Exercise Science

Curtin School of Allied Health

Developing Future Champions: Sport-Specific Motor Skill Performance in Youth Triathlon

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1.0 Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

The research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007) – updated March 2014. The proposed research study received human research ethics approval from the Curtin University Human Research Ethics Committee (EC00262), Approval Numbers #2020-0682, #2021-0071, #2022-0048.

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2.0 Acknowledgements

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4.0 Abstract

Introduction: Triathlon is a relatively new sport that has gained popularity over the last 45 years, culminating in its representation in two Olympic racing formats. As an endurance sport, the surrounding literature heavily emphasises describing and developing physiological capacity. However, understanding the motor skills that govern the biomechanics of swimming, cycling, and running is also crucial, as the biomechanical quality of these motor skills impacts the speed and efficiency of movement. Currently, there is no consensus in the scientific literature regarding the motor skills performed during elite triathlon. Additionally, how these motor skills are learned over time is not well understood. Therefore, the aim of this thesis is to investigate how the performance of important triathlon motor skills changes over time and identify any common factors that affect these changes.

Method: In study one, 25 stakeholders in Australian triathlete development (Mage = 41 years, SD = 12.3 years; male: n = 20, female: n = 5) participated in semi-structured interviews to gain novel insights into the beliefs, attitudes, and experiences of these stakeholders regarding the important motor skills for elite triathlon success. In study two, seven triathletes (female: n = 3, male: n = 4; Mage = 16.29 ± 2.5 years) participated in a sprint-distance triathlon, which was simultaneously filmed and monitored by a single trunk-mounted wearable IMU to validate the measurement of swimming strokes, cycling pedal strokes, and running strides. Following this, in study three, a peak detection algorithm and machine learning model were created for use in triathlon to automatically detect and measure triathlon motor skills. Finally, in study four, 12 junior triathletes (female: n = 4, male: n = 8; Mage = 16.85 ± 1.16 years; average time in sport = 4.15 ± 1.74 years) wore a wearable IMU during every race for two years to understand how triathlon motor skill performance changes over time.

Results: Study one identified that stakeholders in Australian triathlon believe it is essential to train the invariant features of the motor skills required for each discipline, as well as relevant discrete skills such as cornering, change of direction, and transition skills. They also emphasised the importance of training adaptability in performance to different environmental and task contexts. The results of studies two and three demonstrated that a single trunk-mounted IMU could validly measure and automatically detect movement cadence in triathlon; however, further investigation is required to validate changes in cycling subtasks to create a more comprehensive measurement tool. The final study found substantial individual variation in changes in movement cadence over time, but there was a positive, non-significant trend of improvement over the course of the two seasons. Furthermore, changes in movement cadence were largely influenced by temporal factors and the coaching received.

Conclusion: The investigations performed in this thesis demonstrate a ‘roadmap’ to identifying the important motor skills for success at the elite level in a sport, create a measurement tool to measure motor skills performance with high ecological validity and practical utility, and monitor changes in motor skill performance to demonstrate how performance changes over time.

5.0 Contents

6.0 List of Abbreviations and Terminology

6.1 Abbreviations

ANOVA; Analysis of variance

AT#; Administrator or technical official number

C#; Coach participant number

CI; Confidence interval

COM; Centre of mass

CNN; Convolutional neural network

FTEM; Foundations, Talent, Elite and Mastery framework

GMP; Generalised motor program

GPS; Global positioning system

Hz; Hertz

IMU; Inertial measurement unit

LoA; Limits of agreement

LTAD; Long Term Athletic Development

Mage; Mean age

MEMS; Micro-electromechanical systems

ŋ^2; partial eta squared

POT#; Parent of triathlete number

RMSEP; Root mean square error prediction

ROM; Range of motion

RPM; Revolutions per minute

SD; Standard deviation

SS#; Support staff participant number

STFT; Short-Time Fourier transform

TA; Triathlon Australia

TRI#; Triathlete participant number

6.2 Terminology

1) ‘Wearable Sensor’ and ‘Inertial Measurement Unit’ (IMU)

The term ‘wearable sensor’ has been used initially to refer to a measurement device worn by participants in this research that collects movement information and allows it to be combined to infer the gross movements of the wearer. As the research has progressed, I have begun to recognise that this term does not accurately reflect the operation of the technology. A more accurate description of the measurement tool used in this thesis is that it contains multiple sensors, each providing a different stream of information: tri-axial linear acceleration (accelerometer), tri-axial angular acceleration (gyroscope), and global position coordinates (GPS). These sensors are housed together in an “inertial measurement unit” (IMU); thus, the measurement tool should be termed as a ‘wearable IMU’ rather than a ‘wearable sensor’.

As Chapters 2, 3 and 4 are either published or under peer review it would be inappropriate to change the terminology. Therefore, I would like to acknowledge that there will be some inconsistencies between the chapters and ask that these terms be regarded as synonymous.

7.0 List of Tables

8.0 List of Figures

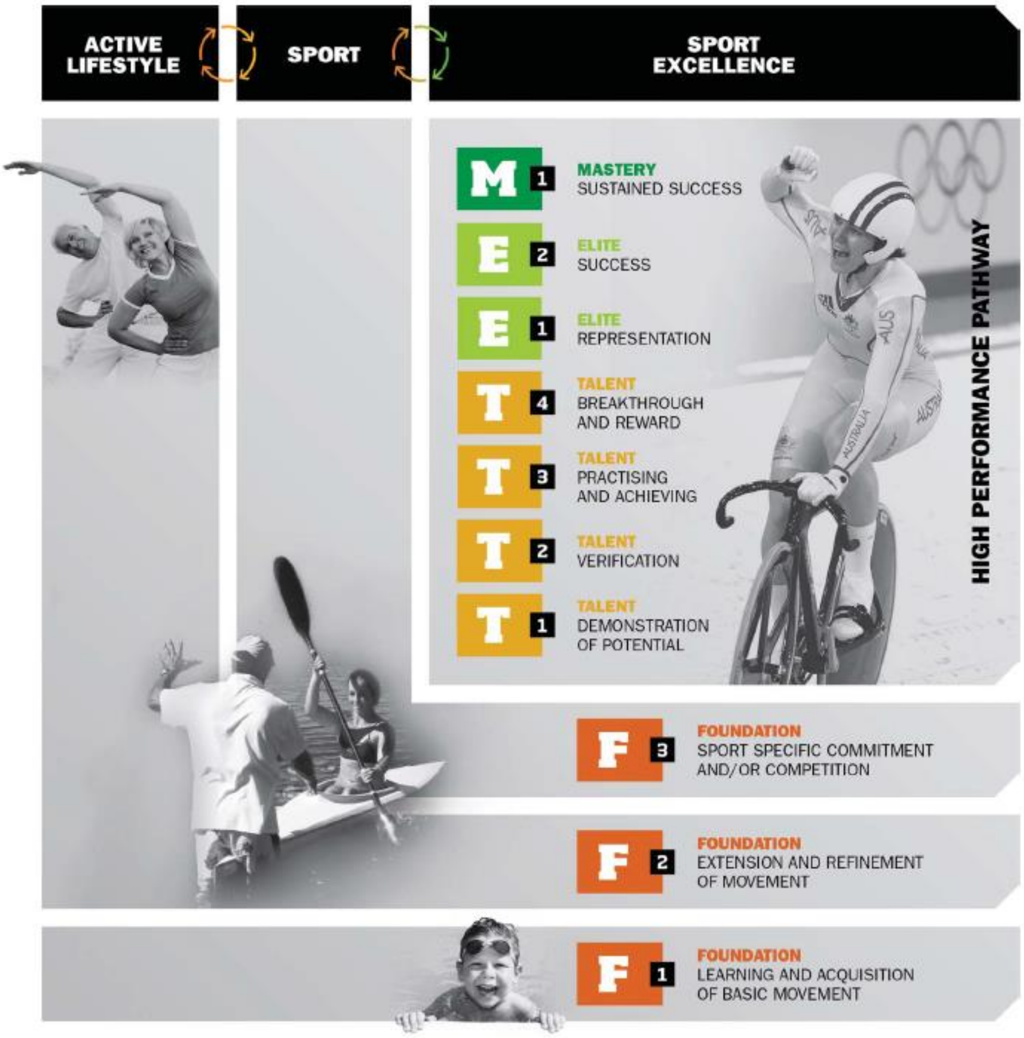
9.0 Chapter 1: Literature Review

9.1 Youth Athletic Development in Triathlon

At the 2000 Olympic games in Sydney, Australia, the growing popularity of triathlon resulted in the “Olympic distance” triathlon (1.5 km swim, 40 km cycle, and 10 km run) being included for the first time in an Olympic games (Markus & Arimany, 2020). In the modern era, professional triathlon racing is mostly completed over relatively short distances rather than long duration Ironman triathlons, which take more than seven hours to complete. The popularisation of shorter-duration triathlons has culminated in the recent creation of the “super-sprint” format, where triathletes race at distances of up to 400 m swim, 10 km cycle, and 2.5 km run (Walsh, 2019). Short distance triathlon racing has proven substantially more popular with spectators, evident by the emergence of Super League Triathlon, which focusses on short and exciting triathlon formats where competitors can complete a triathlon in under 15 minutes. The rise in popularity of shorter duration triathlons has also coincided with the inclusion of the mixed team relay in the Tokyo 2020 Olympics. Triathlon’s Olympic sport status and the prize money offered by professional triathlon leagues like Super League, create substantial interest in developing and optimising elite triathlon performance. As a consequence of differences in physical requirements, strategies, and skills (i.e. drafting) between ‘Ironman’ and short distance triathlons, triathletes tend to specialise in one of the formats (Bentley et al., 2002). Thus, long and short distance triathlons should be investigated separately.

Triathlon has typically been viewed as a ‘late specialisation’ sport where triathletes begin competing in their adolescence but remain competitive for longer than athletes in most strength and power sports (Baker et al., 2006). However, shorter duration triathlons which are more accessible, have begun to make it an attractive sport for younger children to participate in. With the introduction of younger triathletes participating in triathlon, principles of ‘long term athletic development' (LTAD) are important so that coaches can ensure that training remains age appropriate (Balyi et al., 2013). There are several athletic development models (Balyi & Hamilton, 2004; Côté, 1999; Ericsson et al., 1993; Gulbin et al., 2013). Three predominant models are the ‘LTAD’ model (Balyi & Hamilton, 2004), Foundations, Talent, Elite and Mastery framework (FTEM) (Gulbin et al., 2013), and the Developmental Model of Sports Participation (Côté, 1999). All these models focus on a holistic approach to developing athletic performance over time with consistent and age-appropriate training that emphasises a gradual progression towards specialisation in later years (Till et al., 2022). Specifically, the FTEM model (Figure 1) will be referred to throughout this thesis as it has been widely adopted in Australia by national sporting organisations and provides a contextually relevant and ecologically valid framework to discuss triathlete development (Côté & Vierimaa, 2014).

