Effect of Incline Treadmill Running on Metabolic Power and Running Efficiency Measured with Stryd Pods

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KNES 590: Honours Thesis

For Dr. Martin MacInnis

April 11, 2025

Acknowledgements

This project has been a rewarding opportunity to engage in research as an undergraduate student and become exposed to the world of academia. I have learned a lot about the nature of research over the past year, and I have gained so much valuable experience working alongside inspiring master's students, PhD candidates and post-docs who always expanded my growth and helped me become a better student.

I would like to thank Martin for being an excellent mentor and for your guidance this past year. I deeply appreciate the time and energy you put into my project, as well as the efforts you made to include me in lab activities, team meetings and extracurriculars. You've created an awesome team environment filled with mutual respect and camaraderie, and I'm grateful to have been a member of your team.

I would also like to thank Rachel, Hilkka, Cody, Tom, Alex, Zoe and Jim for supporting my learning and being great mentors. I've enjoyed all interactions we've shared together, both inside and outside the lab, and I consider myself lucky to have been surrounded by such a great group of people.

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Chapter I: Literature Review

1.1 Popularity of Wearable Technology and Exercise

Continuing improvements in technology have had large impacts on the average person's inter and intrapersonal behaviour (Ferreira et al., 2021). With information and communications technology specifically, the widespread adoption of smartphones has created a growing desire for new and innovative devices that can utilize a smartphone's computing power and connectivity to improve an individual's technology ecosystem (Ometov et al., 2021). Consumers want seamless integration between all their devices, and there are established technology giants as well as constantly emerging start-ups aiming to create the best product experience to gain as large a share of an ever-growing multi-billion-dollar industry as possible (Dehghani et al., 2022).

The development of wearable technology to monitor health status in clinical populations and track exercise metrics to monitor and analyze performance in a variety of populations are of growing interest (Apoorva et al., 2024). These wearable health and exercise devices commonly take the form of watches, wrist bands, and pedometers (Apoorva et al., 2024; da Silva, 2024), and, within the fitness industry, wearable exercise trackers are typically wristwatches that display a wide variety of information users may find interesting and useful for informing their exercise training goals. Common sport and health related metrics included on wearable devices are heart rate, GPS, elevation, speed, predicted maximal oxygen uptake ($\dot{V}O_2$Max), recovery status, sleep tracking, calories burned, and daily activity monitoring (da Silva, 2024; Sher et al., 2024). These and many other features give consumers more information to better track their health, wellness, and exercise performance, and research shows consumers are very receptive to features they find useful and beneficial to their daily lives (Lunney et al., 2016). Not only are people receptive to useful features, but they are also more likely to increase their physical activity and adherence to training programs the more they perceive benefits and utility of their wearable device (Lunney et al., 2016; McFadden, 2021; Sher et al., 2024). One metric that is gaining popularity is running power. To understand the value of measuring this metric, it is important to understand cardiorespiratory fitness, exercise intensity domains, and running economy.

1.2 Measuring Cardiovascular Fitness and Exercise Intensity

1.2.1 What is $\dot{V}O_2$

Every time we engage our muscles, energy stored in the form of adenosine triphosphate (ATP) is required for muscle fiber contractions to occur (Chaplain & Frommelt, 1972). This ATP is supplied by muscle tissue via three different metabolic pathways: phosphocreatine (PCr), anaerobic glycolysis and oxidative phosphorylation (OXPHOS). PCr and glycolysis are part of the body's anaerobic energy pathways and respond very rapidly to high energy demands (Boulay et al., 1985). PCr is essentially a form of stored ATP inside muscle tissue that responds immediately to high-energy demands (Binzoni et al., 1997), but it is limited in supply so it only has a capacity to provide energy for about 15 to 20 seconds (Gastin, 2001). Anaerobic glycolysis has slightly slower on-kinetics than PCr but also produces ATP anaerobically, which allows it to satisfy energy demands for longer periods of time than PCr; however, it is a relatively inefficient metabolic pathway and produces small amounts of ATP with high P_i, H^+, and lactate concentrations (Jones et al., 2008)**,** which contribute to muscle fatigue. Anaerobic glycolysis can only supply near maximal energy demands for short periods of time in the range of 15-60 seconds (Gastin, 2001), so it is not a suitable energy pathway for prolonged periods of dynamic muscle contractions. Unlike PCr and glycolysis, OXPHOS is an energy pathway capable of providing ATP for very long periods of time, but it requires oxygen in order to operate and may take several minutes for the ATP production from OXPHOS to match the demands (Walsh et al., 2005). During exercise, the greater the energy demands, the greater the Volume of oxygen required to oxidize carbohydrates and lipids to aerobically produce ATP, and this rate of oxygen uptake can be measured and is referred to as $\dot{V}O_2$.

The rate at which oxygen is consumed by the body is termed $\dot{V}O_2$ (Hill et al., 1924; Wasserman et al., 1973), and the maximum rate of oxygen consumption is termed $\dot{V}O_{2max}$. The majority of the oxygen is consumed by muscle mitochondria to aerobically supply energy (i.e., synthesize ATP) for muscle contraction and the maintenance of muscle homeostasis. Mathematically, $\dot{V}O_2$ is the result of the arterial-venous blood oxygen difference, which is determined by the arterial oxygen content of blood (CaO_2) and the ability of cells to consume oxygen to lower the venous oxygen content of blood ($C_{\dot{V}O2}$), multiplied by cardiac output (Q), the product of heart rate and stroke volume (Yamamoto et al., 2014). This relationship is represented by the Fick equation.

Fick Equation. $\dot{V}O_2 = Q \times (CaO_2 - C_{\dot{V}O2})$

$\dot{V}O_2$ is a strong indicator of cardiovascular fitness and is considered the gold standard in assessing cardiopulmonary health, as it is inversely related to all-cause mortality (Hawkins et al., 2007; Lee & Zhang, 2021). In athletic populations, $\dot{V}O_{2max}$ is used to quantify fitness, evaluate the effectiveness of training programs, and predict potential for Olympic success (Tønnessen et al., 2015).

1.2.2 How $\dot{V}O_2$ is Measured

The gold standard measurement of $\dot{V}O_2$ is the use of Douglas Bags (Hill et al., 1924). Briefly, these are empty bags an individual exhales into during an exercise protocol via a mask and hose for the purpose of quantifying pulmonary gas exchange. After exercise is complete, the volume and composition of the gas within the bags are analyzed and volumes of oxygen and carbon dioxide are measured to determine $\dot{V}O_2$. Douglas bags are very accurate, but they are somewhat cumbersome and impractical in most exercise applications, particularly in comparison to modern methods.

An easier method of measuring $\dot{V}O_2$, that overcomes some of the limitations of Douglas bags while maintaining high measurement accuracy, is the use of a metabolic cart (Cullum et al., 1999). Metabolic carts are noninvasive specialized equipment consisting of a mask, sampling line, hose, gas analyzers and a pneumotach. Collectively, this equipment is used to measure gas concentrations and inhaled/exhaled Volumes of gas and can display an individual’s physiological and metabolic response to exercise in real time (Keir et al., 2022). Metabolic carts can be set up to sample from mixing chambers in discrete time intervals, or they can be set up to measure gas exchange for every breath a person takes. Metabolic carts provide information about a person’s $\dot{V}O_2$, Volume of carbon dioxide produced ($\dot{V}CO_2$), minute ventilation (V_E) breathing frequency (fB), and respiratory exchange ratio (RER) (Keir et al., 2022). These variables, in the context of the exercise protocol, can help inform health and/or training status (Iannetta et al., 2019; Swank et al., 2012; Tønnessen et al., 2015), and are commonly used to identify training zones and prescribe training intensity (Keir, Paterson, et al., 2018).

