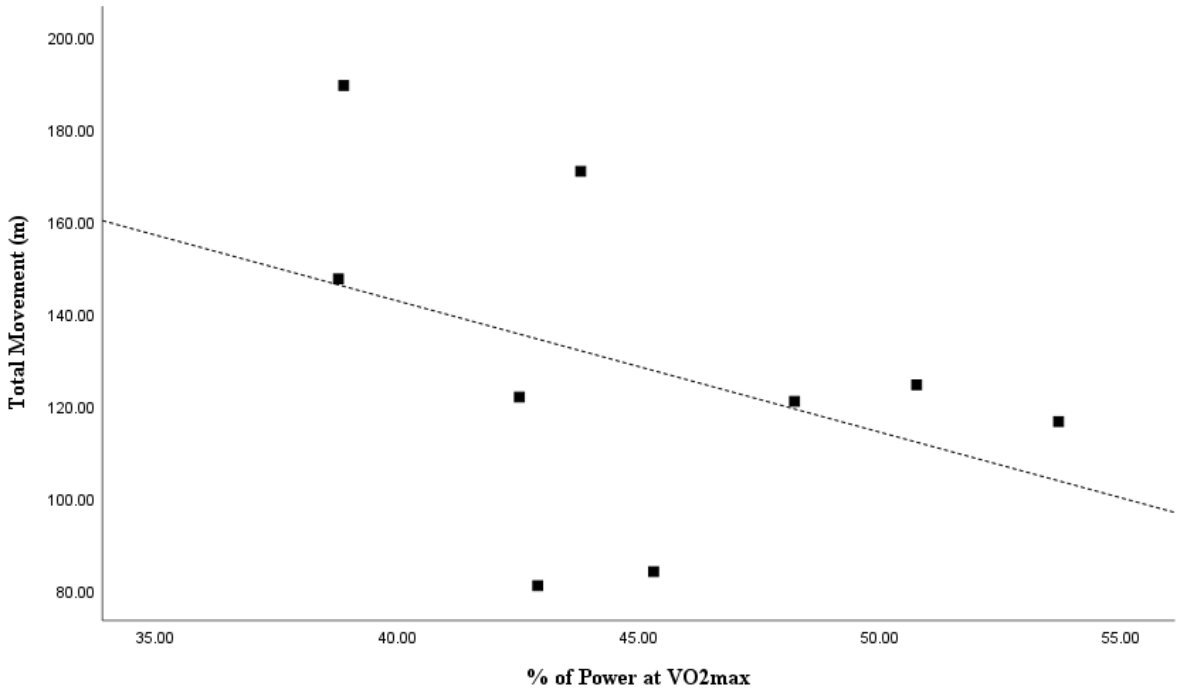

Figure 8. Scatterplot showing correlation between % Power at $\dot{V}O_2$max and Total Movement.

4.3 – Discussion

The present study compared upper body muscle activation, ventilatory responses and lateral handlebar movement between stationary ergometers and rollers. No significant differences were found in sEMG activation between the two modalities. Nor were any differences found in ventilatory data ($\dot{V}O_2$, RER and V_E). However, a difference in lateral handlebar movement was observed with the rollers having substantially more movement that the Cyclus2. These findings suggest that although rollers presented less stability, both modalities require similar metabolic costs at matched workloads. This suggests that rollers can be a viable option when choosing training modalities. Furthermore, the increased handlebar movement on rollers may provide a closer simulation to overground cycling dynamics, potentially offering additional benefits in terms of balance and bike handling skills. Moreover, the increased demand for balance may enhance cognitive engagement, potentially making this training approach more stimulating and appealing for athletes.

No significant differences were detected in upper body muscle activation between the two cycling modalities, contrary to the proposition of Miller et al. (2013). The increase in requirement for stability theoretically suggests that variations in activation of upper body stabiliser muscles should be expected. However, the results of this study were unable to identify them. This could be due to several reasons, the first being that the participants' experience/ training status varied. That is, the higher skilled participants could potentially maintain balance through highly efficient motor strategies rather than increased muscular activation. This is reflected in balance and postural control literature, where training enhances efficiency and reduces muscle activation for the same task (Hunter & Enoka, 2003). A study where participants underwent balance training found that although balance improves, muscle activation in the key core muscles decreased (Anderson et al., 2016). This suggests that training enhances coordination efficiency, meaning that cyclists will rely on improved

coordination, timing and muscle collaborations to counterbalance instability, rather than increasing muscle activation. Furthermore, although no activation increase was observed in the tested muscles, it is possible that an increase in activation may have been observed elsewhere, particularly in the lower limb stabilisers and deeper core muscles. This highlights the complexity of postural adjustments required for cycling on rollers and suggests that stability demands may be met through distribution of muscular coordination rather than isolated increases in trunk or upper-body activity.

Additionally, the workload used in this study was submaximal, meaning that under such conditions, the mechanical instability posed by the rollers may have been more manageable through fine neuromuscular adjustments alone. These adjustments likely occurred through subtle alterations in grip, trunk positioning and micro corrections in steering (Miller et al., 2013); all actions which may rely more on coordination and timing rather than an increase in muscle activation.

Metabolic responses ($\dot{V}O_2$, RER, V_E) did not differ significantly between rollers and the stationary ergometer at matched workloads. This is likely explained by the fact that external workload and cadence were tightly controlled across conditions. $\dot{V}O_2$, RER, and V_E primarily reflect metabolic demand, which is determined by the total mechanical power output and exercise intensity. Since there was also no significant difference in muscle activation, participants would have produced similar workloads in both conditions which would explain the similarities in metabolic cost. This is contrary to previous research by Miller et al. (2013) who found an increase of ~ 2.5% in $\dot{V}O_2$ on a roller setup compared to a fixed ergometer setup at matched workloads. They attributed this increase in metabolic cost to the increased activation of upper body stabiliser muscles, which the current study found not to be the case in the measured muscles. It is understandable that Miller et al. (2013) would attribute this to increased upper body stabiliser activation as theoretically in both conditions lower body

activation should stay similar (as workloads are matched). An increase in upper-body muscular activation would require additional ATP for actin and myosin cross-bridge cycling, thus cumulatively increasing $\dot{V}O_2$ (Barclay & Curtin, 2023). Furthermore, additional muscular contraction would increase cardiac output to keep up with O_2 demand (Popel, 1989).