Figure 1. *The Integrated FTEM Framework for Sport and Athletic Development*



Note. From An Integrated Framework for the Optimisation of Sport and Athlete Development: A Practitioner Approach, by J. P. Gulbin, M. J. Croser, E. J. Morley, J. R. Weissensteiner, 2013, *Journal of Sports Sciences, 31(12),* pg. 1323 (10.1080/02640414.2013.781661). Copyright 2013 by Routledge.

Following the principles of the FTEM framework, the early stages of sport participation should focus primarily on learning and improving the skills required to participate in the sport, through an approach centred around deliberate play, supported with some deliberate practise (Gulbin et al., 2013). Then, as athletes progress to the end of the ‘Foundations’ stage, there is an increased focus on training, practise and competition. Once an athlete is recognised as ‘talented’ they are considered to be within a high performance pathway and demonstrate “measurable gifts or talents in one or more of the physical, physiological, psychological, and skill domains” (Gulbin et al., 2013, p. 1325). Gulbin et al. (2013) deliberately put no age recommendations or boundaries on progression through the framework as there is a large variation in possible methods and speeds of progression. However, the emphasis on play, supported with some deliberate practise in the foundation stages highlights motor skill development during a time when children experience increased neural plasticity and a propensity to learn and improve motor skills (Tymofiyeva & Gaschler, 2021). During this period, children are also less responsive to cardiovascular fitness training as they have not gained the physical size required to support physiological adaptations (Borms, 1986).

Within the overarching framework of FTEM, it is also important to identify the determinants of performance at the elite levels of competition to guide the training of young triathletes. It is well understood that triathletes require high levels of cardiovascular fitness, their bodies need to be injury resistant, and they require efficient and effective movement biomechanics (Etxebarria et al., 2019). Suriano and Bishop (2010) reported that adult male triathletes recorded very high $\dot{V}O_{2max}$ values (as high as 78.5 $ml.kg^{-1}min^{-1}$) during running. This is consistent with Degens et al. (2019) who compared $\dot{V}O_{2max}$ values of endurance, power, and team sport athletes to healthy non-athletic populations and found endurance athletes had significantly higher $\dot{V}O_{2max}$ results than all three comparisons ($p < 0.001$). To attain the required levels of cardiovascular fitness, high volumes of continuous training are typically prescribed, which can increase the risk of children suffering burnout and/or overuse injuries (Bergeon et al., 2015; Wall & Côté, 2007). Therefore, this style of training young triathletes should be undertaken with caution and is better emphasised in later stages of development.

While a high level of aerobic power ($\dot{V}O_{2max}$) is a clear requirement for elite performance in triathlon, it has been shown that elite triathletes who experience success and those who do not differ very little in their $\dot{V}O_{2max}$ (Nevill et al., 2003;

Schneider & Pollack, 1991). These authors instead suggest that a performance determinant such as movement economy is much better for discerning between successful and non-successful endurance athletes at the elite level. Movement economy describes the amount of energy used per unit of work and is positively influenced by the biomechanics of movement (Candotti et al., 2009; Swinnen et al., 2018; Toussaint, 1990). The study of human biomechanics is primarily concerned with understanding the structure, anatomy, and movement of the human body (McGinnis, 2013). Furthermore, sport and exercise biomechanics aims to understand human movement, with particular interest in the forces involved in sports and exercise to obtain performance improvements (McGinnis, 2013). However, the study of biomechanics does not tend to be concerned with how movement is learned or controlled. When training for any sport, practitioners should also consider how motor control and learning govern the biomechanics of movement so they can understand how to improve the biomechanics of motor skills. Given that children experience higher levels of neural plasticity (Tymofiyeva & Gaschler, 2021), it is therefore sensible to prioritise teaching swimming, cycling, and running motor skills to young triathletes before prioritising the development of physical qualities like cardiovascular fitness.

9.2 Performance Determinants in Triathlon

9.2.1 Physiological Determinants of Triathlon Performance

An understanding of performance determinants at the elite level is essential for coaches and sport scientists when training triathletes. As an endurance sport, there is considerable interest in enhancing triathletes' endurance through aerobic capacity training (Borrego-Sánchez et al., 2021; Millet et al., 2011; Suriano & Bishop, 2010). The most commonly identified determinant of aerobic performance is $\dot{V}O_{2max}$ (Cuba-Dorado et al., 2022; Suriano & Bishop, 2010), which represents the physiological capacity for oxygen consumption and aerobic energy transfer. Additionally, $\dot{V}O_{2max}$ is positively correlated with success in triathlon and its component disciplines (O'Toole & Douglas, 1995; Sleivert & Rowlands, 1996; Sleivert & Wenger, 1993). Increases in $\dot{V}O_{2max}$ result from increased stroke volume due to left ventricle enlargement in response to cardiovascular endurance training (Cuba-Dorado et al., 2022). It is common for male triathletes to achieve relative $\dot{V}O_{2max}$ values greater than 70 mL/kg^{-1}/min^{-1} at elite levels, compared to 55 to 67 and mL/kg^{-1}/min^{-1} at recreational levels (Sleivert & Rowlands, 1996). Female triathletes exhibit similar trends, scoring approximately 65 mL/kg^{-1}/min^{-1} and 44 to 60 mL/kg^{-1}/min^{-1} at elite and recreational levels respectively (Cuba-Dorado et al., 2022; Sleivert & Rowlands, 1996). Additionally, there is a moderate to strong relationship between relative $\dot{V}O_{2max}$ and race performance in each discipline ($r = -049, -0.78$, and -0.84 for swimming, cycling, and running) (Sleivert & Rowlands, 1996). However, the association between race performance and $\dot{V}O2max$ diminishes when elite triathletes are compared to one another.

To gain a more comprehensive understanding of elite aerobic performance, it is recommended to measure additional variables such as lactate threshold (LT) and ventilatory threshold (VT) (Borrego-Sánchez et al., 2021; Millet et al., 2011; Suriano & Bishop, 2010). The LT is defined as the limit of work that can be sustained before blood lactate accumulates faster than it can be cleared, serving as an important performance variable (Todd, 2014). Substantial rises in blood lactate are a biomarker for greater glucose utilisation and the generation of metabolic byproducts like hydrogen ions during exercise (Todd, 2014). This has pacing implications for triathletes, as exercising at intensities above this threshold for too long may result in negative performance outcomes. Individual LTs are dependent on aerobic fitness, muscle fibre size, and muscle fibre type distribution (Suriano & Bishop, 2010).

Additionally, VT represents the limit of work rate where carbon dioxide expiration exceeds oxygen consumption, resulting in higher ventilatory rate and greater lactate production. Both thresholds often occur at similar percentages of $\dot{V}O_{2max}$ (81 – 88% in elite male triathletes) (Cuba-Dorado et al., 2022; Sleivert & Rowlands, 1996; Suriano & Bishop, 2010). Suriano and Bishop (2010) have reported that among a homogenous group of well-trained cyclists, LT and VT have a strong correlation with performance ($r = 0.90$) and are better differentiators of performance when participants had similar $\dot{V}O_{2max}$.

Beyond $\dot{V}O_{2max}$, LT, and VT, movement economy is also recognised as an important physiological determinant of triathlon performance and is defined as the amount of oxygen consumed per unit of movement (O'Toole & Douglas, 1995). In other words, for a given effort in any discipline, the individual with the greatest movement economy uses the least oxygen for the same work (Bonacci et al., 2009; O'Toole & Douglas, 1995). When comparing triathletes to single discipline swimmers, cyclists, and runners, single discipline athletes have repeatedly demonstrated better movement economy in their specific discipline than triathletes (Candotti et al., 2009; Swinnen et al., 2018; Toussaint, 1990). Research by Candotti et al. (2009); Swinnen et al. (2018) and Toussaint (1990) all attributed lower movement economy in triathletes to inferior technique, and suggested that triathletes should practise swimming, cycling, and running technique to achieve more economical movement. Furthermore, Dengel et al. (1989) identified a positive relationship between movement economy and triathlon race performance (swimming: $r = 0.91$; cycling: $r = 0.78$; and running: $r = 0.87$) (Dengel et al., 1989), highlighting the link between physiological factors and movement control, where athletes with superior motor skills exhibit greater energy efficiency.

Overall, the literature indicates that elite triathlon performance is achieved by maximising aerobic energy production ($\dot{V}O_{2max}$), raising the threshold of exercise at which lactate is produced and practising swimming, cycling, and running skills to move more economically. As triathletes must balance training across three modes of locomotion, understanding the central control of swimming, cycling, and running is essential for maximising training effectiveness during practise (O'Toole & Douglas, 1995).

9.2.2 Biomechanical Determinants of Triathlon Performance

While a complete review of the biomechanics required for triathlon success has not yet been published, investigations into the biomechanical determinants of performance in individual disciplines have been conducted (Preece et al., 2019; Ribeiro et al., 2017; Turpin & Watier, 2020). In each discipline, performance is determined in approximately the same way, the mechanical work produced per unit of distance versus the energy cost of that movement. In swimming, the mechanical work performed is determined by the timing (co-ordination pattern and stroke frequency) and stroke length generated by the swimmers propulsive actions (Ribeiro et al., 2017; Seifert et al., 2004). The energy cost of movement depends on limb kinematics, stroke coordination patterns and the swimmer's ability to overcome drag (Figueiredo et al., 2013; Figueiredo et al., 2011). Although this research was conducted in a pool, considerable transfer to open-water swimming (predominant format in the triathlon swim leg) is likely, albeit with increased unpredictability due to the open environment.