1.2.3 $\dot{V}O_2$ and Intensity Domains

It is very common to use metabolic carts to measure an individual's $\dot{V}O_{2Max}$ and utilize gas exchange data to identify exercise intensity domains (Iannetta et al., 2019, 2020; Keir et al., 2022). There are three intensity domains that are demarcated by two thresholds, indicated by significant/notable changes in metabolic/physiological responses to increases in exercise intensity. The three domains are the moderate (MOD) domain, heavy (HVY) domain, and severe

(SVR) domain, and they are separated by the gas exchange threshold (GET) and respiratory compensation point (RCP) (Binder et al., 2008; Keir et al., 2022; Whipp et al., 2005). (Kirby et al., 2021; Lee & Zhang, 2021). GET is commonly equated with terms such as aerobic threshold, first lactate threshold, lactate breakpoint, and first ventilatory threshold (Binder et al., 2008), while RCP is associated with many different terminologies such as anaerobic threshold, maximal lactate steady state, second lactate turn point, secondary ventilatory threshold, and critical power (CP) (Binder et al., 2008). These terms are sometimes used interchangeably, which may technically be incorrect, but they are all valid surrogates of the maximal metabolic steady state (MMSS) (Bergstrom et al., 2013; Keir et al., 2018), which is the metabolic rate above which exercise becomes unsustainable (Keir et al., 2018). Some thresholds are named depending on how the threshold was identified. The first and second lactate thresholds, for example, are determined using invasive lactate testing in conjunction with a graded exercise protocol consisting of discrete constant load exercise stages which are increased in intensity every 1-5 minutes until exhaustion (Bentley et al., 2007). These lactate thresholds represent the same metabolic changes as the ventilatory thresholds associated with GET and RCP (Binder et al., 2008; Carey et al., 2005; Keir et al., 2018).

1.2.4 Moderate Domain

The MOD domain represents the highest exercise intensity that can be maintained with no significant shifts in physiological homeostasis or metabolic acidosis (Keir et al., 2022). It is a purely aerobic state with a low (i.e., baseline) blood lactate concentration, stable blood pH and minor reductions in phosphocreatine (PCr) concentration (Black et al., 2017), to name a few. It is an exercise intensity that can be maintained for hours.

1.2.5 Heavy Domain

Above GET and below RCP is the HVY domain, which represents a physiological zone where increases in work rate result in significant metabolic imbalances in blood lactate, pH, PCr, and CO_2 production as a result of increased glycolysis (Black et al., 2017). Within this domain, despite marked metabolic changes, a metabolic steady state can be attained, and these values stabilize, allowing exercise to continue (Whipp, 2009). In theory, if the intensity of exercise is held below the MMSS, individuals remain metabolically stable and can maintain exercise within the HVY domain for extended periods of time (Poole et al., 1988); however, practically, exercise at or just below the MMSS lasts between ~30-60 min among relatively well-trained individuals (De Lucas et al., 2013).

1.2.6 Severe Domain

Exercise intensity above MMSS results in metabolic and physiological changes that are beyond the body's ability to constrain, preventing the attainment of a metabolic steady state (Binder et al., 2008; Keir et al., 2022). Unlike in the HVY domain where the body can adapt to metabolic imbalances, in the SVR domain the aerobic system is incapable of providing the energy required to sustain exercise intensity above CP resulting in energy increasingly supplied via anaerobic glycolysis. Higher rates of glycolysis result in elevated P_i, lactate, and H^+ (Jones et al., 2008). If given enough time, exercise within this domain will cause $\dot{V}O_2$ to continually increase until $\dot{V}O_{2max}$ is reached and time to exhaustion is achieved (Hill et al., 2002). The duration for which severe exercise can be maintained depends on the intensity; however, it is generally less than 30 min and potentially only seconds for very high intensities.

1.2.7 $\dot{V}O_2$ as a Measure of Metabolic Work

If $\dot{V}O_2$ and $\dot{V}CO_2$ are known, it is possible to calculate an individual's RER. Frequently, RER is used as a measure of the relative amounts of carbohydrate and lipid substrates being oxidized to produce ATP (Hill et al., 1924a), with an RER of 0.707 indicating 100 percent lipid oxidation and an RER of 1.000 indicating 100% carbohydrate oxidation (Issekutz & Rodahl, 1961). Through RER, one can estimate the total energy expended, per liter of oxygen consumption (Peronnet, 1991). With a metabolic cart and running treadmill, it is possible to use absolute $\dot{V}O_2$ (L/min) and RER to measure absolute metabolic power ($kJ \cdot km^{-1}$) as well as relative metabolic power ($kJ \cdot kg^{-1} \cdot km^{-1}$) per unit distance at different exercise intensities (Van Rassel et al., 2023). $\dot{V}O_2$ and RER allow for the calculation of the metabolic cost of exercise, which can be utilized alongside running velocity or running power output of different IMUs, like Stryd pods, to estimate running economy and mechanical efficiency.

1.3 Running Economy and Mechanical Efficiency

Running economy (RE) is the relationship between $\dot{V}O_2$ and energy expenditure at different running velocities (J. T. Daniels, 1985), whereas mechanical efficiency (ME) is the ratio of external mechanical power to metabolic power (Aura & Komi, 1986; Keir et al., 2012). RE is constant at submaximal velocities (Batliner et al., 2018), and there is considerable variance in RE between individuals based on multiple variables such as training status, running technique, and body composition (González-Mohíno et al., 2020; Melo et al., 2020; Roberts & Belliveau, 2005). As running speed or incline increases, oxygen and energy demands also increase, resulting in a higher metabolic cost of exercise and a worsened RE. The utility of RE is the ability to express the metabolic cost of running as a function of work, either individually or between individuals, and compare energy expenditure at different velocities for a given incline or at a set velocity and different inclines. Doing so has practical applications for athletes and coaches who want to monitor improvements in training status and performance (Conley & Krahenbuhl, 1980).

While RE is relatively easy to measure, ME is more difficult to quantify. ME can be calculated by converting external mechanical power output (W) into relative energy per unit of distance travelled ($kJ \cdot kg^{-1} \cdot km^{-1}$) and dividing this value by the metabolic power ($kJ \cdot kg^{-1} \cdot km^{-1}$) derived from $\dot{V}O_2$ and RER (Van Rassel et al., 2023). For the most part, it has not been possible to measure the mechanical power output associated with running, preventing measures of ME.

1.3.1 Running Power

Power (W) is a measurement of the amount of work (Joules) done per unit of time (seconds) and is represented by the SI unit, Watts. In cycling, power is easy to quantify. A measured force output is applied against a known resistance that moves a flywheel a known distance allowing for easy calculation of work and power. The ease of calculating cycling power has resulted in the development and widespread use of cycling power meters, which are used to inform training and race performance. Given that cycling efficiency is relatively stable across a range of intensities, it is not surprising that there are strong, significant correlations between cycling power and $\dot{V}O_2$ (Hawley & Noakes, 1992), and that cycling power is a highly reliable and valid indicator of exercise intensity (Passfield et al., 2017). The simplicity of measuring cycling power, the high validity and reliability of power meters, and the very strong, significant correlation between power and $\dot{V}O_2$, has led to widespread adoption of cycling power as a training and racing tool (Passfield et al., 2017). A major factor that further explains the utility of cycling power is that the relationship between power and $\dot{V}O_2$ holds true regardless of changes in terrain and speed, making it very effective for controlling exercise intensity in varying environmental conditions (Leo et al., 2022).