Like the literature on $\dot{V}O_2$ slow component kinetics (Lucía et al., 2000; Billat, 2000; Jones et al., 2011), the present study found that over time $\dot{V}O_2$ increases. This slow component of $\dot{V}O_2$ kinetics is well described in the literature, particularly when exercise is performed near the first ventilatory (VT1) or lactate threshold (LT1). At these intensities, $\dot{V}O_2$ does not reach a steady state but drifts upward as additional motor units are recruited to sustain the workload. The presence of this rise indicates that the prescribed power output was appropriate, as such a response is expected during submaximal exercise close to VT1 and LT1, confirming the physiological validity of the workload selection.

Lateral handlebar displacement was significantly greater on rollers compared to the Cyclus2, reflecting the additional balance demands of outdoor cycling. On rollers, riders must make continuous micro-adjustments through the handlebars to maintain stability, whereas the fixed element of the Cyclus2 removes this requirement. This suggests that rollers may better replicate the postural control demands of outdoor cycling.

The relationship between $\dot{V}O_2$ and total handlebar movement revealed an insignificant weak negative correlation, with higher $\dot{V}O_2$ associated with reduced movement. Although not statistically significant, it is speculated that likely due to small sample size, this suggests that participants with a greater aerobic capacity could demonstrate better stability and cycling economy compared to participants who cycled at a lower $\dot{V}O_2$. A similar weak insignificant correlation emerged when investigating the percentage of $\dot{V}O_{2max}$ at which the participants

cycled at and total lateral movement. This is likely due to multiple factors. Firstly, more experienced/ cyclists with higher aerobic fitness are likely to reach ventilatory thresholds closer to $\dot{V}O_{2max}$ (Poole & Gaesser, 1985; Burke et al., 1994; Londeree, 1997). Moreover, this means that they can sustain higher fractions of their $\dot{V}O_{2max}$ for longer. This reflects an experienced cyclist's adaptations from training e.g. increased mitochondrial density, oxidative enzyme activity and intramuscular capillarisation, all of which delay lactate accumulation allowing them to cycle at higher relative intensities for longer (Hughes et al., 2018). Additionally, the cycling conditioning presented by higher level cyclists may allow them to stay in certain positions for longer periods of time, compared to lower-level cyclists who may need to change body positions during the roller trial, consequently increasing lateral movement through further reduced stability when changing positions. In contrast, the wide spread of data points highlights that individuals with similar $\dot{V}O_2$ values also exhibit different amounts of lateral movement, which suggests that metabolic cost is not strongly associated with stability on the bike. This also supports the notion that the increase in stability demand on rollers is managed through neuromuscular control rather than increased muscle activation. With larger sample size, it is possible that compared to less experienced riders, more experienced rider would have a reduced lateral movement in the roller condition (Cain et al., 2016).

Limitations

A notable limitation of the present study is that different power measurement systems were used for the roller and Cyclus2 conditions. This is particularly relevant when interpreting physiological measures such as $\dot{V}O_2$, RER and V_E, as even small differences in actual mechanical power could contribute to variation in metabolic cost independent of the condition's individual physiological requirements. Additionally, lateral handlebar movement was used as a representation for stability demands, but this metric does not capture the

multidimensional nature of postural control, including subtle compensatory adjustments in the lower body or trunk rotation. Finally, the sample size was smaller than that required to achieve the desired statistical power, and the findings should therefore be interpreted as pilot data intended to inform future, adequately powered studies. Future studies could benefit from integrating three-dimensional kinematic analysis or motion capture to provide a more comprehensive assessment of balance and coordination.

Conclusion

In summary, while metabolic demands remain similar between rollers and the Cyclus2 under equal workloads, rollers impose substantially greater stability requirements, as shown by the drastic differences in lateral handlebar movement. These differences highlight the potential value of rollers for developing balance and control on the bike in cyclists, whilst still being a viable method of metabolic training/ testing.

Chapter 5 – General Discussion

The present thesis aimed to investigate the methodological considerations in cycling research, focusing on the validity of power measurement tools and the ecological realism of different cycling ergometers. Two complementary studies were conducted: Study I assessed the agreement between Garmin Rally RK100 power pedals and the Cyclus2 ergometer, while Study II compared upper body muscle activation, oxygen uptake and stability between stationary cycle ergometry and rollers. Collectively, these studies provide insight into how methodological choices influence measurement accuracy and the interpretation of cycling performance data.

An important finding across the two studies is the similarity in ventilatory responses ($\dot{V}O_2$, RER and VE) between cycling on rollers and on the Cyclus2, despite the increase stability demands of the roller condition. A plausible explanation for this could be the systematic underestimation of power by the RK100 pedals. As these were used to prescribe power in the roller condition, with a mean bias of -11.76 W, participants may have been working at a slightly lower external load (i.e. producing slightly less mechanical power) on the Rollers than on the Cyclus 2 ergometer, even when target POs were set equally. This small yet consistent reduction in workload could have hidden any additional metabolic demand (i.e. internal load) imposed by the additional stability demand on the rollers, resulting in comparable gas exchange measurements between the two conditions. Interestingly, Miller et al. (2013) reported that the difference in $\dot{V}O_2$ observed when cycling on rollers versus a stationary ergometer corresponded to an estimated 9.3 W. This corresponds with the results of both present studies, where the pedals present a lower power output compared to the Cyclus2 (for instance, a reading of 150 W on the pedals equated to approximately 161 W on the Cyclus2). This is important to note as the results from these studies suggest that the roller condition was actually performed at 11 W higher than the Cyclus2, which highlights the