The biomechanical determinants of cycling performance have been reviewed by Turpin and Watier (2020), who explained that maintaining a high power output over time is the primary determinant of performance. Maximal power at the pedal crank is determined by the orthogonal forces known as "effective forces" multiplied by the angular velocity of the pedals (Turpin & Watier, 2020, p. 3). However, even elite cyclists do not always produce purely effective force, as force is often not optimised in positions that allow the cyclist to produce completely orthogonal forces. Both effective forces and pedal velocity are influenced by muscular properties, such as force-length and force-velocity relationships, meaning that the bike setup and cadence that produce optimal power are highly individual. Furthermore, the cost of forward movement is affected by the combined mass of the bike and cyclist, aerodynamic and wheel friction drag forces, gravitational resistance (depending on road incline), and gear selection (Turpin & Watier, 2020). Turpin and Watier (2020) described the relationship between motor control and biomechanics in cycling as the cyclist's coordination and force application on the pedals serving as the 'input' that determines the total 'output' of power. However, while the output (biomechanics) can be measured and explained in detail, the input (motor control) remains poorly understood.

Like swimming and cycling, the performance goal of endurance running is to optimise running power output against the energy cost. However, fluid drag is less substantial compared to swimming and cycling, and kinetic energy recycling occurs via the stretch shortening cycle. In running, both velocity and economy are determined primarily by the kinematics and spatiotemporal properties of the running stride (Moore, 2016; Pizzuto et al., 2019; Preece et al., 2019). Preece et al. (2019) identified biomechanical differences between elite endurance runners and recreational runners while controlling for the difference in running speeds between the two groups. Elite endurance runners showed increased vertical impulse and centre of mass (COM) velocity, with longer flight times, while managing to maintain a more vertical shank angle and mid to forefoot strike position underneath the COM. While greater vertical fluctuations of the COM are associated with lower running performance (Folland et al., 2017), Preece et al. (2019) identified that vertical COM oscillation was deleterious during the stance phase and that vertical COM velocity at toe off was required to achieve greater stride length.

Running economy has been extensively investigated, and while there is some conflict and ambiguity in the literature regarding the exact determinants that influence running economy, some suggestions are: knee flexion/extension range of motion (ROM) during stance phase; knee and hip adduction/abduction ROM during stance phase (Pizzuto et al., 2019); stride length; vertical displacement of the COM; ground contact times; and foot placement (Moore, 2016). Additionally, running performance has the highest relationship (r = 0.82) with short-course triathlon success (Etxebarria et al., 2021). It is not clear exactly why this relationship exists, however, Etxebarria et al. (2021) suggest that it may be due to the high unpredictability of the swimming and cycling legs. Nonetheless, understanding the learning and control of this motor skill is important.

9.2.3 The Cadence of Movement in Triathlon

A common determinant of performance analysed by athletes, scientists and coaches in triathlon is movement cadence, defined as the frequency of locomotive movements in a specified period (usually one minute) (Tudor-Locke et al., 2018). Terms such as stroke frequency in swimming (Ribeiro et al., 2017) and stride frequency in running (Moore, 2016) are used to refer to movement cadence, while ‘cycling cadence’ or ‘revolutions per minute’ (RPM) is used in cycling (Turpin & Watier, 2020). In swimming and running, movement cadence is intrinsically linked to stroke or stride length (McLean et al., 2010). When movement velocity is kept constant, any changes in stroke or stride frequency are reflected by inverse changes in stroke or stride length (McLean et al., 2010). These changes are predicated on the force-velocity relationship of muscle contractions, where muscles can produce smaller amounts of force more quickly than larger forces (Hill, 1922; Wilkie, 1949). Over time, improvements in the frequency or force of movement that exceed the reductions in the opposing variable will result in greater movement velocity. However, in cycling, this relationship is more difficult to measure, as the length of the pedal cycle is constrained by the pedal crank, and gearing systems allow for substantial variation in movement velocity for the same cycling cadence (Hay, 2002).

In swimming, stroke frequency affects physiological and motor skill determinants of performance independently from increases in speed. Investigations into swimming motor skills have shown that stroke frequency is highly correlated with coordination between the propulsive action of the arms (Seifert et al., 2015; Seifert et al., 2010). Additionally, for a swimming speed of 1 m/s, researchers found that oxygen consumption, heart rate and rating of perceived exertion increased when stroke rate was reduced from an individual's preferential stroke rate, but not when it was increased (McLean et al., 2010). This may relate to kicking activity, which increased when stroke rate decreased to maintain buoyancy (McLean et al., 2010). Furthermore, the index of coordination increases significantly when stroke rate is increased, resulting in a greater dominance of superposition, a stroke coordination type that features overlapping propulsive phases (Simbaña-Escobar et al., 2020).

In cycling, alterations in cadence significantly affect key performance metrics (Foss & Hallén, 2005). Cycling at 80-100 RPM has been shown to significantly improve race completion time, gross efficiency measured by accumulated $\dot{V}O_2$, and energy turnover rate (Foss & Hallén, 2005; Leirdal & Ettema, 2011). However, some conflict in the literature exists, with one review reporting that many investigations show that cycling efficiency is greater at lower cadences (around 60 RPM) (Ettema & Lorås, 2009). In these investigations participants were working at relatively low average work rates (~125 Watts) compared to elite cycling (~350 Watts) (Ettema & Lorås, 2009). The authors suggest that when work rate increases to elite levels, high movement cadences become more efficient, indicating that the optimum cadence is closely tied to work rate (Ettema & Lorås, 2009; Foss & Hallén, 2005). Additionally, altering cycling cadence also affects the kinetics and kinematics of cycling motor skills independently from changes in cycling work rate. Changes in cycling cadence influence the relative power provided by the hip and knee joint (Aasvold et al., 2019), range of motion in the ankle and activation of calf muscles (Sanderson et al., 2006), and activation of gluteus maximus, biceps femoris, semimembranosus, and vastus medialis (Hug & Dorel, 2009). There is also a trend for peak EMG activity to occur earlier in the pedalling cycle when pedalling rate is increased, while work rate remains constant (Hug & Dorel, 2009).

Investigations of stride frequency in running show that when runners perform a test at 80% of VT, they tend to use a lower stride frequency than that which optimises energy cost (de Ruiter et al., 2014). As runners gained experience, they tended to increase their stride frequency, reducing the gap between self-selected and optimal frequencies (de Ruiter et al., 2014). This is supported by findings showing that elite endurance runners typically have shorter overall stride lengths due to faster stride rates (Anderson, 1996). This suggests that the ability to modulate stride rate to optimise stride length is dependent on expertise and can be modified through intentional training strategies (Williams et al., 2019).

It is evident that changes in movement cadence have a myriad of effects on physiological and motor skill determinants of performance in triathlon, making it a valuable performance metric for developing elite triathletes. Interestingly, in each discipline, as athletes became more elite, the movement cadence that resulted in the greatest energy efficiency increased or surpassed their self-selected frequency of movement (de Ruiter et al., 2014; Ettema & Lorås, 2009; Foss & Hallén, 2005; McLean et al., 2010).

9.2.4 Motor Control in Triathlon

As summarised above, triathletes require well developed endurance physiology and motor skills to achieve biomechanically effective movement for success. Even though the acquisition of high-quality swimming, cycling, and running motor skills is required for effective movement biomechanics, our understanding of motor skill control in triathlon remains limited. So far, investigations have explored limb coordination in front crawl swimming, leading to the creation of ‘index of coordination’, which measures lag time between propulsive phases (Silva et al., 2022). This research also identified distinct front crawl swimming techniques including catch-up, opposition, and superposition. In cycling, investigations are demonstrating that muscle coordination can be voluntarily adjusted using a conditioning procedure (Torricelli et al., 2020), and while assessments of motor coordination are being explored for their predictive utility in identifying future talent, success has been limited (Mostaert et al., 2022).

Research has also examined phase transitions from walking to running. As walking speed increases, a spontaneous transition to running gait occurs, initiated by changes in muscle activation timings during the swing and stance phases of the gait cycle (Cappellini et al., 2006). More recently, Wilson and Likens (2023) systematically reviewed the variability of motor control during running gait, showing long range correlations between steps. However, research on motor control in triathlon is primarily limited to studies of muscle recruitment patterns in running, particularly immediately after cycling (Bonacci et al., 2009), or in comparisons between triathletes and single-discipline athletes (Chapman et al., 2007). While progress is being made in understanding motor coordination across all triathlon disciplines, the central control mechanisms governing swimming, cycling, and running remain unidentified.

9.3 The Control of Human Movement

Research on motor learning has been prominent for over a century, beginning with a PhD by Woodworth (1899) titled “The Accuracy of Voluntary Movement,” which investigated the central nervous system's role in intentional movement. Motor skills are defined as “activities or tasks that require voluntary control over movements of the joints and body segments to achieve a goal” (Magill & Anderson, 2014, p. 1), where the quality of movement is the primary determinant of success. The study of motor skill acquisition aims to understand how skilled human movement is learned, remembered, performed, and adapted, to enhance the quality of various movement skills. While there is no universally accepted theory of human movement learning and control, two dominant theories are ‘Schema Theory’ and ‘Dynamical Systems Theory’, originating from cognitive and ecological psychology, respectively.

Schema Theory, proposed by Richard Schmidt in 1975, describes an information processing model based on motor programs, which explains how the central nervous system controls and coordinates motor skills (Schmidt, 1975). In this theory, it is proposed that motor skills are learned through the development of motor programs, which he described as memory-based constructs that guide the initiation, organisation, and control of movement. Schmidt (1975) extended Keele (1968) and Adams (1971) work by theorising that motor programs could generalise to a class of actions, termed ‘generalised motor programs’ (GMPs).

A ‘class of actions’ refers to a set of different actions that have similar and unique features termed ‘invariant features’ (Schmidt, 1975). So far the invariant features that have been investigated include the relative timing of skill components, their sequencing, and the relative force produced by the muscles (Schmidt, 1975; Schmidt et al., 1979). Collectively, these invariant features guide the general form of how a skill should be performed, the nervous system then applies parameters to the movement to define how it should be performed within the context of the situation (Schmidt, 1975). Parameters can be thought of as the specific instructions that are applied to a GMP to modify it, so that a movement is performed correctly (correct speed, or total force, etc) as a suitable response for the specific movement problem (Schmidt, 1975). The suggestion of parameters is important as it solves the ‘storage problem’ of the central processor (brain) having to store an individual movement solution for each of the immense number of ways the human body can move.