For running power to be useful for monitoring and prescribing exercise, it also should be independent of terrain and speed. In other words, running power and $\dot{V}O_2$ should be linearly related across a large range of intensities. There is currently no universally agreed upon definition of running power (Arampatzis et al., 2000). Several methods have been proposed to measure running power, including using IMUs to measure work required to move the center of mass and work done to move body limbs (Zamparo et al., 2016); using force plates to measure ground reaction forces (Taboga et al., 2022); and using commercial products like Garmin, Polar and Stryd to measure power output based on proprietary algorithms (Jaén-Carrillo et al., 2020). These different methods all result in different estimates of power (Arampatzis et al., 2000), leading to a lack of consensus for which method of measuring power is most appropriate. Another difficulty when measuring running power is the inconsistency in gait, stride frequency, vertical oscillations, running form, and ground reactions forces a person may experience during a run, leading to variability in running power estimates (Vernillo et al., 2020). Despite the challenges in measuring running power, many different companies are producing wearable technology that provide an estimate of running power individuals can use to monitor their training.

A specific wearable accessory that is growing in popularity among amateur and professional runners is the Stryd Pod. These devices are consumer-grade inertial measurement units that attach to the laces on a running shoe and give runners real-time estimates of their running power (Jaén-Carrillo et al., 2020). The algorithms used by Stryd to determine running power are not publicly available, limiting insights on their validity. Nevertheless, the reliability of Stryd running power measurements is excellent (Berzosa et al., 2024; Dearing & Paton, 2023; Imbach et al., 2020; Jaén-Carrillo et al., 2020), and Stryd running power can be utilized to delineate training domains, prescribe individualized submaximal running intensity, and assess aerobic fitness on flat terrain (Berzosa et al., 2024; Dearing & Paton, 2023; García-Pinillos et al., 2019; Imbach et al., 2020; Van Rassel et al., 2023; Van Rassel et al., 2023). A growing body of research looks into the relationship between Stryd power and $\dot{V}O_2$ during exercise to establish relationships between critical speed, critical power and the metabolic cost of exercise (Jaén-Carrillo et al., 2020; Van Rassel et al., 2023); however, much less is known about the relationship between metabolic cost and mechanical efficiency when running on variable terrain and differing inclines.

With the use of a metabolic cart, graded exercise test, and commercial IMUs, it is possible to determine the $\dot{V}O_2$, running speed and running power associated with GET and RCP (Van Rassel et al., 2023). The speed of the treadmill and power recorded by Stryd pods represent the external training load experienced by a runner, and the metabolic cart measures $\dot{V}O_2$ which gives insight into the internal training load associated with exercise (Impellizzeri et al., 2019). This internal training load represents the $\dot{V}O_2$ and metabolic cost of exercise at given exercise intensities, and, for the purposes of exercise prescription, running speed and power serve as proxies for a desired metabolic and physiological response to exercise.

1.3.2 Speed, Power and $\dot{V}O_2$ on Flat and Incline Terrains

On flat terrain RE is approximately constant with the average runner having a linear relationship between $\dot{V}O_2$ and speed, while elite runners have a slightly curvilinear relationship when running at submaximal intensities (Batliner et al., 2018; J. Daniels & Daniels, 1992). More recent research has demonstrated that power also follows this trend with a linear relationship between $\dot{V}O_2$ and power (Van Rassel et al., 2023). The strongly correlated nature between $\dot{V}O_2$, speed and power, when running on flat terrain, results in CS and CP representing the same metabolic boundary; this demonstrates that running power is a valid method of measuring exercise intensity (Patoz et al., 2022; Van Rassel et al., 2023). Knowing this association between CS and CP, both can be used interchangeably to prescribe personalized exercise intensities within desired training domains (MOD, HVY, SVR) by using external speed and power loads to estimate internal $\dot{V}O_2$ load and optimize training and performance; however, running speed is terrain dependent, and it remains to be determined whether running power is independent of terrain (particularly grade).

While running speed induces predictable metabolic and $\dot{V}O_2$ responses on flat terrain, the predictive relationship between the external and internal training loads of running speed and $\dot{V}O_2$ dissociates when running on variable terrain. As incline increases, the $\dot{V}O_2$ and metabolic cost of running at a given speed also increases, worsening RE (Lemire et al., 2021). There are a combination of factors contributing to changes in incline RE, including stride frequency, stride length, ground contact time, biomechanical joint angles, and general running technique (Van Hooren et al., 2024). The relationship between RE and incline is not extensively documented, and there is almost no literature investigating the relationship between RE, energy cost, ME and running power on variable terrain. Table 1, below, summarizes some of the literature investigating the relationship between RE, energy cost and incline. The findings suggest a significant effect of incline on RE at running speeds below MMSS (Breiner et al., 2019) with a relationship that may be linear in nature (Lussiana et al., 2013), but there is potentially conflicting data pointing to significant differences in RE between speeds at different inclines instead of differences in RE at changing inclines (Kolyfa et al., 2022). More research is required to gain a better understanding of the relationship between RE and speed and power on variable terrain.

1.4 Objective

The overall objective of this study is to investigate the relationship between RE, speed and Stryd running power at varying inclines, and determine if there are changes in ME with changes in grade. Previous research in this lab has helped establish the validity of Stryd power as a tool to quantify running intensity and identify MMSS on flat terrain (Van Rassel et al., 2023). We wish to use Stryd power and metabolic energy cost to estimate RE at a combination of varying inclines and running speeds to observe how RE changes with changing inline. We hypothesize that incline will cause changes in running biomechanics and ground reaction forces therefore causing a non-linear relationship between power and $\dot{V}O_2$ at ever increasing inclines.

We also want to determine if the relationship between external running power and internal metabolic power remains constant across variable terrain similar to cycling mechanical efficiency. We hypothesize, as above, that incline will cause changes in biomechanics and ground reaction forces which will result in varying ratios between internal metabolic power and external mechanical power and a decrease in ME.

Table 1.1. Summary of some publications that have evaluated the effect of incline on running economy and energy expenditure.

Author	Participants	Training Status	Grade %	$\Delta\dot{V}O_2$ or ΔEnergy Cost/incline	Primary Findings
Snyder & Farley. 2011	n = 9 males	Competitive runners capable of running sub 18:30min 5km	-3%, 0%, +3%	metabolic cost at 3%, 0%, +3%: 2.28, 3.17, 4.46 J/kg/m	Study tested the effect of running stride on energy cost at different inclines, but gave some insight into RE at different grades
Balducci et al. 2016	n = 10 males	High level endurance mountain runners	0%, 12.5%, 25%	Energy Cost ranging 0.192, 0.350, 0.516 mlO_2/kg/m	Significant difference in energy cost and RE at different inclines with RE at 0% not a predictor of RE at steeper grades.
Lussiana et al. 2013	n = 14 males	Experienced runners completing minimum 45km/week	-8%, -5%, -2%, 0%, +2%, +5%, +8%	net difference of 0.15-0.35 mlO_2/kg/m across -8% to +8% incline	Study was testing difference in RE between running shoes, and found a near linear relationship in RE and incline
Kolyfa et al. 2022	n = 15 males	Moderately trained runners with at least 2 years running experience	3%,6%,9 %	1.012-1.80/1% grade	Significant difference in RE at different speeds at the same grade, but there were no significant differences in RE for speed per 1% increase in grade
Breiner et al. 2019	n = 19 males	Well-trained runners with uphill running part of routine training.	-5%, 0%, +7.5%	$\dot{V}O_2$ cost at -5%, 0%, 7.5% grade: 47.0, 46.8, 48.0ml/kg/min	Significant difference in RE in level and uphill running

Chapter II: Introduction

2.1 Overview

Increased access to technology and continual improvements in computing processing have led to high consumer demand for wearable technology, resulting in large-scale growth in the wearable technology market and increased integration of smart devices into people's daily lives (Ferreira et al., 2021). Wearable tech is particularly common within the health and wellness industry, and technology companies like Apple, Polar, and Garmin produce watches and other products that measure a variety of health and fitness metrics people may find interesting and useful (Apoorva et al., 2024). Common metrics associated with these products are heart rate, GPS tracking, speed, calories burned, sleep quality, and daily active monitoring (da Silva et al. 2016). New features are being added to fitness trackers all the time, and an exercise metric that is gaining popularity is running power.