importance of considering device specific differences when interpreting physiological data. Although this study was unable to reveal any differences in metabolic cost between the two modalities it is important to critique the methodologies and see where they differ, as small differences in protocol could be responsible for the differences in metabolic cost. Firstly, the study by Miller et al. (2013) performed a similar submaximal task. However, their protocol was performed at 70% of $\dot{V}O_{2max}$ and $\dot{V}O_2$ data were only averaged for the final 2 minutes of a 4-minute trial. In contrast, the present study adopted a more extended approach, with participants cycling at VT1 for 30 minutes, with $\dot{V}O_2$ averaged over a 1-minute period every 5 minutes (in line with EMG epochs). This longer duration and repeated sampling allow for a better representation of submaximal steady state $\dot{V}O_2$. Furthermore, the choice of VT1 rather than a fixed percentage of $\dot{V}O_{2max}$ allows a more individualised prescription of workload. Moreover, the workload prescription of this study corresponded to 39 – 48%. The distinction in workload prescription is particularly relevant, as their workload could have placed participants in a different intensity domain than the intensity of the present study. At 70% of $\dot{V}O_{2max}$ oxygen uptake kinetics and sensitivity to more subtle increases in workload may behave differently to exercise at 39 – 48%. Since 70% of $\dot{V}O_{2max}$ is closer to the top-end of the heavy intensity domain and lower end of the severe intensity domain, this may elicit higher variability in $\dot{V}O_2$ potentially explaining why they found this difference (Colosio et al., 2020).

Additionally, the study by Miller et al. (2013) used a formula to predict power adjusted $\dot{V}O_2$ if the participants power output was different across conditions: $\dot{V}O_{2\,(Adjusted)} = \dot{V}O_{2\,(measured)} - [(power_{measured} - power_{trainer}) / slope_{regression}]$. However, the present study did not, which suggests that if any differences in $\dot{V}O_2$ were observed between conditions, they may better have reflected true variations in $\dot{V}O_2$, rather than being mathematically corrected for discrepancies in power output. Though, the absence of adjustment introduces a potential

methodological limitation, since the lack of observed differences could be attributed to device-related variation in power measurement rather than underlying physiology.

Future Directions

Future research should seek to replicate the present study ("A comparative study of muscle activation and oxygen uptake between stationary cycle ergometry and rollers.") while accounting for the systematic difference in power output between the Garmin Rally RK100 power pedal system and the Cyclus2 ergometer. Specifically, adjusting target workloads on the rollers to reflect the underestimation observed by the pedals, would allow for more accurate matching of workload across the two conditions. This would help to determine whether the physiological and biomechanical responses observed are a consequence of cycling modality or a reflection of unequal workloads. Additionally, conducting the study with a greater sample size (19+ participants after a power calculation) would enhance statistical power and provide a better understanding of the physiological differences between roller riding and stationary ergometer riding.

Limitations

Although this thesis provides insight into cycling physiology, biomechanics and power measurement technologies, several limitations should be noted. Firstly, the use of steady-state exercise may not accurately represent real-world cycling racing. However, to compare muscle activation, metabolic cost and lateral movement across modalities accurately this sacrifice must be made. Additionally, the sample size and participant characteristics for both studies may constrain generalisability of the findings, particularly to elite or highly trained individuals.

Conclusions

In conclusion, this thesis demonstrates that cycling on rollers and stationary ergometers elicits similar physiological responses, but with distinct biomechanical demands. Rollers impose greater movement and balance demand, without altering global metabolic cost, making them a valuable tool for cycling training. Additionally, Garmin Rally RK100 pedals were shown to underestimate power consistently. However, this consistent nature of their underestimation still allows them to be used as a training tool, if they are the sole form of power measurement. Collectively, these findings highlight the importance of considering both the measurement tools and cycling modality when evaluating performance.

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Chapter 6 – Appendices

Appendix 1 – Participant information sheet

A comparative study of muscle activation and oxygen uptake between stationary cycle ergometry and rollers.

You are being invited to take part in a research study. Prior to deciding on whether to participate or not, it is important that you read this document so that you understand what you are being asked to do. Please take some time to read the following information carefully. If you have any further questions, you require additional information, or something is not clear, please do not hesitate to contact a member of the research team using the email addresses below. Thank you for taking the time to read this.

Purpose of the research

We are aiming to compare the muscle activation, lateral movement and oxygen uptake when cycling on two different types of cycle ergometer: A fixed ergometer and Rollers. With fixed ergometers (which are similar to a 'turbo trainer') the bike is fixed onto a stable base which keeps the bike upright regardless of the skill or experience of the person riding it. With rollers, the bike is not fixed, and the person riding must keep going in a straight line and use their balance to stay upright – a bit like riding on a road. Some experiments might be better suited to using one of these ergometer types over the other, and the aim of this study is to understand some the implications of that decision.

Who can take part?

This research study will look to recruit 20 - 30 participants. We are seeking male and female participants who are healthy, aged 18-55 years and moderately active (participate in exercise at least 3 hours per week) and confident in riding a bicycle. You must also either have experience of or be willing to learn how to ride on rollers. We will assess your physical suitability for the study using a health questionnaire.

Do I have to take part?

No. As participation is voluntary, you are not obliged take part in the study and have the right to withdraw from the study at any point without reason or any disadvantage to yourself. There is also no pressure to continue to participate once testing has started. However, if you do decide to take part, you will be asked to complete and sign a health questionnaire and informed consent form to confirm your participation.

What are the advantages and benefits of taking part?