The specific movement instructions within the GMP, combined with initial body conditions, external sensory information, and performance outcomes, form a motor response schema (Schmidt, 1975). This schema is a memory representation of how the motor skill should be performed in the future and is improved upon with practise enhancing future skill execution (Schmidt, 1975). When performing a motor skill, the motor response schema is integrated with the initial conditions and desired outcomes, and parameters are applied to adjust the skill for the context. As the movement is executed, the performer evaluates the performance, combines sources of feedback, and updates the motor response schema (Schmidt, 1975).

In contrast, the ‘dynamic systems approach’ (Kelso & Tuller, 1984) challenges Schema Theory, arguing that it fails to account for the degrees of freedom available at each joint involved in movement (Bernstein, 1967). Instead, this paradigm posits that movement self-organises, emerging from interactions among individual, task, and environmental constraints (Schöner & Kelso, 1988). Within this paradigm of motor control, motor learning is inferred as an individual gains mastery of the many degrees of freedom in the task by reducing mechanical degrees of freedom through synergies and recognises more affordances in the environment (Newell et al., 2003; Turvey, 1990). This research is framed within the context of Schema Theory.

Considerable interest in understanding motor learning to master sport specific motor skills exists amongst researchers, coaches, and sport scientists to gain a competitive advantage over opponents. While it is established that motor skill improvement results from practise, the optimal amount, type, and conditions for effective skill development remain unclear. Ericsson et al. (1993) proposed that to gain mastery of a skill, large amounts of deliberate practise had to be amassed over ten years or more. Ericsson et al. (1993) defined deliberate practise as task repetition motivated by a desire to improve performance, with immediate, informative feedback to guide future efforts. Ericsson et al. (1993) also stipulated that deliberate practise would be solitary and directed by a qualified teacher. However, it has been pointed out that mastery of sporting skills still takes place despite the criteria of deliberate practise being fulfilled (Ericsson & Harwell, 2019). Other terms such as ‘purposeful’ (individual practice activities without a teacher) and ‘naïve’ practise (engaging in domain relevant activities) were later suggested to help explain why this occurs (Ericsson & Harwell, 2019). Nonetheless, it remains undisputed that substantial amounts of intentional, motivated, and directed repetition are essential for mastering motor skills.

Motor learning describes the acquisition of new motor skills or the reacquisition and enhancement of previously learned motor skills (Magill & Anderson, 2014). Since learning cannot be directly measured, it is inferred from relatively stable changes in the capability of a person to perform a skill, resulting from practice or experience (Ericsson et al., 1993; Magill & Anderson, 2014). Improvements in the execution of the motor response schema (measured by enhanced invariant features), or the ability to apply parameters to the motor skill indicate motor learning. Magill and Anderson (2014) identified six characteristics of learning: improvement in skill performance (there is an improvement in the outcome of the skill), consistency of performance (subsequent performances look more similar), stability of performance (resistance to disruption of skill performance from internal or external perturbations), persistence of progress in skill learning (learning is retained), adaptability (the improved performance is adaptable to different situations), reduction in the attention demand of performing the skill (performance maintained while concurrently performing a second task).

In the development of a hypothesis for how learning can be inferred, it is useful to contextualise learning by applying a sporting example. For instance, in running, improvements in the relative timing of the gait can be assessed between two time points to infer learning (Magill & Anderson, 2014). Thus, improvements in the relative timing of the running gait could infer learning as follows: If gait timing improves and results in increased speed or economy, this is seen as improved skill performance; if timing consistency increases during and between cycles, this indicates improved consistency; if performance remains stable despite internal or external perturbations, stability is confirmed; persistent improvements post-washout suggest learning retention; adaptable timing across different contexts shows adaptability; and maintaining running performance while executing a secondary task indicates reduced attention demands.

By measuring improvements in performance characteristics that infer motor skill learning, repeated measurements can be plotted over time to create a learning curve (Harlow, 1949). A learning curve shows the trajectory and rate of motor skill learning and has been used in sporting contexts to show changes in learning over time (Franceschini et al., 2017). Plotting individual learning curves could be used to identify slow and fast learners when compared to the aggregate learning curves of the target population (Magill & Anderson, 2014). To be able to create a learning curve, an appropriate field-based measurement tool is required to be able to measure performance data on which to base the construction of the curve. Further, mapping individual learning curves is of interest to identify periods of accelerated, decelerated, or plateaued learning, represented by changes in the shape of the learning curve (Magill & Anderson, 2014). This in turn can facilitate appropriate training design to maximise the motor skill learning for the individual (Franceschini et al., 2017).

While learning improves motor skill performance by practise and experience, development improves motor skill performance via biological and psychological maturation (Haibach-Beach et al., 2023). Developmental improvements in motor skills reflect increases in strength and physical size through musculoskeletal maturity, gains in fitness by a maturing cardiopulmonary system, and neurological maturation that enhances sensory processing, central sensorimotor control, arousal, and motivation (Dwyer et al., 2009; Haibach-Beach et al., 2023). The difference between learning and development is an important distinction to draw as it can be difficult to accurately distinguish improvements due to learning while an individual is not yet at maturity. However, some useful practices can be taken from the analysis of development and applied to the analysis of learning, such as the identification of developmental milestones.

Milestones act as ‘signposts’ that are markers within a systematic approach to assess the learning of a motor skill (Johnson & Blasco, 1997). These have been used to evaluate fine and gross motor skills development in infants (Johnson & Blasco, 1997). The World Health Organisation's ‘Multicentre Growth Reference Study’ collected longitudinal data on infant motor development through direct observation and parent surveys for infants aged birth to five years, accounting for ethnic, genetic, cultural, and environmental variability (de Onis, 2006; Wijnhoven et al., 2004). This investigation monitored 800 infants in six diverse locations (Brazil, Ghana, India, Norway, Oman, and United States of America) for two years and recorded milestones in bi-pedal movement development, creating 'windows of achievement' that define 'typical windows of development' (de Onis, 2006). A similar prospective approach could be applied to identify sport-specific motor skill learning milestones, aiding practitioners in understanding the nature of related learning curves.

Learning milestones have been investigated in several sporting contexts. Baker et al. (2005, p. 67) conducted interviews to examine the sporting experiences as well as the structure and amount of training of expert, “middle of the pack”, and “back of the pack” ultra-endurance triathletes. Erickson et al. (2007) aimed to identify the necessary experiences of high-performance sports coaches through retrospective interview. Alternatively, Johnson et al. (2008) investigated phenomenological comparisons of the experiences of elite and sub-elite swimmers to identify key experiences that lead to expertise development. Extending this work Bruce et al. (2013) sought to identify the key performance milestones and training history of expert, developmental, and recreational netball players through questionnaires. These investigations identified that the pathway to expertise is often marked with common, sequential, and distinct experiences that indicate a significant period of learning has taken place. While this is a useful starting point to understanding the development of expertise, these investigations were qualitative and centred around sporting experiences further investigation is required to fully understand expertise attainment.

Currently, it is undetermined whether milestones exist for complex, sport specific motor skills. However, given the existence of milestones for infant motor learning (de Onis, 2006; Wijnhoven et al., 2004) and learning experiences of elite athletes (Bruce et al., 2013; Johnson et al., 2008), it is reasonable to consider that learning milestones for complex sport-specific motor skills may also exist. Therefore, identifying the important motor skills for elite success in triathlon and objectively measuring their learning over time could provide a novel insights into motor skill acquisition in triathlon, and any other sport.

9.4 Coaching and Skill Acquisition in Triathlon

Triathlon is not merely the sum of its individual sports, but as a sport that requires specific knowledge and experience to combine three sports in sequence (Strock et al., 2006). This presents a complex challenge where coaches must possess high levels of knowledge and coaching ability in four sports simultaneously (swimming, cycling, running, and triathlon). Like many sports, triathlon training is usually conducted outside competition conditions so that specific aspects of performance can be practised. However, some practise under competition conditions is important for athletes to transfer their learning into competition. This concept is known as ‘transfer of learning’ which Rosalie and Müller (2012) describe as the ability to use previous performance experiences and adapt these to similar or different contexts (Barnett & Ceci, 2002). The quality of learning transfer depends on game knowledge, the physical environment, temporal, social, personal, functional, and modality factors as well as the skill of the athlete, where more expert athletes can transfer learning to dissimilar domains more successfully (Barnett & Ceci, 2002; Rosalie & Müller, 2012). With this concept in mind, it is thought that athletes who can transfer learning into competition more effectively will perform better.

Rosalie and Müller's (2012) “Near-to-Far” learning transfer continuum provides a framework to assess the transfer from training to competition. In triathlon the practise domain is often different to competition, and the temporal sequence of how each discipline is performed is not usually replicated. For example, pool swimming with lane ropes divides swimmers and provides direction, while open-water swimming requires navigation through waves, competitor-induced disturbances, differences in buoyancy and water temperature (Rosalie & Müller, 2012). Additionally, when competing, triathletes also adopt a swimming motor pattern that allows them to swim closely behind their competitors to take advantage of reduced fluid drag (Janssen et al., 2009) and they must regularly raise their head forward out of the water to ensure they are swimming in the correct direction (Davis, 2013). These differences in the physical domain affect the functional, temporal and social factors of learning transfer (Rosalie & Müller, 2012). Thus, when analysing skill acquisition in triathlon the incongruence between the learning and competition domain, is an important consideration.

During training sessions, triathletes typically practise in a single discipline instead of performing multiple disciplines sequentially. While replicating the sequence of a race in training would align with principles of learning transfer, there is evidence of motor learning interference when different motor skills are practised within short intervals. Brashers-Krug et al. (1996) demonstrated that learning interference occurs if a new motor task is introduced within four hours of another skill, disrupting consolidation and resulting in poorer performance of the initial skill. Such interference may explain findings by Chapman et al. (2007), who investigated leg muscle recruitment of elite cyclists vs. elite triathletes with matched cycling loads and found that triathletes tended to have muscle recruitment patterns more like a novice than an elite cyclist. If such a motor learning interference effect exists within triathlon, coaches have a difficult decision to create training sessions that are specific to the physical and temporal contexts of competition, or structure sessions that may avoid learning interference.

In addition to the large, specialised knowledge requirements of coaches, the complexities of learning transfer and potential learning interference between each discipline, the challenge of coaching triathletes is compounded by the difficulty of monitoring performance in real-time during races. Triathlon courses often feature large bodies of water, with cycling and running courses that span large areas, which make it hard for coaches to observe triathletes directly (Wells et al., 2023). This problem persists at the elite level unless athletes can be continuously filmed throughout a race (i.e. the leader of the race during a television broadcast). Since pressure can alter psychological, physiological, and kinematic aspects of performance (Cooke et al., 2011), it is problematic to assume that motor skills performed in training are the same quality as motor skills performed in competition. Therefore, a remote method of measuring the performance of triathletes throughout a race, would provide coaches with more accurate and race specific information to make more accurate coaching decisions.