Measuring power for exercise purposes is not a new concept. Cycling power meters, for example, have been utilized to monitor and prescribe exercise for decades. These devices have proven to be highly reliable measures of power and valid indicators of exercise intensity (Passfield et al. 2017), as cycling power and $\dot{V}O_2$ are strongly correlated with each other (Hawley & Noakes, 1992) and this relationship is not affected by terrain. Accordingly, cycling power is useful for coaches and athletes to target specific internal training loads and has inspired the development of running power meters in hopes the same utility can be transferred to running; however, there is no consensus on how to measure running power (Arampatzis et al., 2000). Several methods of measuring power have been proposed, such as measuring work required to move the center of mass (Zamparo et al., 2016) or force plates to measure ground reaction forces

(Taboga et al., 2022). Providing users with measures of power output could revolutionize approaches to training and racing for runners.

Stryd pods are lightweight commercial IMU's that easily attach to a runner's shoelaces, and interface with both smartphones and fitness watches to provide real-time estimates of running power (Jaén-Carrillo et al., 2020). Stryd does not publish their algorithms, limiting the ability to validate their estimates of power, but their ability to measure power has proven to be highly reliable (Berzosa et al., 2024; Imbach et al., 2020). This reliability and their ease of use make Stryd pods great tools for use in studies, with research showing that running power, like running speed, is correlated with running economy and can be used to estimate mechanical efficiency (Van Rassel et al., 2023). Stryd pods can be used to inform the internal training load and $\dot{V}O_2$ associated with running and can be used to delineate training domains, prescribe submaximal running intensity, and assess aerobic fitness (Patoz et al., 2022; Van Rassel et al., 2023); however, more research is needed to use Stryd pod running power in the same manner as cycling power.

Stryd pods have helped demonstrate that running power is highly correlated with $\dot{V}O_2$ and metabolic responses to exercise on flat terrain, but whether ME is constant on inclined terrain is unclear. It is known that RE at a given running speed worsens with increasing incline (Lemire et al., 2021), as the oxygen cost of running at a given speed increases with grade. Mechanical efficiency is mostly unaffected by changes in grade for cycling, but changes in running form, biomechanics, stride frequency, and contact time may reduce mechanical efficiency for inclined running, either because changes in stride mechanics reduces tendon elastic energy return (Schroeder & Kuo, 2021) or the energy cost to maintain speed increases (Roberts & Belliveau, 2005).

2.2 Hypothesis

Accordingly, we hypothesize that the relationship between running power and $\dot{V}O_2$ and metabolic power on flat terrain will be significantly different when measured at inclines between zero and eight percent grade while controlling running power output. We also hypothesize that running mechanical efficiency will be significantly different at varying inclines when compared to flat running when controlling power output.

Chapter III: Methods

3.1 Participants

This is a pre-experimental study consisting of six male and three female trained runners for a total of nine participants. The average age, height and weight of male and female participants are reported in Table 1. This study utilized convenience and snowball sampling to recruit participants, with most participants recruited from University of Calgary students, faculty members, varsity athletes, staff, friends and family members. The study was promoted via email and word of mouth. All participants were informed of their rights and were routinely reminded they can revoke their participation at any time and for any reason.

3.1.1 Inclusion and Exclusion Criteria

Inclusion criteria for this study were male or female recreationally active or competitive runners aged 18 – 45 years old; training volume of at least 25 km/week for the past 3 months; and personal best 10km running time under 50 minutes for men and 55 minutes for women. Exclusion criteria were complete a Get Active Questionnaire (GAQ) with no markers selected which preclude them from exercise; a BMI > $30 kg \cdot m^{-2}$; pregnancy; taking medications which affect cardiovascular and/or metabolic responses to exercise, such as beta-blockers, anti-inflammatories, insulin, etc.; undergoing a diet for the purpose of weight loss or following a low carbohydrate diet; smoking, vaping or using any tobacco products within the last 12 months; consuming excessive amounts of alcohol (>21 units/week); self-identification with any one of the following conditions: renal or gastrointestinal disorders, metabolic disease, heart disease, vascular disease, rheumatoid arthritis, diabetes, poor lung function, uncontrolled blood pressure, dizziness, thyroid problems, or any other health condition currently being treated and could confound results of the study; orthopedic conditions which limit exercise ability; using investigational drug within the past 30 days; self-identification of contraindication to exercise; and inability to understand English.

3.2 Ethics

Ethical approval was obtained through the University of Calgary Conjoint Health Research Ethics Board (CHREB). Participation in this study required informed consent and a signed, completed Get Active Questionnaire (GAQ). Participants were provided with the necessary information to weigh the potential benefits and risks of partaking in the study. The testing protocols had the potential to cause discomfort such as muscle pain/fatigue, increased perspiration, elevated breathing, elevated heart rate, dizziness, generalized fatigue or nausea. The SRS had an increased risk of cardiac event (i.e. heart attack dysthymia, etc) estimated to occur between 0.2 and 6 events per 10,000 person hours in healthy, low risk and unhealthy participants. Risks associated with exercise and testing were minimal, but all forms of exercise carry some amount of risk and potential discomfort for the exerciser. At least two experimenters were present for all testing trials with at least one experimenter being CPR certified. 3.3 Experimental Design Overview

3.3.1 Protocol

This study consisted of two visits to the Molecular, Environmental and Exercise Physiology (MEEP) Lab at the University of Calgary, and both sessions took place on a Woodway running treadmill (Desmo Pro EVO, Woodway USA Inc., Waukesha, WI, USA). Participants were fitted with Stryd pods (Stryd, Boulder, CO) which are lightweight (8.0g) commercial IMUs (Model v.19, 2.1.32.1.1) that sample at frequencies of 1Hz. These devices were secured to each participant's shoelaces in the middle of the dorsal aspect of the foot.

Visit one was a step-ramp-step (SRS) protocol that consisted of an easy warm up, moderate intensity (MOD) step, ramp incremental test, and a heavy intensity (HVY) step. The SRS protocol was used to identify the $\dot{V}O_2$, running speed and running power associated with GET and RCP, and the values at these thresholds were used to determine running speed and running power for the second day of testing.

The second visit consisted of a warm-up and series of 5-min intervals at varying inclines and speeds to elicit a constant power output that was 10% below the runner's power at RCP. The inclines for each interval were set in a random order ranging from 0-8% grade, and speed was adjusted to achieve the correct power output. To achieve an equal testing distribution across different combinations of conditions but also ensure conditions were randomized, we randomized participants to one of five unique trials for which the order of conditions was counterbalanced. An outline of trials and incline orders can be seen in Table 3.1.

Table 3.1. Running Incline Combinations for Constant Power Trials.

Trial	Incline Order (%)				
1	0	4	8	6	2
2	4	8	6	2	0
3	8	6	2	0	4
4	6	2	0	4	8
5	2	0	4	8	6

After completing the five trials, the treadmill was returned to 0% grade and set to the individual's speed associated with RCP -10%. Then, subjects ran 30 second intervals at the five different inclines without changing speed to understand how power increases with changes in incline.