Participation in this study will provide you with the opportunity to undertake physical activity, which is beneficial for a healthy lifestyle. Furthermore, you can request feedback of your maximal oxygen uptake test (VO_{2max}, an indication of your aerobic fitness), which will give an indication of your cardiovascular fitness. You will also be contributing to further our

knowledge of the differences in muscle activation and oxygen uptake between cycling on an ergometer and on rollers.

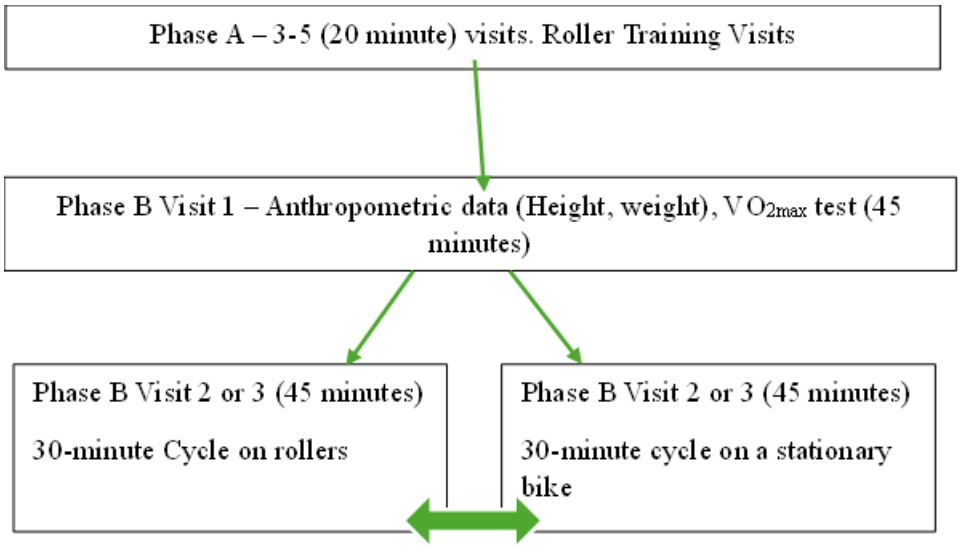
What will be required if I take part?

You will be asked to report to the Chipperfield Building foyer. University of Kent Canterbury campus CT2 7NZ on 6 – 8 occasions over the course of about 2-3 weeks. Your participation will be split into a Phase A and B. Each visit in phase A will be approximately 20 minutes and the visits in phase B will be approximately 45 minutes each.
Prior to all visits, you will be required to refrain from:

- Undertaking any vigorous exercise (24 hours before each visit)
- Consumption of alcohol (48-hours prior to each visit) and caffeine (6 hours prior to each visit)

For each visit you will be required to attend the lab in clothes that you would feel comfortable cycling in. All participants must wear shorts to minimise risk of getting caught in the chain. It is recommended that you bring a water bottle. Helmets will be supplied, however feel free to bring you own.

What will be required from each visit?



This study will be split into two phases, A and B.

At the start of the first visit, you will complete a health questionnaire and an informed consent form. At the start of each subsequent visit, you will complete a pre-test retest form, which will check whether your initial responses from the health questionnaire have changed. After completing your informed consent form, you will be given a unique participant number. This is the number that your data will be under so none of your personal data will need to be used. Phase A consists of you learning how to cycle on rollers and will consist of 3 – 5 short visits of 20 minutes to get more comfortable on the rollers (see figure 1). This phase will be complete when you and the researcher feel confident in your ability to ride on rollers. By the

end of Phase A if the researcher does not consider you competent enough to undertake an exercise test on rollers, then you will be unable to progress into phase B.

In the first visit of phase B, you will undergo anthropometric measurements: Height and body mass. After this measurement has been taken you will be asked to complete a VO_{2max} test. This test consists of you riding on a stationary bike and gradually increasing the intensity until you can no longer maintain the required pace.

Visits 2 and 3 involve cycling either on rollers or on the stationary ergometer for 30 minutes at a fixed pace (this will be challenging pace but will not be exhaustive). Whatever intervention you do on visit 2, you will do the other in visit 3.

Figure 1. An example of a roller setup

Are there any potential risks to me?

There is an element of risk associated with riding a bike on rollers as they can be unstable at lower speeds and may cause a participant to fall, just like there is a very small risk of falling off while riding a bike outdoors. You will be given full instructions and observe a demonstration of all elements of the procedure, including mounting, dismounting, and how to stop. We will be using the rollers in a controlled setting and with the addition of detailed instruction and safety equipment (helmets), you will be harnessed to a cage surrounding the rollers which will catch you should you fall off the rollers.

As with any exercise, there are also slight risks associated with heavy intensity and maximal exercise such as cardiovascular events (e.g. heart attacks, irregular heartbeats) and muscle injury. To mitigate these risks, you will have a warmup and warm down in each session, and a first aider will always be on site during testing, and you are allowed to withdraw from exercise should you feel like it at any point.

Who has approved the study?

The University of Kent, Sport and Exercise Sciences Research Ethics and Advisory Group (REAG) (65) have approved this study.

What will happen to my data after completing the study?

All results will be subsequently analysed and written up for a report. It will also be used to publish a peer-reviewed paper and be part of a master's by Research thesis. These results may also be written up in the form of a conference paper.

Will I find out the results of the study?

Yes. You are entitled to request a written summary of the results. If you wish to request results from this study, please feel free to email one of the researchers (listed below) and they will be able to forward you a summary of the results.

What about my privacy and confidentiality?

Your data will be protected throughout the study in line with data protection legislation. As part of this, you will receive a unique personal identification code which is used (instead of your name) to identify data. The consent form is the only document that will contain information that can identify you (e.g. name) and this will be stored securely within the School of Sport and Exercise Sciences' premises in accordance with the Data Protection Act 2018 and the University's own data protection procedures. In accordance with the Data Protection Act 1998, and the superseding General Data Protection Regulation, all electronic data will be kept securely in a password-protected folder on a password-protected laptop computer that belongs to the researcher, as well as on a password-protect computer stored at the School of Sport and Exercise Sciences. This data will be kept securely for up to 5 years. No identifiable data will be passed on to any third parties.