In summary, addressing the complexities of skill acquisition and coaching in triathlon requires a systematic approach that considers incongruities between training and competition, potential motor learning interference, and effective methods for remote performance monitoring.

9.4.1 Measuring Motor Skill Performance in Triathlon

Measuring motor skill performance in triathlon requires a tool that can be utilised during both training and competition. It needs to have suitable dimensions to not add meaningful weight to the triathlete and a method of attachment or measurement that does not disrupt the performance of the wearer. It also needs to conform to the International Triathlon Union's rules and regulations on uniform and external attachments on the body (World Triathlon Technical Committee, 2022). Commonly available wearable inertial measurement units (IMUs) used in sport are lightweight and small (i.e. Catapult Optimeye S5: Approximately 67 grams, 96.5 x 52 x 14 mm) and can be attached posteriorly to the torso. Wearable IMU's most often contain a combination of micro-sensors including global positioning system (GPS) components and inertial measurement components like tri-axial accelerometers, gyroscopes and magnetometers (Crang et al., 2021). Several systematic reviews have demonstrated the utility and validity of wearable sensor technology for measuring aspects of motor skills in the individual disciplines of triathlon (Ancillao et al., 2018; Benson et al., 2018; Camomilla et al., 2018; Mooney et al., 2016). However, no single sensor has been validated to measure motor skills performance in all three disciplines, in sequence.

Specifically, wearable sensors have been used in the individual disciplines of triathlon to analyse swim stroke kinematics like stroke type, joint position and joint accelerations (Ganzevles et al., 2017; Mooney et al., 2016); stroke phase detection (Cortesi et al., 2019; Mooney et al., 2016); stroke count and rate (Ganzevles et al., 2017; Mooney et al., 2016); swimming velocity; and kick count and rate (Mooney et al., 2016). To measure these performance metrics, sensor attachment locations such as the head, wrist, upper arm, chest, upper and lower back, thigh, shank, and ankle have all been investigated (Mooney et al., 2016). While these sensor attachment locations are effective to measure swimming performance metrics, some of them may be impractical to measure features of important motor skills in cycling and running.

Investigators have also used wearable sensors to measure running performance metrics like ground contact time and strike patterns; stride rate, length and time; lower leg accelerations; running speed; vertical oscillations; arm movement; and stride kinematics (Benson et al., 2018). In these investigations, similar sensor attachment locations (foot, ankle, shank, lower and upper back, upper arm, wrist, chest, and head) have been used as those in the validation of wearable sensors for measuring swimming performance (Benson et al., 2018). However, it is unclear which performance metrics from both swimming and running can be measured concurrently throughout an entire triathlon, using only a single wearable sensor that is practical enough to be worn during races.

In contrast to swimming and running, wearable sensor research investigating the validity and utility of this technology in cycling is limited. The only identified instances of investigators using wearable IMUs to measure cycling performance have been the quantification of knee joint kinematics (Cordillet et al., 2019) and modelling power output, speed, and kinetics of cycling performance in uncontrolled conditions (Millour & Plourde-Couture, 2023). By validating a wearable IMU to measure motor skills in triathlon, changes in characteristics of learning can be detected by measuring biomechanical changes in movement over time (see section 5.4).

9.4.2 The Role of Data Science in Measuring Triathlon Performance

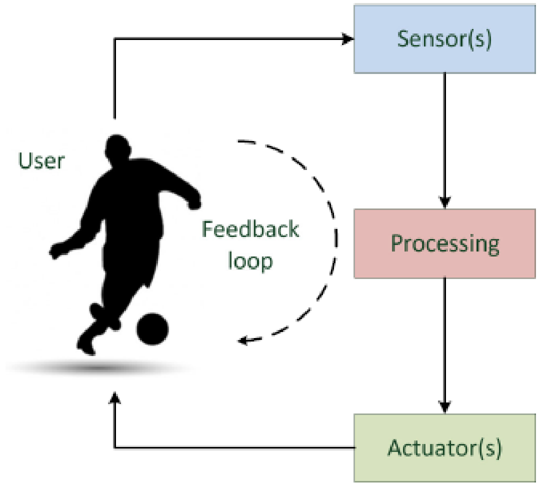
Performance analysis is common across all levels of adult sport, especially among professional teams where coaches highly value the insights it provides. However, as these analyses increase in complexity and detail, they can become extremely time consuming and labour intensive, especially when analysing many athletes. Machine learning and automatic detection and recognition algorithms can automate and hasten the labour and time-intensive manual data analysis process to make these insights available to coaches quickly. Furthermore, these techniques can identify patterns from combined data streams that may be too complex for human perception (Pustišek et al., 2019).

These algorithms have already been employed extensively in several sports to detect and recognise sporting movements or events. For instance, Jowitt et al. (2020) used machine learning algorithms to automatically detect fast bowling deliveries in cricket and monitor the workload associated with high volumes of fast bowling, given the injury risk. Similarly, Chambers et al. (2019) employed wearable IMUs and machine learning algorithms to automatically detect tackling and ruck events in rugby union to quickly understand the physical load accrued from contact. Hendry et al. (2020) applied the same strategies to detect and quantify ballet specific movement to gain a better understanding of training load in ballet dancers. Finally, Marsland et al. (2015) used this strategy to identify and classify skiing techniques to build an automatic detection algorithm of skiing kinematics in the field. These are just some examples of the wide range of applications of wearable microsensor technology combined with data science techniques in sport.

Since it is challenging for triathlon coaches to continuously observe their athletes during races, combining wearable sensors with data science could offer critical performance insights even when athletes are out of view. A technique to do this has already been described in cross country skiing where athletes ski on racecourses during a variety of environmental conditions, on racecourses as long as 50km and with visual obstruction by trees (International Ski Federation, 2023; Marsland et al., 2015). Further, coaches are required to remain in a specific zone to watch their athlete (extending as long as 30 metres) (International Ski Federation, 2023). Thus, performance analysis in cross country skiing has been advanced by using wearable sensor technologies and data science techniques to automatically classify and measure multiple skiing motor skills used by cross country skiers in competition (Marsland et al., 2012; Marsland et al., 2015).

While automatic motor skill detection and recognition algorithms can aid coaches of sports where athletes cannot be seen, wearable IMUs combined with data science can also aid individual motor skill learning without coach intervention. Pustišek et al. (2019) proposed a technology-supported motor learning model (Figure 2) where augmented feedback is provided by a smart system to replace coach provided feedback. During triathlon training, a system such as this could use wearable sensors to gain information from every swimming stroke, cycling pedal stroke, and running stride and provide audible or kinaesthetic feedback (actuator) when specific errors were made.

Figure 2. *Technology-Supported Motor Learning Model*



Note. From The Role of Technology for Accelerated Motor Learning in Sport, by M. Pustišek, Y. Wei, Y. Sun, A. Umek, & A. Kos, 2019, *Person and Ubiquitous Computing, 25,* pg. 4 (10.1007/s00779-019-01274-5). Copyright 2019 by Springer.

9.5 Summary, Gap Analysis and Thesis Design

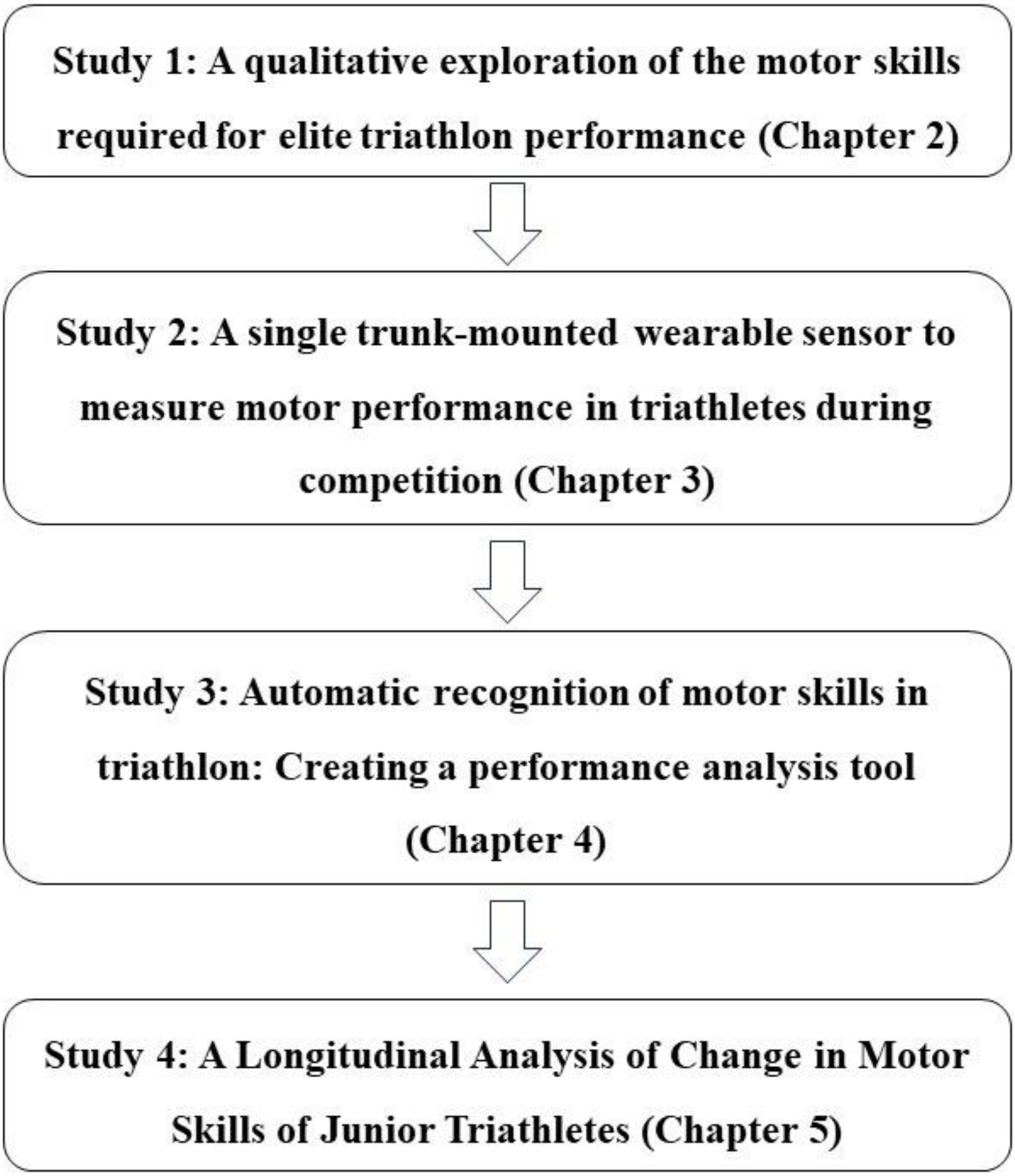
To summarise, the physiology and biomechanics of swimming, cycling, and running have been extensively studied in triathlon, as they are critical for elite performance. However, measuring biomechanics alone only quantifies the control of a motor skill. Therefore, understanding how motor skills are performed and how performance change over time is advantageous to creating elite success in triathlon. Currently, the scientific literature does not clearly identify which motor skills contribute to elite-level success, how these performances change over time or the factors that influence these changes.