3.3.2 Metabolic cart

All trials used a Quark CPET metabolic cart (COSMED, Rome, Italy) and mixing chamber (COSMED) to monitor $\dot{V}O_2$ and ventilatory gas variables. Participants wore facemasks (7450 Series V2, Hans-Rudolph, Shawnee, KS, USA) outfitted with 2-way non-rebreathing valves (Hans-Rudolph) and a gas collection hose connected to the metabolic cart. The metabolic cart was calibrated with a 3L syringe and gas mixture composition of 5% CO_2, 16% O_2, and N_2 to balance the gases. The mask was worn for the entirety of the running trials to track pulmonary gas exchange responses to exercise and calculate metabolic work.

3.3.3 SRS Protocol

The SRS protocol used in this experiment is identical to an established protocol previously used in Stryd running research done in this lab by Van Rassel et al. (2022). The protocol has an 18-minute warm-up consisting of a 6-minute interval at 4.3mph, followed by a MOD step at 5.3mph for 6 minutes, and a final 6-minute interval at 4.3mph. These speeds should be well below a participant's GET allowing the MOD step to properly estimate the mean response time (MRT) with low risk of the $\dot{V}O_2$ slow component impacting the estimate. The ramp portion of the SRS began immediately after the 18-minute warm-up. The ramp incremental started at 4.3mph and increases in speed by 0.5mph every minute until the participant cannot maintain running speed or stops running due to heavy fatigue. After the ramp, there was a 30-minute passive recovery period followed by a HVY step to determine the $\dot{V}O_2$ slow component within the HVY domain. This step consists of a 4-minute warm up at 4.3mph followed by a 12-minute step at 50% of the speed between GET and RCP. This 50% delta is determined by estimating GET and RCP from ramp incremental $\dot{V}O_2$ data during the participant's 30-minute recovery period. RPE was recorded in the last minute of warm up, at the end of every minute step in the ramp incremental, and in the final minute of the HVY step.

3.3.4 Constant-power protocol

The constant-power protocol included a 10-minute warm-up, with 5 minutes at the runner's power at LT and 5 minutes at 10% below the runner's power at RCP, followed by five 5-min intervals at pre-set inclines with speed manually adjusted to target the correct running power. There was no rest between bouts. The rationale for including a 5-minute RCP bout within the warm-up was to have runners achieve, or come close to, a $\dot{V}O_2$ steady state before beginning the testing trials to ensure a $\dot{V}O_2$ steady state was achieved within the final minute of the first incline trial. This reduced the likelihood of recording data before a steady state is achieved which could have affected analysis. Speed was recorded at each five-minute stage to monitor changes in speed per change in gradient.

At the end of the five intervals the treadmill was reset to 0% grade and speed set at 10% below RCP power, and then participants underwent five 30 second intervals at 0, 2, 4, 6, and 8% incline. This was done to monitor changes in power as incline increases at a constant speed.

3.4 Data Analysis

3.4.1 Calculating Energy Expenditure and Metabolic Power

The metabolic cart sampled data from a mixing chamber every 10 seconds, so all metabolic gas exchange variables ($\dot{V}O_2$, $\dot{V}CO_2$, VE, RER, and breathing frequency) are recorded in discrete ten second time intervals. Stryd power samples at 60Hz, which meant there was 10 times the data from Stryd compared to Cosmed. To align Stryd and gas exchange data, power was averaged into 10-second bins and time matched with Cosmed output. This allowed for gas exchange data and Stryd power to be directly compared. For analysis of all variables at differing inclines, we averaged the final 60 seconds of every five-minute condition. With the metabolic cart, this meant averaging six data points, and with Stryd power this corresponded to six 10-second binned data points. Heart rate was recorded using a Polar watch, which samples every second, and 60-second averages were taken from the end of all 5-minute intervals.

There are multiple methods of EE and metabolic power based on $\dot{V}O_2$ and $\dot{V}CO_2$ that are outlined in a meta-analysis by Kipp et al. (2018). For this analysis, the formula by Péronnet and Massicotte was used for estimating EE in kJ/s which is easily converted to power (W).

$$EE\ (kJ/s) = (16.89 \times \dot{V}O_2\ (L/s)) + (4.84 \times \dot{V}CO_2\ (L/s))$$

In this formula, $\dot{V}O_2$ and $\dot{V}CO_2$ are converted to liters per second as opposed to the more conventional liters per minute. For analysis, the above formula for EE was applied to every $\dot{V}O_2$ and $\dot{V}CO_2$ data point with the final 60 seconds of every 5-minute interval averaged. To obtain EE in units of W, EE is simply multiplied by 1000. To calculate efficiency, running power is divided by the metabolic power calculated from EE to give a percentage.

$$ME\ (\%) = Stryd\ Power\ (W) / (EE\ (kJ/s) * 1000)$$

Finally, to measure changes in power across incline conditions, 10 second averages were calculated from each 30 second interval conducted at the end of visit two. A linear regression was then calculated to find the slope of power versus incline. A linear regression was also performed to find the change in speed across incline conditions. Speeds were manually altered for every 5-minute trial, so they were simply plotted against inclines.

3.4.2 Rating of perceived exertion

Rating of perceived exertion (RPE) was measured at the beginning and end of the ramp incremental on visit one of testing, and every 5 minutes during the constant load RCP trials on visit two. RPE was measured using the Borg 6-20 RPE scale.

3.5 Statistics

GraphPad Prism (10.4.1) and Microsoft Excel were used to compile and analyze participant descriptives, gas exchange data, and Stryd power outputs. One-way repeated ANOVAs were used to test the significance between $\dot{V}O_2$ uptake, heart rate, running economy, efficiency, RER, Ventilation, breathing frequency and RPE at varying inclines. If ANOVAs were significant, repeated measures were conducted using Fisher’s LSD multiple comparisons tests with 0% grade treated as the control condition. This strategy was used because statistical significance between other incline conditions is not relevant to this analysis, as we were interested in where differences from a baseline emerged.

Chapter IV: Results

4.1 Participant Characteristics

Participant age, height, weight, $\dot{V}O_{2max}$ and $\dot{V}O_2$ at GET and RCP are reported in the table below.

Table 4.1. Summary of participant characteristics.

Subject	Sex	Age (years)	Height (cm)	Weight (kg)	$\dot{V}O_{2max}$ (L/min)	$\dot{V}O_{2max}$ (mL/kg/min)	$\dot{V}O_2$ @ GET (L/min)	$\dot{V}O_2$ @ RCP (L/min)
1	F	38	170.0	60.4	3.20	53.0	2.40	2.90
2	M	38	181.0	68.2	3.80	57.5	2.50	3.00
3	M	21	186.5	86.3	5.20	60.0	3.60	4.30
4	M	35	183.0	74.8	4.70	63.1	2.80	3.40
5	M	34	167.0	62.4	3.90	62.5	2.60	3.30
6	F	22	167.0	67.0	3.00	44.0	2.20	2.60
7	M	25	191.0	70.2	4.70	66.5	2.80	3.85
8	F	22	172.0	67.2	2.50	37.8	2.15	2.70
9	M	19	183.0	76.7	4.70	61.6	3.35	4.25
Mean ± SD		**28 ± 8**	**177.8 ± 8.5**	**70.4 ± 7.6**	**3.97 ± 0.88**	**56.2 ± 9.1**	**2.71 ± 0.47**	**3.36 ± 0.60**

Maximal oxygen uptake, $\dot{V}O_{2max}$; oxygen uptake, $\dot{V}O_2$; gas exchange threshold, GET; respiratory compensation point, RCP. Data are reported as mean and standard deviation (M ± SD).