For more Information on the University's privacy policy please follow the link below. https://media.www.kent.ac.uk/se/40432/ResearchParticipantUniversityLevelPrivacyNotice.pdf

What if I wish to withdraw from the study?

Participation in this study is voluntary, and you are free to withdraw from the research study at any time without reason or consequence. If you wish, you can request for any data collected from yourself to be extracted from the data set and destroyed.

Who should I contact for more information?

If you are interested in participating in this study, would like additional information, or have any general questions about the study not answered by this information sheet, please contact the lead researcher on the email address below. If you have any concerns or wish to complain about any aspect of the way you have been approached or treated during the course of this study, you may contact the Head of School of Sport & Exercise Sciences, Professor Glen Davison by email (G.Davison@kent.ac.uk) or the chair of the SSES Research Ethics and Advisory Group, Dr Katrina Taylor (K.Taylor@kent.ac.uk).

Research team

Mr Harry Doy – hd357@kent.ac.uk

Professor Lex Mauger (Supervisor) – L.Mauger@kent.ac.uk

Dr Sam Smith (Supervisor) – S.A.Smith-75@kent.ac.uk

Thank you for showing interest in this study and taking time to read this information sheet. If you wish to participate in the study, please sign the informed consent form for confirmation.

Appendix 2 – Participant health questionnaire

HEALTH QUESTIONNAIRE

Participant Number: _____

Please answer these questions truthfully and completely.
The sole purpose of this questionnaire is to ensure that you are in a fit and healthy state to complete the exercise test.

ANY INFORMATION CONTAINED HEREIN WILL BE TREATED AS CONFIDENTIAL.

SECTION 1: GENERAL HEALTH QUESTIONS

Please read the questions below carefully and answer each one honestly: check YES or NO.

	YES	NO
1. Has your doctor ever said that you have a heart condition or high blood pressure?	☐	☐
2. Do you feel pain in your chest at rest, during your daily activities of living, or when you do physical activity?	☐	☐
3. Do you lose balance because of dizziness, or have you lost consciousness in the last 12 months? (Please answer NO if your dizziness was associated with over-breathing including vigorous exercise).	☐	☐
4. Have you ever been diagnosed with another chronic medical condition (other than heart disease or high blood pressure)?	☐	☐
If yes, please list condition(s) here:		
5. Are you currently taking prescribed medications for a chronic medical condition?	☐	☐
If yes, please list condition(s) and medications here:		
6. Do you currently have (or have you had within the past 12 months) a bone, joint or soft tissue (muscle, ligament, or tendon) problem that could be made worse by becoming more physically	☐	☐

active? Please answer NO if you had a problem in the past but it *does not limit your ability* to be physically active.		
If yes, please list condition(s) here:		
7. Has your doctor ever said that you should only do medically supervised physical activity?	□	□
8. Are you, or is there any chance you could be, pregnant?	□	□
9. Are you currently taking any nutritional supplements? **If 'YES' please inform the researcher what supplements are being taken**	□	□
10. Are you involved in any other research project? **If 'YES' please inform the researcher about the details of the project**	□	□
11. Do you have a metallic or electrical implant of any kind?	□	□
12. Do you have any infectious diseases or infectious skin alterations?	□	□

If you answered NO to all of the questions above, you are cleared to take part in the exercise test

Go to SECTION 3 to sign the form. You do not need to complete section 2.

If you answered YES to one or more of the questions in Section 1 - PLEASE GO TO SECTION 2.

SECTION 2: CHRONIC MEDICAL CONDITIONS

Please read the questions below carefully and answer each one honestly: check YES or NO.

		YES	NO
1.	**Do you have arthritis, osteoporosis, or back problems?** If YES answer questions 1a-1c. If NO go to Question 2.	☐	☐
1a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking any medications or other treatments).	☐	☐
1b.	Do you have joint problems causing pain, a recent fracture or fracture caused by osteoporosis or cancer, displaced vertebrae (e.g. spondylolisthesis), and/or spondylolysis/pars defect (a crack in the bony ring on the back of the spinal column)?	☐	☐
1c.	Have you had steroid injections or taken steroid tablets regularly for more than 3 months?	☐	☐
2.	**Do you have cancer of any kind?** If YES answer questions 2a-2b. If NO, go to Question 3.	☐	☐
2a.	Does your cancer diagnosis include any of the following types: lung/bronchogenic, multiple myeloma (cancer of plasma cells), head and neck?	☐	☐
2b.	Are you currently receiving cancer therapy (such as chemotherapy or radiotherapy)?	☐	☐
3.	**Do you have heart disease or cardiovascular disease? This includes coronary artery disease, high blood pressure, heart failure, diagnosed abnormality or heart rhythm.** If YES answer questions 3a-3e. If NO go to Question 4.	☐	☐
3a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking any medications or other treatments).	☐	☐
3b.	Do you have an irregular heartbeat that requires medical management? (e.g. atrial fibrillation, premature ventricular contraction)	☐	☐
3c.	Do you have chronic heart failure?	☐	☐
3d.	Do you have a resting blood pressure equal to or greater than 160/90mmHg with or without medication? Answer YES if you do not know your resting blood pressure.	☐	☐
3e.	Do you have diagnosed coronary artery (cardiovascular) disease and have not participated in regular physical activity in the last 2 months?	☐	☐