Thus, the aim of this doctoral thesis is to answer the following questions:

1) What are the important skills for elite triathlon success?
2) Are there any patterns of change in performance over time that are common between youth triathletes for important triathlon motor skills?
3) Are there any common and identifiable milestones of improvement during triathlon motor skill practise?
4) What personal and racing related factors affect changes in motor skill performance in triathlon?

To address this gap in understanding this thesis aims to first explore which motor skills are required to be successful at the elite level in triathlon. This is essential to lay a foundation from which to direct motor skills research in the sport. Secondly, this thesis will discuss and show how a single trunk-worn wearable sensor can be used in the field to measure the performance of important triathlon motor skills. It is important to have a field-based measurement tool to measure the changes in performance of motor skills with high contextual validity. Further, this will create a tool that can be used by triathlon coaches and scientists in a real setting. To be able to do this, this tool must also provide easily accessible and timely insights into the performance of the wearer, and so the third study of this thesis will demonstrate the creation of a human activity recognition tool. Finally, the culmination of the thesis will use each of the three prior studies to conduct a longitudinal analysis of the performance of important motor skills in triathlon over multiple triathlon seasons to gain insights into how the performance of these skills changes over time and affect the overall performance goal in triathlon (Figure 3).

Figure 3: *Thesis Flow Chart*



The structure of this thesis is underpinned by the 'design thinking process' framework posited by Dunne and Martin (2006). Originally developed for product innovation in business, this framework has been widely adapted to fields such as education (Panke, 2019), health care (Altman et al., 2018), and sport coaching (Chambers, 2018). Adapting an existing framework from a similar field is required as there is no existing framework within the literature that investigates how motor skill performances change over time in sport.

The design thinking process framework provides a human-centered approach to innovating, problem solving and answering questions (Carlgren et al., 2016). It begins with ‘empathising’—understanding the experiences and perspectives of those affected. Next the problem is defined and understood, by an iterative process of framing and then re-framing the problem to incorporate multiple perspectives. Then ideas are proposed to solve the problem, and a ‘prototype’ is developed by testing a solution to the problem. Finally, those using the design thinking process ‘experiment’ by engaging with the potential users and deploying the solution that was created and refining the solution further.

The proposed thesis flow chart (Figure 3) demonstrates an application of the design thinking process framework. Initially, ‘empathising’ will be conducted by interviewing stakeholders in triathlon (Study 1) to understand their beliefs, attitudes and experiences surrounding important motor skills for success in triathlon. This will provide a foundation to understand how to proceed investigating motor skill performance improvement in junior triathlon. Next, a solution for improving motor skill performance will be developed and tested (Study 2 and 3) by validating and automating a method of measuring an important aspect of triathlon motor skills. Finally, the solution will be applied by engaging triathletes in the field (Study 4) and applying the solution to understand more about changes in motor skill performance in triathlon.

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10.0 Chapter 2: A Qualitative Exploration of the Motor Skills Required for Elite Triathlon Performance

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10.1 Abstract

Purpose: The purpose of this research was to investigate the beliefs, attitudes, and experiences of stakeholders in youth triathlon regarding the important motor subskills that are required to be successful at the elite level of competition of triathlon. **Method:** Twenty-five participants were recruited from five stakeholder groups in triathlon and interviewed via video conference. A constructionist and relativist approach to thematic analysis was used to identify three first order themes and several second order themes. **Results:** The first, first order theme was 'Continuous motor skills' which consisted of the invariant features of triathlon's continuous motor skills and the parameterization of continuous motor skills. The second, first order theme was 'Discrete Motor Skills' and consisted of discrete motor skills involved with cornering and change of direction in each discipline and transition phases in triathlon. The final first order theme was 'Adaptability to continuous and discrete motor skills'. **Conclusion:** This research provides a novel and more broad understanding of the beliefs, attitudes, and experiences of stakeholders in triathlon regarding important motor skills that are required to succeed at the elite level of the sport. This novel and broad understanding of important triathlon motor skills has theoretical implications for evaluating triathlon performance with skill acquisition as a primary focus. Additionally, this research is practically important for coaches, administrators, and athletic performance staff who design training programs and pathways for young, developing triathletes.

10.2 Introduction

Triathlon is a locomotion based sport which is characterised by athletes swimming, cycling and running to complete a set racecourse in the shortest time possible (Etxebarria et al., 2019). The primary performance goal in triathlon is to simultaneously maximise the average speed and optimise economy of locomotion. The achievement of the performance goal in triathlon is determined by biomechanical, physiological, psychological, and motor control factors. The former three factors have been previously investigated (Etxebarria et al., 2019; Millet et al., 2011; Preece et al., 2019; Ribeiro et al., 2017; Turpin & Watier, 2020), however, it is crucial to understand how movements of the body are centrally controlled as this underpins some of the important biomechanical and physiological performance factors. For example, economical use of energy during running (running economy) is understood to be an important physiological determinant of running performance (Millet et al., 2011), however, it is heavily impacted by running stride and foot strike position which are centrally controlled features of running gait (Shapiro et al., 1981). While this is one example of the quality of motor skill performance affecting a physiological performance variable, a comprehensive understanding of how motor skills are performed to maximise triathlon performance is not available.

Research into swimming, cycling, and running motor skills has not specifically focussed on identifying the subskills that lead to elite performance (Gísladóttir et al., 2019; Zeuwts et al., 2016). Subskills related to safety such as accident avoidance have been investigated in cycling (Zeuwts et al., 2016) and fundamental skills development and motor skills dysfunction have been investigated in running (Gísladóttir et al., 2019). Although these investigations provide some insight into the subskills required to successfully perform motor skills in sport, they do not translate to performance optimisation in elite level triathletes. In swimming, elite level coach perspectives of skill acquisition methods and training drill prescription have been explored, however the subskills themselves were not identified (Brackley et al., 2020). To the best of our knowledge, research has not yet identified the skills that athletes require to perform at elite level in triathlon, and the learning curves for these skills. Consequently, triathlon motor skills lack an evidence-based skill development pathway.

To construct an evidence-based pathway for triathlon motor skill development, it is crucial to understand which motor skills are important for elite performance and the rate at which these skills are learned. One way to measure the rate of motor skill learning longitudinally is to typify milestones of motor skill performance for the cohort of interest (de Onis, 2006; Gerber et al., 2010). Milestones act as a standard learning trajectory to which an individual's performance can be compared at key points in development. Such approaches currently exist for walking (de Onis, 2006; Gerber et al., 2010) and prehension (Gerber et al., 2010; Johnson & Blasco, 1997). As triathlon is comprised of sport-specific skills that are either fundamental motor skills (running) or strongly related to fundamental motor skills (cycling and swimming), the milestone approach is appropriate to measure motor skill development in youth triathletes. However, it is unclear from the literature whether triathlon coaches already use milestones to monitor the learning of these skills by their youth triathletes.

While the creation of an evidence-based triathlon motor skill learning pathway would be useful for youth triathlete coaches; it is unknown what people involved in the sport believe regarding the determinants of successful skill performance at the elite level. Qualitative research methodologies are most appropriate for investigating relatively unknown phenomena and the meanings individuals make from their lived experiences. Qualitative research methodologies have been used in field hockey to examine participant beliefs regarding anticipation and goalkeeping during a penalty corner drag flick (Morris-Binelli et al., 2020), anticipation to return-serve by expert tennis players (Vernon et al., 2018), and skill acquisition approaches applied by elite swimming coaches (Brackley et al., 2020). Morris-Binelli et al. (2020) found that hockey goalkeepers and coaches had only identified some important components of anticipating and saving a penalty corner drag flick compared to a previously investigated model of anticipation (Morris-Binelli et al., 2020). They also identified that there was an over-reliance on the physical and physiological components of goalkeeping resulting in a need to place more emphasis on sport expertise and psychological elements which are key differentiating factors of superior performance (Morris-Binelli et al., 2020). These findings provided a basis for the construction of a targeted skills training program to improve anticipation (Müller et al., 2019). This has implications for triathlon as qualitative research methodologies could be used inductively to develop novel theories regarding important triathlon motor skills and provide a basis for an evidence-based skill learning pathway.

To explore the important motor skills required to compete in elite triathlon, coach and athlete perceptions are not the only points of view that are crucial to understand. In Australia, triathlon is controlled by a governing organisation (Triathlon Australia [TA]) that provides education and accreditation to coaches and determine the course set at some races. Features of the course such as different environments (weather, terrain and course placement) and rules (draft legal) affect the type and way motor skills and subskills are used by triathletes to navigate the racecourse in the fastest time and therefore influence their learning (Renshaw & Chow, 2018). As such, understanding the race organiser's perception of important motor skills is crucial to ensure that young triathletes learn the correct skills to navigate racecourses. Further to this, parents are believed to be key drivers of athlete participation in training and their support is considered necessary for motivation and engagement in sport (Keegan et al., 2009). Keegan et al. (2009) also notes that parents and coaches (including support staff such as strength and conditioning coaches) are held in high esteem by their children/athletes and therefore the opinions of parents, coaches and support staff can influence what youth triathletes engage with and learn. Therefore, parents and support staff may also play an important role in determining which motor skills their children or athletes place intentional effort learning. Thus, the purpose of this research is to gain rich and detailed insight into beliefs, attitudes, and experiences of stakeholders in triathlete development regarding the important motor skills for elite triathlon success and how these motor skills are learned by young triathletes.