4.2 Effects of Incline on running metrics

One-way ANOVA testing showed a significant main effect of incline for $\dot{V}O_2$ (F = 5.29, df = 4p = 0.010), running economy (F = 379.4, df = 4; p < 0.001), metabolic power (F = 8.15, df = 4; p = 0.002), and efficiency (F = 8.37, df = 4; p = 0.001. As shown in Figure 4.1, significant differences from 0% were found at 6% and 8% inclines for $\dot{V}O_2$ (p = 0.012 & 0.022), metabolic power (p = 0.019 & 0.005), and running efficiency (p = 0.027 & 0.001). Running economy (Figure 4.1) was significant across all incline conditions (p < 0.001).

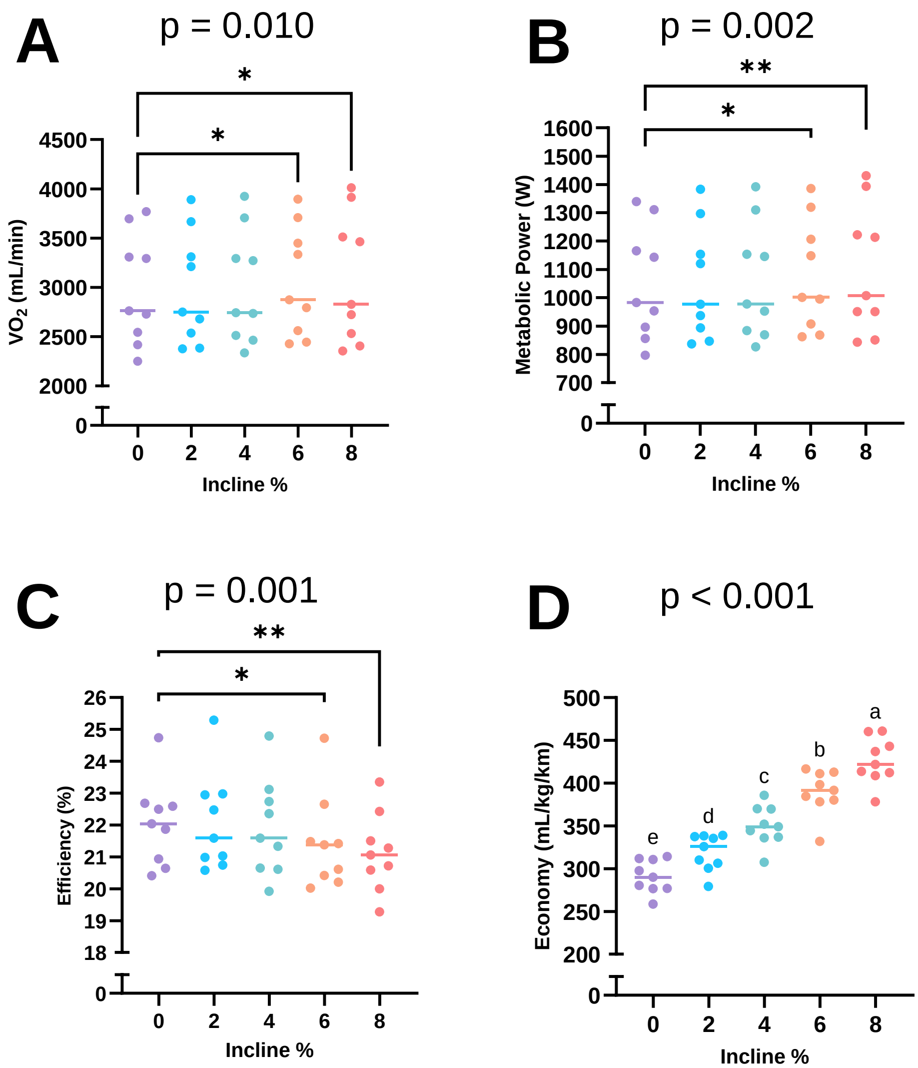

Figure 4.1. Running energetics for constant power treadmill running across 5 different incline conditions. Oxygen uptake ($\dot{V}O_2$; L/min; Panel A), metabolic power (W; Panel B), efficiency (%; Panel C), and economy (mL/kg/km; Panel D) are plotted separately. Each panel is a scatterplot encompassing all participant data with horizontal bars representing mean values and circles representing individual values. One-way ANOVA results are reported for each panel, and for post hoc tests, P values < 0.05 are denoted by * while p values < 0.01 are denoted by **. In panel D, conditions that do not share a letter are significantly different from one another. n=9 for all panels.

As shown in Figure 4.2, there was no significant difference for the main effect of incline for heart rate (F = 0.12, df = 4; p = 0.950), RPE (F = 0.26, df = 4; p = 0.819), ventilation (F = 0.67, df = 4; p = 0.572), breathing frequency (F = 1.21, df = 4; p = 0.320) or RER (F = 2.16, df = 4; p = 0.146).

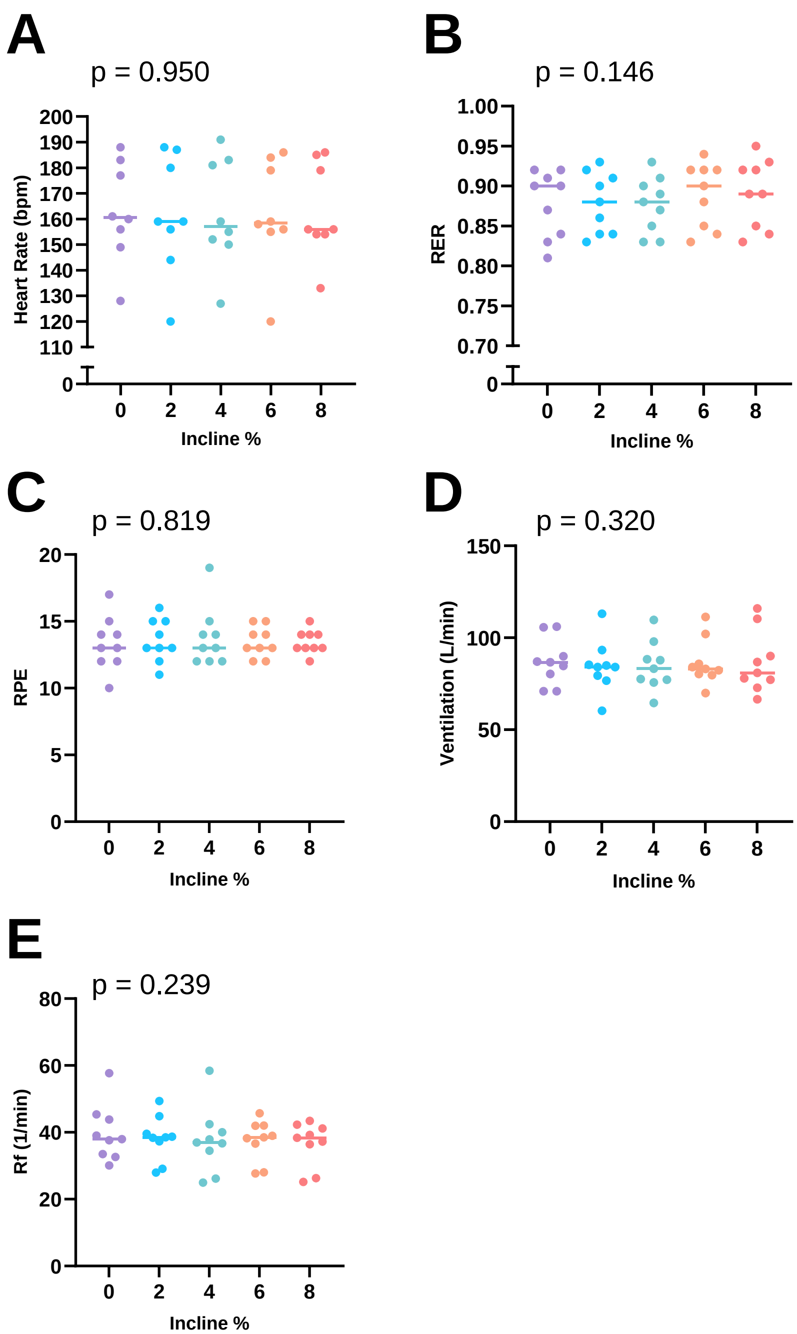

Figure 4.2. Physiological responses for constant power treadmill running across 5 different incline conditions. Heart rate (beats per minute; Panel A), RER (Panel B), RPE (Panel C), ventilation (L/min; Panel D) and breathing frequency (Rf; Panel E) Each panel is a scatterplot encompassing all participant data with horizontal bars representing mean values and circles representing individual values. One-way ANOVA results are reported for each panel. n=9 for all panels.