		YES	NO
4.	**Do you have any metabolic conditions? This includes Type 1 Diabetes, Type 2 Diabetes and Pre-Diabetes.** If YES answer questions 4a-4c. If NO, go to Question 5.	☐	☐
4a.	Is your blood sugar often above 13mmol/L? (Answer YES if you are not sure).	☐	☐
4b.	Do you have any signs or symptoms of diabetes complications such as heart or vascular disease and/or complications affecting your eyes, kidneys, OR the sensation in your toes and feet?	☐	☐
4c.	Do you have other metabolic conditions (such as thyroid disorders, current pregnancy related diabetes, chronic kidney disease, or liver problems)?	☐	☐
5.	**Do you have any mental health problems or learning difficulties?** This includes Alzheimer's, dementia, depression, anxiety disorder, eating disorder, psychotic disorder, intellectual disability and down syndrome. If YES answer questions 5a-5b. If NO go to Question 6.	☐	☐
5a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking any medications or other treatments).	☐	☐
5b.	Do you also have back problems affecting nerves or muscles?	☐	☐
6.	**Do you have a respiratory disease?** This includes chronic obstructive pulmonary disease, asthma, pulmonary high blood pressure. If YES answer questions 6a-6d. If NO, go to Question 7.	☐	☐
6a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking any medications or other treatments).	☐	☐
6b.	Has your doctor ever said you blood oxygen level is low at rest or during exercise and/or that you require supplemental oxygen therapy?	☐	☐
6c.	If asthmatic, do you currently have symptoms of chest tightness, wheezing, laboured breathing, consistent cough (more than 2 days/week), or have you used your rescue medication more than twice in the last week?	☐	☐
6d.	Has your doctor ever said you have high blood pressure in the blood vessels of your lungs?	☐	☐
7.	**Do you have a spinal cord injury?** This includes tetraplegia and paraplegia. If YES answer questions 7a-7c. If NO, go to Question 8.	☐	☐
7a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking any medications or other treatments).	☐	☐
7b.	Do you commonly exhibit low resting blood pressure significant enough to cause dizziness, light-headedness, and/or fainting?	☐	☐
7c.	Has your physician indicated that you exhibit sudden bouts of high blood pressure (known as autonomic dysreflexia)?	☐	☐

		YES	NO
8.	**Have you had a stroke?** This includes transient ischemic attack (TIA) or cerebrovascular event. If YES answer questions 8a-8c. If NO go to Question 9.	☐	☐
8a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking any medications or other treatments).	☐	☐
8b.	Do you have any impairment in walking or mobility?	☐	☐
8c.	Have you experienced a stroke or impairment in nerves or muscles in the past 6 months?	☐	☐
9.	**Do you have any other medical condition which is not listed above or do you have two or more medical conditions?** If you have other medical conditions, answer questions 9a-9c. If NO go to Question 10.	☐	☐
9a.	Have you experienced a blackout, fainted, or lost consciousness as a result of a head injury within the last 12 months OR have you had a diagnosed concussion within the last 12 months?	☐	☐
9b.	Do you have a medical condition that is not listed (such as epilepsy, neurological conditions, and kidney problems)?	☐	☐
9c.	Do you currently live with two or more medical conditions?	☐	☐
	Please list your medical condition(s) and any related medications here:		
10.	**Have you had a viral infection in the last 2 weeks (cough, cold, sore throat, etc.)?** If YES please provide details below:	☐	☐
11.	**Is there any other reason why you cannot take part in this exercise test?** If YES please provide details below:	☐	☐
12.	**Please provide brief details of your current weekly levels of physical activity (sport, physical fitness or conditioning activities), using the following classification for exertion level:** **L = light (slightly breathless)** **M = moderate (breathless)** **V = vigorous (very breathless)** **Activity Duration (mins.) Level (L/M/V)** **Monday** **Tuesday** **Wednesday** **Thursday** **Friday** **Saturday** **Sunday**		

Please see below for recommendations for your current medical condition and sign this document:

If you answered NO to all of the follow-up questions about your medical condition, you are cleared to take part in the exercise test.

If you answered YES to one or more of the follow-up questions about your medical condition it is strongly advised that you should seek further advice from a medical professional before taking part in the exercise test.

Appendix 3 – Participant Consent Form

Title of project: A comparative study of Muscle activation and oxygen uptake between Stationary Cycle Ergometry and Rollers.

Name of researcher:
Harry Doy

Participant Identification Number for this project:

Please initial box

1. I confirm I have read and understand the information sheet dated XX/XX/XXXX for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason. If you wish to withdraw, please contact project supervisor: hd357@kent.ac.uk ☐

3. I understand that my responses will be anonymised before analysis. I give permission for members of the research team to have access to my anonymised responses. ☐

4. I understand that the information collected about me will be used to support other research in the future, and may be shared anonymously with other researchers. ☐