10.3 Methods

10.3.1 Philosophical Assumptions

A relativist ontological and constructionist epistemological approach to qualitative data collection was used to co-construct ideas from the participants' beliefs, attitudes, and experiences regarding motor skills required for elite triathlon performance. Ontological relativism accepts that there are multiple realities through which the world can be interpreted, and that these interpretations are subjective to the individual (Smith & McGannon, 2018). A constructionist epistemological approach assumes that information is socially constructed and its meaning is based on the experiences of the people that construct it (Smith & McGannon, 2018). Furthermore, an inductive-deductive approach was used to identify all themes in the data about the important motor skills required for elite success in triathlon, after which any potential overlap of the identified themes and existing theories will be interpreted.

10.3.2 Participants

Twenty-five stakeholders in Australian youth triathlete development (M_{age} = 41 years, *SD* = 12.3 years, male: *n* = 20, female: *n* = 5) participated in this study. The total sample consisted of national and state level triathlon coaches (*n* = 6; M_{age} = 46 years; *SD* = 6.53 years); triathletes ranging from Olympic to amateur competition levels (*n* = 5; M_{age} = 27 years, *SD* = 5.6 years); parents of triathletes who competed at state level or above (*n* = 5; M_{age} = 54 years, *SD* = 6.1 years); national and state level support staff including physiologists, performance scientists and strength and conditioning coaches (*n* = 5; M_{age} = 35 years, *SD* = 9.5 years); and state and national level administrators and technical officials (*n* = 4; M_{age} = 41 years, *SD* = 16.1 years).

10.3.3 Interview Procedure

Ethical approval for this study was obtained from the institution's human research ethics committee. Word of mouth and snowball recruitment were used to recruit participants via TA. The inclusion criteria to participate in the research were as follows: triathletes must have had a TA racing licence; parents of triathletes were only included if the child held a TA racing licence; coaches must have held a TA accredited coaching qualification; administrators, technical officials, and support staff must have been working within a triathlon organisation or state institute of sport. These criteria were assessed by conducting a short eligibility survey (Appendix A) prior to participation. Further, participants were required to provide recorded, verbal informed consent prior to participating. An iterative approach to purposive sampling was used to recruit participants from seven different triathlon clubs and organisations. To identify coach-athlete-parent and organisational relationships that may influence the views of the participant, the investigatory team asked participants to provide details of their role as a stakeholder in youth triathlon development. Any instances of these relationships existing were reported to increase transparency. The primary investigator continued to conduct interviews with a relatively even number of participants per stakeholder group until a saturation of themes occurred where no new themes were identified (Smith & Sparkes, 2016).

The primary investigator conducted semi-structured interviews with participants via online video calls (Webex, version 40.2.7.7, Cisco Webex, Cisco Systems, Milpitas, California) which were recorded. One interview was conducted in person at a quiet café at the request of the participant. At the start of each interview, the researcher introduced himself, explained the background of the research, and asked the participants if they had any questions or comments. The participants were encouraged to speak openly and honestly and were reminded that they could choose not to answer any of the questions if they wished. Upon the completion of each interview, participants were offered an opportunity to provide comments or ask questions. The interview duration ranged from 51 mins to 116 mins (*M* = 77.1 mins, *SD* = 17.3 mins).

10.3.4 Interview Guide

To allow for a flexible style of interviewing with further probing questions to gain more detailed insight into participants' beliefs, attitudes and experiences, a semi-structured interview guide was created in accordance with recommendations by Smith and Sparkes (2016). To improve order, relevance, and appropriateness of questions in the interview guide two pilot interviews – which were supervised and reviewed by an experienced qualitative researcher – were conducted (Smith & Sparkes, 2016). Based on evaluation of the pilot interviews and interviewee feedback, the interview guide was further refined. The final semi-structured interview guide (Appendix B) consisted of questions about the following topics: motor skills and motor skill components required for elite triathlon performance; the timing of triathlon motor skill learning; beliefs surrounding the existence of any significant and observable milestones of triathlon motor skill performance; opinions of features of triathlon motor skills that indicate expertise has been obtained.

10.3.5 Data Analysis and Quality

An inductive-deductive semantic approach to 'big Q' thematic analysis was taken by following the 'six phase model of thematic analysis' as originally described by Braun and Clarke (2006) and updated in 2016 (Braun et al., 2016). This type of thematic analysis is intended to be reflexive and recursive with the investigators immersing themselves in the data in order to deeply understand the beliefs, attitudes, and experiences of the participants (Braun et al., 2016). Accordingly, thematic analysis commenced with the primary investigator familiarising themselves with the data by transcribing all interviews verbatim from audio recordings and then repeatedly reading them (phase one). Once an interview was transcribed, all potentially identifiable information (names, nationalities, and world rankings) were removed, and a label was assigned to the participant to ensure the participants' confidentiality and blind their identity to other members of the research team. Labels were based on the order of interview and the stakeholder group they most identified with (Coach [C#], triathlete [TRI#], parent of triathlete [POT#], support staff [SS#] and administrator or technical official [AT#]). These abbreviations will also be used to refer to these stakeholder groups throughout.

The primary investigator then imported transcribed interviews into NVivo qualitative data management software (Version 12, QSR International, Melbourne, Australia) where they were systematically coded to group similar data (phase two). The primary investigator then collated codes into potential themes (phase three) and the investigatory team checked this to identify coherent patterns formed by the coded data (phase four). Where coherent patterns within themes were not clear, the primary investigator re-organised coded data to create new themes, fit the data within existing themes or discarded it. Once complete, the investigatory team generated and reviewed a thematic 'mind map' to ensure it accurately reflected meanings in the data set. The research team then defined themes and identified meanings within which were then demonstrated by reporting extracts from transcripts (phase six). Deductive reasoning was then used to analyse the themes that had been created against an accepted theory of skilled movement behaviour (Schmidt, 1975, 2003).

Consistent with our relativist approach, validity was established by embedding study-specific evaluative strategies into the research process to ensure rigour (Burke, 2016; Smith & McGannon, 2018). To begin, the investigators ensured 'internal coherence' by designing the methods of the study to fit with the philosophical assumptions that were taken by the investigators. This included the aforementioned pilot testing of the interview guide to improve the credibility of the data (McGannon et al., 2021). To improve confirmability, the interviewer took reflective field notes on their interviewing technique and interaction with the participants during data collection (McGannon et al., 2021). To improve transparency during data analysis an audit trail was kept to outline the decisions made during coding and constructing themes (Tracy, 2010). In addition to this, a 'critical friend' scrutinised theoretical stand points and decisions made during data analysis (McGannon et al., 2021; Tracy, 2010). During the writing of the final report, the data was reported by including direct quotes from participants to re-enforce the identified themes. Further, during report writing, external coherence with established motor learning theory was identified with the aim of making a substantive contribution to the understanding of skill learning in youth triathletes that would also achieve 'resonance' by producing findings that are transferable outside of triathlon (Tracy, 2010).

10.4 Results and Discussion

Participants described motor skills as forms of "deliberate movement" (C4), "body movement patterns" (C2) that an athlete must "practise and repeat" (SS2), so the execution "gets a certain result" (C4). All participants agreed that motor skills were important to optimal performance in all triathlon disciplines, while some added that motor skills were also important to prevent injuries. Through analysis of the participants' beliefs, experiences, and attitudes, we identified three first order themes regarding the important motor skills for success in triathlon. These were 1) Continuous motor skills, 2) Discrete motor skills and 3) Adaptability in continuous and discrete motor skills. Continuous motor skills like running are defined as repetitive movements with no defined beginning or end. Discrete motor skills like a dive from blocks in swimming are defined as a single movement with a clearly defined beginning and end such as (Magill & Anderson, 2014). Lastly, adaptability in continuous and discrete motor skills refers to an individual's ability to change aspects of motor skill performance to suit the context specific demands.

Figure 4: *Participant's Beliefs, Experiences, and Attitudes of the Important Motor Skills for Success in Elite Triathlon.*

^{1}Continuous Motor Skills

- ^{2}Invariant features of continuous motor skills
    - ^{3}*Kinematics of locomotion*
    - ^{3}*Forming and maintaining posture*
    - ^{3}*Stabilising the body*
    - ^{3}*Navigation and breathing*
- ^{2}Parameterization of absolute duration of continuous motor skills

^{1}Discrete Motor Skills

- ^{2}Cornering and change of direction skills
- ^{2}Transition skills

^{1}Adaptability in Continuous and Discrete Motor Skills

Note. Figure 4 presents the first, second and third order themes identified within the data. Theme order is indicated by a different superscript number: First order themes are denoted by '^{1}Theme', second order themes by '^{2}Theme' and third order themes by '^{3}Theme'

10.4.1 Continuous Motor Skills

All participants believed that motor skills in triathlon referred to continuous motor skills that were important for performance in each triathlon discipline: "Movement patterns that are specific to our discipline which is swim, bike and run" (C2). Participants believed that it was important to train features of continuous motor skills, which refers to characteristics of the locomotion patterns that are performed in a relatively similar fashion between performances. Further, many participants agreed that it was important that triathletes were able to scale the absolute duration of continuous motor skills to perform them in accordance with contextual factors such as the environment, race position and proximity of opponents.

As such, participants' discussion of important triathlon motor skills shared characteristics with Schmidt's 'Schema Theory', which can be used to understand how motor skills may be centrally controlled (Schmidt, 1975). Schmidt (1975) theorised that the initiation, organisation, and control of movement is based on motor programs which are memory-based constructs that are generalised to a class of actions (generalised motor programs [GMP]). A class of actions refers to "a set of different actions having a common but unique set of features" which Schmidt termed 'invariant features' (Schmidt et al., 1979). Together, the invariant features of a GMP govern how a motor skill from that class of actions is performed. The individual is then required to apply parameters to scale and adapt each motor skill performance to relevant contextual factors and carry out the skill within the specific constraints of a situation (Schmidt, 1975).

Invariant Features of Continuous Motor Skills.