4.3 ANOVA Results for Interval Order

As shown in Figure 4.3, the interval order did not significantly affect $\dot{V}O_2$ (F = 1.94, df = 4; p = 0.170), metabolic power (F = 1.54, df = 4; p = 0.239), running efficiency (F = 1.55, df = 4; p = 0.234) or running economy (F = 0.09, df = 4; p = 0.913).

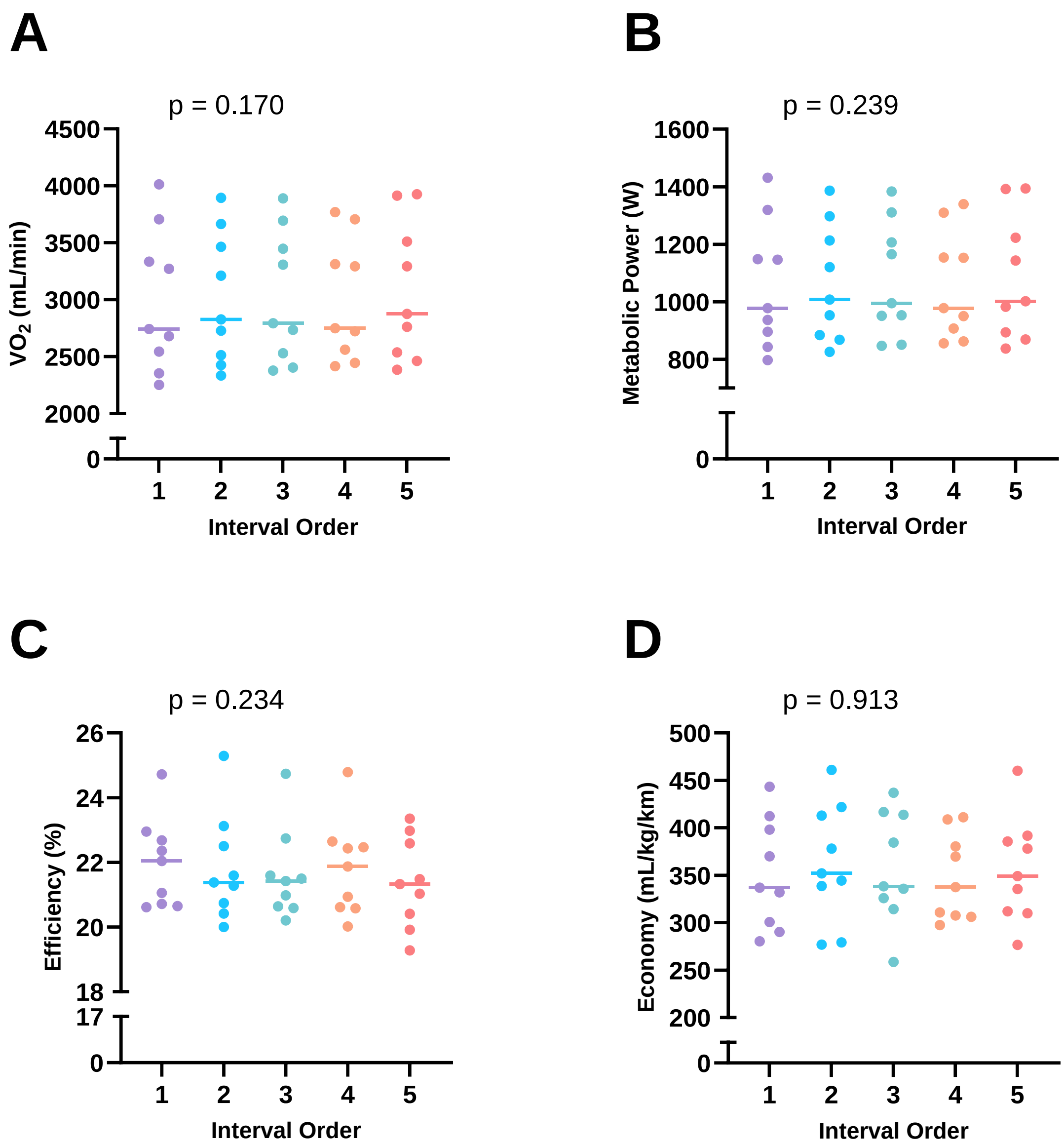

Figure 4.3. The influence of interval order on running energetics. Oxygen uptake ($\dot{V}O_2$; L/min; Panel A), metabolic power (W; Panel B), running efficiency (%; Panel C) and running economy (mL/kg/min; Panel D). Each panel is a scatterplot encompassing all participant data with horizontal bars representing mean values and circles representing individual values. One-way ANOVA results are reported for each panel. n=9 for all panels.

4.4 Linear Regression of Speed and Power

Linear regressions for speed and power across incline conditions were performed to see how speed and power are affected by incline. Among the nine participants, speed decreased by an average of 0.25mph (R^2 = 0.456) and power increased by 11.8W (R^2 = 0.328) per 1% increase in incline (Figure 4.4).

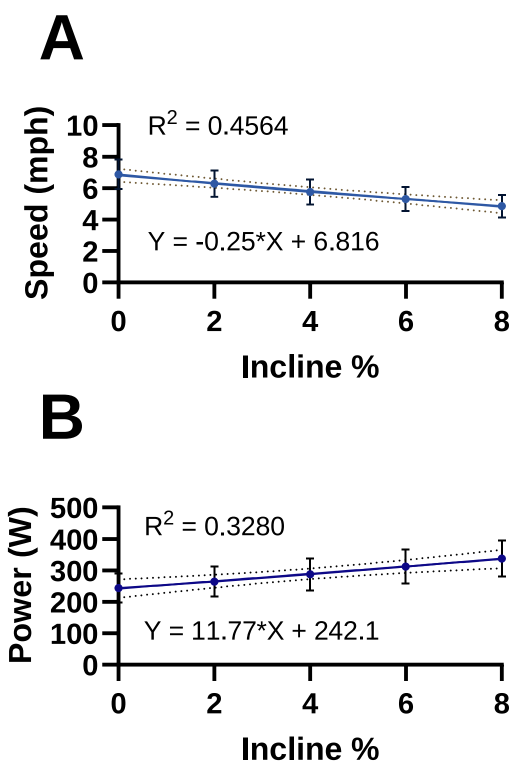

Figure 4.4. The independent effect of running incline on speed and power. When power output is held constant, speed decreased by ~0.25 mph/% (**A**). When speed was held constant, power output increased by ~12 W/% (**B**). The mean ± SD, regression line, R^2, and 95% confidence interval are plotted. n=9 for all panels.

Linear Regression of Economy

Linear regression for economy across incline conditions was performed to see how economy was affected by incline (Figure 4.5). Among the nine participants, economy increased ~17mL/kg/km per increase in incline.