5. I agree to take part in the above research project. ☐

6. I have completed the general health questionnaire associated with this project ☐

Name of participant	Date	Signature
Name of person seeking consent	Date	Signature

To be signed and dated in presence of the participant

Appendix 4 – sEMG MATLAB script (Rollers)

```
baseDir = "/Users/hazdo/Downloads/01 - EMG/";

folderNames = {'ROLLERS_05MIN', 'ROLLERS_10MIN', 'ROLLERS_15MIN', ...
               'ROLLERS_20MIN', 'ROLLERS_25MIN', 'ROLLERS_30MIN'};

muscleNamesPerFolder = {
    'Tricep', 'MidTrap', 'Abs', 'Obl';
    'Tricep', 'MidTrap', 'Abs', 'Obl';
    'Tricep', 'MidTrap', 'Abs', 'Obl';
    'Tricep', 'MidTrap', 'Abs', 'Obl';
    'Tricep', 'MidTrap', 'Abs', 'Obl';
    'Tricep', 'MidTrap', 'Abs', 'Obl';
};

A_TABLE = table();

for i = 1:length(folderNames)
    currentFolder = fullfile(baseDir, folderNames{i});
    durationTag = extractAfter(folderNames{i}, 'ROLLERS_');

    for j = 1:4
        fileName = sprintf('%sROLLERS_%d.mat', durationTag, j);
        filePath = fullfile(currentFolder, fileName);

        if isfile(filePath)
            fprintf('\nProcessing file: %s\n', filePath);
            load(filePath);

            fs = 2048;
```

```
f_low = 10;
f_high = 200;
order = 4;
Wn = [f_low f_high] / (fs / 2);
[b, a] = butter(order, Wn, 'bandpass');

EMG = double(Data{1, 1});
totalRows = size(EMG, 1);
startIdx = max(1, floor((totalRows - 20480) / 2));
endIdx = min(totalRows, startIdx + 20480);
EMG = EMG(startIdx:endIdx, :);

EMGfilt = filtfilt(b, a, EMG);
EMGabs = abs(EMGfilt);

MAV = mean(EMGabs);
SD = std(EMGabs);
AREA = trapz(EMGabs);
FFT = fft(EMGabs);
TotalPower = sum(abs(FFT).^2)/length(FFT);

rms = sqrt(mean(EMGabs.^2));

muscleName = muscleNamesPerFolder{i, j};
A_TABLE = [A_TABLE; table( ...
   string(folderNames{i}), string(muscleName), MAV, SD, AREA, TotalPower, rms, ...
   'VariableNames', {'Folder', 'Muscle', 'MAV (mV)', 'SD (mV)', 'Area (mV)', 'TotalPower (mV2/Hz)', 'rms'})];

fprintf('Muscle: %s | MAV: %.4f | SD: %.4f\n', muscleName, MAV, SD, AREA, TotalPower, rms);
```

```
        else
            fprintf('File not found: %s\n', filePath);
        end
    end
end
```

Appendix 5 - sEMG MATLAB script (Cyclus)

```
baseDir = "/Users/hazdo/Downloads/01 - EMG/";

folderNames = {'CYCLUS_05MIN', 'CYCLUS_10MIN', 'CYCLUS_15MIN', ...
            'CYCLUS_20MIN', 'CYCLUS_25MIN', 'CYCLUS_30MIN'};

muscleNamesPerFolder = {
   'Tricep', 'MidTrap', 'Abs', 'Obl';
   'Tricep', 'MidTrap', 'Abs', 'Obl';
   'Tricep', 'MidTrap', 'Abs', 'Obl';
   'Tricep', 'MidTrap', 'Abs', 'Obl';
   'Tricep', 'MidTrap', 'Abs', 'Obl';
   'Tricep', 'MidTrap', 'Abs', 'Obl';
};

A_TABLE = table();

for i = 1:length(folderNames)
   currentFolder = fullfile(baseDir, folderNames{i});
   durationTag = extractAfter(folderNames{i}, 'CYCLUS_');

   for j = 1:4
      fileName = sprintf('%sCYCLUS_%d.mat', durationTag, j);
      filePath = fullfile(currentFolder, fileName);

      if isfile(filePath)
         fprintf('\nProcessing file: %s\n', filePath);
         load(filePath);

         fs = 2048;
         f_low = 10;
         f_high = 200;
```

```
        order = 4;
        Wn = [f_low f_high] / (fs / 2);
        [b, a] = butter(order, Wn, 'bandpass');

        EMG = double(Data{1, 1});
        totalRows = size(EMG, 1);
        startIdx = max(1, floor((totalRows - 20480) / 2));
        endIdx = min(totalRows, startIdx + 20480);
        EMG = EMG(startIdx:endIdx, :);

        EMGfilt = filtfilt(b, a, EMG);
        EMGabs = abs(EMGfilt);

        MAV = mean(EMGabs);
        SD = std(EMGabs);
        AREA = trapz(EMGabs);
        FFT = fft(EMGabs);
        TotalPower = sum(abs(FFT).^2)/length(FFT);

        rms = sqrt(mean(EMGabs.^2));

        muscleName = muscleNamesPerFolder{i, j};
        A_TABLE = [A_TABLE; table( ...
            string(folderNames{i}), string(muscleName), MAV, SD, AREA, TotalPower, rms,
...
            'VariableNames', {'Folder', 'Muscle', 'MAV (mV)', 'SD (mV)', 'Area (mV)',
'TotalPower (mV2/Hz)', 'rms'})];

        fprintf('Muscle: %s | MAV: %.4f | SD: %.4f\n', muscleName, MAV, SD, AREA,
TotalPower, rms);
    else
        fprintf('File not found: %s\n', filePath);
    end
```

```
    end
end
```

Appendix 6 – MATLAB Lateral movement script

```
clearvars;
close all;
clc;

globalFolderPath = uigetdir(pwd, 'Select the global folder');
if globalFolderPath == 0
    error('No folder selected. Script terminated.');
end

addpath(globalFolderPath);
allFiles = dir(fullfile(globalFolderPath, '**', '*.xlsx'));
targetFiles = allFiles( ...
    contains({allFiles.name}, 'ROLLERS', 'IgnoreCase', true) | ...
    contains({allFiles.name}, 'CYCLUS', 'IgnoreCase', true));

if isempty(targetFiles)
    error('No files found.');
end

fprintf('\nFound %d matching file(s):\n', numel(targetFiles));
disp({targetFiles.name}');

results = {};
```

```
for i = 1:length(targetFiles)
    fileName = targetFiles(i).name;
    filePath = fullfile(targetFiles(i).folder, fileName);
    fprintf('\nProcessing file: %s\n', filePath);

    try
        data = readtable(filePath);
    catch ME
        warning('Error reading file %s: %s', fileName, ME.message);
        continue;
    end

    if ~all(ismember({'Frame', 'Time', 'Handle_BarY'}, data.Properties.VariableNames))
        warning('Missing required columns in %s. Skipping.', fileName);
        continue;
    end

    diffY = diff(data.Handle_BarY);
    total = round(sum(abs(diffY)) / 1000, 3);

    N = length(data.Handle_BarY);
    edges = round(linspace(1, N, 7));
    sextileMovements = zeros(1, 6);
    for s = 1:6
```

```
        segment = data.Handle_BarY(edges(s):edges(s+1));
        sextileMovements(s) = round(sum(abs(diff(segment))) / 1000, 3);
    end

    fprintf('S1: %.3f | S2: %.3f | S3: %.3f | S4: %.3f | S5: %.3f | S6: %.3f\n',
sextileMovements);
    results(end+1, :) = [{fileName, total}, num2cell(sextileMovements)];
end

resultsTable = cell2table(results, ...
    'VariableNames', {'Filename', ...
                      'CumulativeLateralMovement_m', ...
                      'S1_LateralMovement_m', ...
                      'S2_LateralMovement_m', ...
                      'S3_LateralMovement_m', ...
                      'S4_LateralMovement_m', ...
                      'S5_LateralMovement_m', ...
                      'S6_LateralMovement_m'});

% === Extract Subfolder ===
numResults = height(resultsTable);
subfolderNames = cell(numResults, 1);
if globalFolderPath(end) ~= filesep
    globalFolderPath = [globalFolderPath filesep];
end
```

```
for i = 1:numResults
    idx = find(strcmp({targetFiles.name}, resultsTable.Filename{i}), 1);
    if isempty(idx)
        subfolderNames{i} = 'Unknown';
    else
        relPath = extractAfter(targetFiles(idx).folder, strlength(globalFolderPath));
        if isempty(relPath)
            relPath = 'Root';
        end
        subfolderNames{i} = relPath;
    end
end

resultsTable.Subfolder = subfolderNames;
% === Assign Condition ===
resultsTable.Condition = cell(height(resultsTable), 1);
for i = 1:height(resultsTable)
    if contains(resultsTable.Filename{i}, 'ROLLERS', 'IgnoreCase', true)
        resultsTable.Condition{i} = 'ROLLERS';
    elseif contains(resultsTable.Filename{i}, 'CYCLUS', 'IgnoreCase', true)
        resultsTable.Condition{i} = 'CYCLUS';
    else
        resultsTable.Condition{i} = 'UNKNOWN';
```

```
    end
end

resultsTable = resultsTable(~strcmp(resultsTable.Condition, 'UNKNOWN'), :);
% === Export Table ===
csvFile = fullfile(globalFolderPath, 'wobble_results_summary.csv');
matFile = fullfile(globalFolderPath, 'wobble_results_summary.mat');
writetable(resultsTable, csvFile);
save(matFile, 'resultsTable');
fprintf('\nResults exported to:\n%s\n%s\n', csvFile, matFile);
% === Compute Means & 95% CIs ===
sextiles = {'S1_LateralMovement_m', 'S2_LateralMovement_m', ...
            'S3_LateralMovement_m', 'S4_LateralMovement_m', ...
            'S5_LateralMovement_m', 'S6_LateralMovement_m'};

meanVals = struct('ROLLERS', [], 'CYCLUS', []);
ciVals = struct('ROLLERS', [], 'CYCLUS', []);
computeCI = @(x) 1.96 * std(x) / sqrt(length(x));

for s = 1:6
    sextVar = sextiles{s};
    for cond = ["ROLLERS", "CYCLUS"]
        vals = resultsTable.(sextVar)(strcmp(resultsTable.Condition, cond));
        meanVals.(cond)(s) = mean(vals);
```

```
        ciVals.(cond)(s) = computeCI(vals);
    end
end
% === Final Plot: Discrete Markers + Y-axis Squiggle Starting at 5m ===
figure('Name', 'Mean ± 95% CI by Time Window', 'Color', 'white', 'Position', [100 100 900
600]);
hold on;

x = 1:6;
xticklabels_custom = {'5', '10', '15', ...
                      '20', '25', '30'};
% CYCLUS: black circle (no connecting line)
errorbar(x, meanVals.CYCLUS, ciVals.CYCLUS, ...
    'ko', 'MarkerFaceColor', 'k', 'MarkerSize', 8, ...
    'LineWidth', 1.5, 'CapSize', 10);

% ROLLERS: black square (no connecting line)
errorbar(x, meanVals.ROLLERS, ciVals.ROLLERS, ...
    'ks', 'MarkerFaceColor', 'k', 'MarkerSize', 8, ...
    'LineWidth', 1.5, 'CapSize', 10);

% Axes
xlim([0.5 6.5]);
ylim([5 max([meanVals.CYCLUS + ciVals.CYCLUS, meanVals.ROLLERS +
ciVals.ROLLERS]) + 5]);
```

```
xticks(x);
xticklabels(xticklabels_custom);
xlabel('Time (Min)', 'FontWeight', 'bold', 'FontSize', 12);
ylabel('Displacement (m)', 'FontWeight', 'bold', 'FontSize', 12);


set(gca, 'FontSize', 11, 'LineWidth', 1.5, 'Box', 'off', 'Color', 'none');
grid on;
% Simulated squiggle at y=5m (cosmetic)
squiggleY1 = 4.9; squiggleY2 = 5.2;
line([0.6 0.7], [squiggleY1 squiggleY2], 'Color', 'k', 'LineWidth', 1.2);
line([0.8 0.9], [squiggleY1 squiggleY2], 'Color', 'k', 'LineWidth', 1.2);
% Legend
legend({'CYCLUS', 'ROLLERS'}, 'Location', 'northeast', 'Box', 'off', 'FontSize', 11);
% Export
exportFileFinal = fullfile(globalFolderPath,
'wobble_sextile_timeWindow_CI_plot_updated.png');
saveas(gcf, exportFileFinal);
fprintf('\nFinal updated CI plot exported to:\n%s\n', exportFileFinal);
```