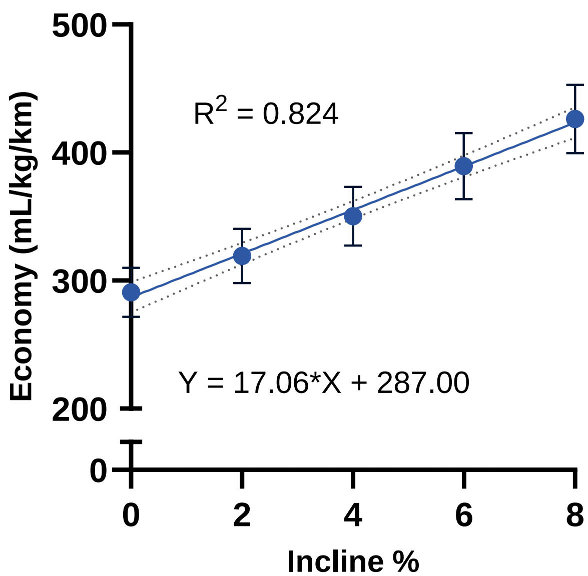

Figure 4.5. The independent effect of incline on running economy. Linear regression shows running economy increasing by ~17 (mL/kg/km/%). The mean ± SD, regression line, R^2, and 95% confidence interval are plotted. n=9.

Chapter V: Discussion

5.1 Stryd Power and Running Efficiency

Comparisons of metabolic power and Stryd power data demonstrated that mechanical efficiency (ME) is not constant across incline conditions, with 6% and 8% incline being significantly less efficient than 0% grade. ME in this study ranged from 20-25% on flat terrain and decreased ~1% at steeper inclines which equates to a ~4% reduction in ME. As the metabolic power changed for a fixed external power, Stryd running power is not a perfect measure of internal training load on inclined terrain; therefore, is likely not an accurate tool for prescribing and monitoring running exercise intensity on steeper grades. Although, as the changes in efficiency are relatively small and occur at inclines greater than 6%, the overall impact on monitoring and prescription could be minor, particularly when most running is performed at flat or less steep inclines.

5.2 Stryd Power and Internal Training Load

Analysis found a significant difference between $\dot{V}O_2$ and metabolic power at steeper incline conditions with 8% grade demonstrating a greater disconnect between Stryd power and internal training load compared to 6%. At those steeper inclines, $\dot{V}O_2$ increased ~2.5-3.5% while metabolic power saw an increase of ~2.5-4%. These findings are in-line with previous research on ME and inclined terrain, which have found that shifts in running mechanics (Roberts & Belliveau, 2005) resulting in increased work and energy demand at the hip (Vernillo et al., 2017). Furthermore, reduced elastic tendon return (Schroeder & Kuo, 2021) caused reduced efficiency along variable terrain. This type of research tends to focus on alterations in biomechanics and muscle activity and has not focused on changes in internal training load represented by $\dot{V}O_2$ or metabolic power. There is some literature showing shifts in running economy, measured in mL/kg/km and mL/kg/min (Austin et al., 2018; Balducci et al., 2016), from flat to inclined terrain, which was theorized to cause changes in ME, but there was no comparison of economy or metabolic power to an external running power device to reflect potential changes in efficiency so the effect on ME is unknown.

Although conditions were randomized, the relatively small sample size could lead to an order effect wherein previous condition(s) could impact subsequent conditions. For $\dot{V}O_2$, metabolic power, efficiency, and economy, the interval order was tested to ensure significant results were not being observed due to runners fatiguing over the course of the testing protocol. The lack of significance gave confidence that the significant differences observed were due to incline and not fatigue due to testing.

5.3 Running Economy and Incline

Linear regression of economy demonstrated an increase of ~17 mL/kg/km per increase in incline which equated to a ~6% change. It was expected to observe an increase in economy as gradient became steeper, but knowing the exact change is somewhat difficult to establish from existing literature. This is because researchers will measure economy in different ways and with different units (e.g. mL/kg/km, mL/kg/min, or J/kg/km), and at incline levels that are somewhat far apart making regression analysis sometimes non-existent (Balducci et al., 2016; Lussiana et al., 2013; Snyder & Farley, 2011). The regression done in Figure 4.5 offers good insight into how economy changes across incremental increases in grade; although, it does not encompass inclines beyond 8% where steeper terrain may cause greater increases in economy.

5.4 Stryd Power and Breathing

Despite increased $\dot{V}O_2$ at steeper inclines, there was no change in breathing frequency or ventilation across conditions. This meant runners were able to accommodate an increasing $\dot{V}O_2$ without needing to increase breathing significantly. Normally it would be expected that an increase in $\dot{V}O_2$ would coincide with increased ventilation and breathing frequency (Carey et al., 2008; Forster et al., 2012). It is unclear whether runners in this study were able to adapt to increased internal load by increasing the efficiency of their breathing or if these are type 2 errors owing to small sample sizes.

5.5 Stryd Power and Heart Rate

Results show that heart rate did not change across incline conditions despite a significant increase in $\dot{V}O_2$. This is an interesting finding since heart rate is one of three critical components of the Fick equation, and it would be expected that heart rate would increase with $\dot{V}O_2$ as the two are typically highly correlated with each other especially among highly trained runners (Reis et al., 2011). It is possible stroke volume increased alongside $\dot{V}O_2$ to meet increased cardiac output demands, or the significant increases in $\dot{V}O_2$ were modest enough that no (statistically significant) increase in Q was required to sustain an increased uptake. Either way, heart rate was unaffected by incline conditions and seemed to be reflective of constant load Stryd power.

5.6 Stryd Power and RER

Increases in metabolic power represent an increase in internal training load that could have resulted in increased glycolysis to meet energy demands. This study showed no significant difference in RER values across incline conditions, so substrate utilization was unchanged despite noted increases in $\dot{V}O_2$ at steeper inclines.

5.7 Study Limitations

There are a few limitations to this study that should be considered for future research. The first is the lack of consensus on how to define running power. This study builds upon previous research and Stryd testing protocols used within this lab (Van Rassel et al., 2023), and while this study found significant differences in $\dot{V}O_2$, metabolic power and efficiency at differing inclines, other running power devices may not find the same results. In relation to Stryd pods, it is not clear how Stryd calculates running power, which limits full confidence in this study's findings. It has been previously established that Stryd pods are reliable (Van Rassel et al., 2023), but without an agreed upon definition of running power efforts to measure changes in efficiency are approximations.

The length of running trials during day two of testing was relatively short and, while participants were running at a steady state below their RCP, it is possible longer trials would elicit greater changes in $\dot{V}O_2$ at lesser inclines if given ample time for changing biomechanics and energy demand to manifest.

5.8 Future Directions

This study took place indoors on a treadmill, and ideally Stryd pods would be tested outdoors on naturally varying terrain. The Stryd IMU tracks movement in 3D space and computes incline by tracking changes in foot displacement, allowing Stryd to measure distance and elevation as you walk or run along a trail. On a treadmill your foot displacement is zero, so corrections are made within the app to accommodate running where a participant is, effectively, staying in the same spot. It is possible the adjustment for indoor running gives a less accurate Stryd power output which could potentially be distorting results.

It would also be interesting to incorporate more IMUs and muscle electromyography to measure any potential changes in kinetics, kinematics and muscle recruitment as participants run along varied terrain. This can offer insights into how running form changes through a range of incline conditions.

Another next step could also be to increase the range of running inclines to go beyond 8% and include negative gradients to see how metabolic power and efficiency change as runners experience greater terrain variation.

5.9 Conclusion

This study found significant differences in $\dot{V}O_2$ and metabolic power at running inclines of 6% and 8%, resulting, respectively, in a ~2.8-4% reduction in running efficiency. Incline condition had no effect on other variables such as breathing frequency, ventilation, heart rate, RPE and RER.

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