We identified four third order themes that describe specific invariant features of continuous motor skills that could be improved through training: Kinematics of locomotion; Forming and maintaining posture; Stabilising the body; and Navigation and breathing. There were two predominant opinions regarding the existence of a most important motor skill to be successful in elite triathlon. One group of participants ($n = 7$) believed that the most important continuous motor skill was running technique: "I would have to say it's run mechanics", "having an efficient cadence, an efficient contact time on the ground, arm swing", "I think that's probably going to be the most important in terms of them being successful at the elite level" (TRI5). The other predominant opinion ($n = 6$) was that there was not a particular motor skill that was most important: "No. Some are used more commonly than others, but what they are will depend on the course and the athlete" (C6). The remaining 12 participants provided a range of different opinions about which motor skill they believed was most important for performance. However, these beliefs were only held by at most two participants. This indicates that there is a lack of consensus regarding the most important motor skills for optimal triathlon performance.

With regards to the most important discipline for success in elite triathlon, most participants (*n* = 13) believed that running was most important for success at the elite level: "The data says if you're in the top 3 in the field [for running] then you're nearly guaranteed a medal" (AT2), while a smaller, separate group (*n* = 4) believed that both the swim and run were equally most important: "The two key parts are a good swimmer but a very good runner you'll podium much more likely" (AT1). While only a small group of participants believed that swimming was most important (*n* = 2), a larger group (*n* = 11) recognised its importance but did not value it equally to running performance. A key nuance of this opinion was that swimming was important to maintain 'front pack positioning' and without this it was very difficult to win even if you were the best runner: "Swimming is important as well because particularly in draft legal races it's important to get the front pack" (POT2), "The swim gets you to the podium, the run gets you on it" (SS2). Consistent with the view that running is the most important discipline for success in triathlon, most participants believe that coaches should spend considerable time training each of the invariant features of all continuous motor skills in triathlon and the ability to parameterise them to prepare their triathletes for competition at the elite level.

Kinematics of Locomotion. All but two (*n* =23) participants believed that the shapes and actions of the main propelling limbs were an important invariant feature of all three continuous motor skills in triathlon. As the main propelling limbs drive the body forward it is important to understand how triathletes should position and move these limbs to optimise forward velocity and energy cost. Participants reported that the important invariant features of running technique that achieve this are: "Lineal movement through that knee drive. And landing sort of straight under hips" (C6), "you don't want to see knees knocking together" (POT5). Participants also acknowledged that the kinematics of the stride in running affects how the foot contacts the ground which has subsequent impacts on ground contact time: "An efficient contact time on the ground and not spending too long there. So, we're not getting that sort of heel to toe action" (TRI5). Lacour and Bourdin (2015) concurred with this result in their literature review which indicated that shortened ground contact times resulted in a more efficient use of energy due to the increased storage and reuse of elastic energy during stance phase of running.

There were differences in opinion among participants regarding the extent to which training of the kinematics of running is useful and the nuances in terms of the extent that individual differences need to be taken into consideration when training running kinematics: "Everyone is going to have their natural movement pattern that you don’t want to change too much" (SS5). This point of view is worth addressing for two reasons. Firstly, if a triathlete transferred from a non-running sport this point of view would assume that they would not be able to learn effective running kinematics. Secondly, it may indicate that some practitioners are reluctant to practise aspects of running technique for fear of losing valuable training time to un-attainable performance improvements. Despite the beliefs of some participants, one systematic review showed ten investigations that were able to create significant improvements in several gait characteristics associated with injury and running performance by providing augmented visual and auditory feedback to recreationally trained runners over two to six weeks (Agresta & Brown, 2015). This incongruence may highlight the need for more knowledge and education on creating intended and meaningful changes in triathletes running gait, as participants emphasised that they believe running is a large predictor of elite performance.

The shapes and actions of the arms in open-water swimming were the second most discussed (*n* = 22) kinematics of continuous motor skills. Participants emphasised the importance of the full range of the stroke: "[hands] Entering with the tips of your fingers (TRI4), "[hands] entering the water at shoulder width" (POT4), "Swimming over a barrel and then also finishing the catch, finishing the stroke making sure you’ve got the right length out the back" (SS3). Participants believed that an open-water swimming stroke should be shorter; with less glide and higher elbow; the duration of the stroke cycle should be shorter; and was more easily disrupted by waves, contact with opponents and the need to sight for navigation. Compared to pool swimming, effective open-water swimming technique has been scarcely researched. Zacca et al. (2020) have begun investigations of the differences in energetics and kinematics of open water compared to pool swimming, however, more work needs to be done to elucidate how open-water swimming can be optimised for energy efficiency and maximum velocity.

Participants (*n* = 20) deemed an effective and efficient pedal stroke to be an important kinematic invariant feature of the cycling continuous motor skill: "The push pull of the pedals is quite important […] if you go to training as a pure cyclist, they would be really honing in on your push pull" (POT4). The participants provided a great level of detail in term of what this pedal stroke should look like, and overall they agreed that it should include: "Use as much of the pedal stroke and putting as much pressure into the pedal for that full 360° rotation" (C4), "you're articulating your ankle to bring the pedal over the dead spot", "it's like scraping mud off your feet" (AT4). This finding is consistent with Theurel et al. (2012) who found favourable outcomes for pedalling effectiveness, peak power reduction over time, time to fatigue and reduced minimum torques during a prolonged cycling exercise when cyclists used a 'push-pull' pedal stroke compared to other strokes.

Teaching pedalling technique is one invariant feature of the cycling GMP that was highlighted by participants as important to learn. Participants mentioned that due to bicycle design, a 'push-pull' pedal stroke could not be taught to triathletes until they owned a bicycle with 'clip in' pedals and shoes. The participants reported that this was a barrier to learning optimal pedalling kinematics among youth triathletes, who commonly simply exert force downwards rather than apply force to the pedal crank consistently throughout 360° of pedalling. If this results in different relative timing of the movement of the segments of the legs (i.e. downstroke occurs faster than upstroke compared to a 360° pedalling style) this would suggest that a different GMP needs to be learned (Heuer & Schmidt, 1988). Nonetheless, this change in pedalling style results in triathletes recruiting different muscles to pull up on the pedals to apply torque to 360° of the pedalling motion, suggesting that a different parametrization strategy could also be required (Shea & Wulf, 2005). To improve the learning of the correct pedalling GMP and parametrization strategy for this motor skill triathletes should be given access to a bike that allows clipping in and taught how to do so as early as possible.

Taken together, these findings suggest that all stakeholders in triathlon believe that the kinematics of the main propelling limbs are an important invariant feature of the continuous motor skills required for success in all disciplines of elite triathlon. Yet, some differences in opinion exist with regards to the extent to which individual differences should be taken into consideration when training these skills.

Forming and Maintaining Posture. All but one participant (*n* = 24) considered posture to be an important invariant feature of continuous motor skill performance for success in triathlon. Participants believed posture forms the foundation for the propelling limbs to work efficiently and effectively in all three triathlon disciplines: "I think maintaining a stable thoracic posture for everything else to operate off […] that's probably the most important" (TRI4). The perceived importance of posture is consistent with Earhart (2013) who describes the ability to regulate postural control during challenging running tasks as crucial to the successful performance of the task. While participants in our study believed that forming and maintaining effective postures was important to support the effective movement of main propelling limbs in all three disciplines, participants also believed there to be further advantages in maintaining specific postures associated with increasing the energy efficiency of movement.

Maintaining a static posture that improves the energy efficiency of locomotion by minimising drag forces was perceived to be important particularly during swimming and cycling. The participants described these postures as those that minimise front on contact with the fluid the athlete is travelling through. In cycling the participants described the posture as such: "Shoulder shrug […] head below your shoulders and looking slightly up" (TRI2). In swimming, a hydrodynamic posture was described as such: "You can see the arch of their back and you can see the top of their backside […] the feet are in line with the body and the water" (AT2), "moving in a straight line […] we don’t want you snaking" (C5). The participants beliefs are consistent with investigations of body position and fluid drag in swimming and cycling (Barry et al., 2015; Morais et al., 2020). Although Barry et al. (2015) acknowledged significant time savings can be achieved by adopting the most aerodynamic postures, they note that posture changes are required based on interactions with the race course, other athletes and the environment. Investigation of power output in different cycling postures has also indicated that less flexible cyclists who were less comfortable in aerodynamic positions experienced large decreases in power output compared to those who reported feeling more comfortable (Polanco et al., 2020). This suggests that for cyclists to take advantage of drag reductions provided by aerodynamic cycling positions, they must spend time training to adopt these postures.

Objective measurement of ability to hold and change postures may also have some applicability to identify motor skills learning. Earhart (2013) suggested that controlling excessive postural movement during locomotion (such as excessive lateral hip movements seen in running) may be a process of transmitting "error" signals based on the actual and desired location of body segments to. If 'excessive movement' as discussed by participants is viewed as a discrepancy between intended and actual body location, then the ability to correct this shows improvements in consistency, a sign of motor learning (Magill & Anderson, 2014). Therefore, it is important for coaches to spend time training triathletes to adopt and produce power from desirable postures for each discipline in triathlon.

Stabilising the Body. Most of our participants (*n = 23)* believed that the kinematics and skilfully timed use of the stabilising limbs were important to counter the reaction forces caused by the movement of the propelling limbs in all triathlon disciplines. Furthermore, doing this in a coordinated fashion incorporating trunk movements was perceived to be important for achieving effective locomotion: "In swimming you almost want to use the core to create a bit of rotation, in the run you want to use your core to not rotate" (SS4), "the body roll initiates the whole cycle of stroke and kick" (C4). In running, arm swing and torso rotation does not contribute directly to propulsive forces but instead provides counter rotation to the forces created by the legs (Hamner et al., 2010). In swimming, the kick helps maintain a horizontal posture in the water and could also be used to reduce intra-cyclic velocity variation when timed appropriately with the arms (Mezêncio et al., 2020). In addition, effective timing of the propelling and stabilising limb movement discriminates between skill level of swimmers (Mezêncio et al., 2020). This is an important finding as it indicates that measuring the timing of upper and lower body coordinated movements can provide an objective indicator of whether a triathlete is learning. However, it is difficult to detect small changes in timing through subjective or 'coaches' eye' assessment and underwater video analysis is not regularly available to many triathletes, let alone in open-water swimming. Therefore, this warrants the exploration of other methods such as wearable sensors to assess this subskill in triathlon.

A smaller group of participations (*n* = 8) also identified 'balance' as a pre-requisite to successful performance of other invariant features of continuous motor skills because it was deemed an important part of stabilising the body, particularly in cycling: "If you’re not balanced you can’t do anything", "they won’t have the confidence to apex the corner" (C5). Balance in running was briefly mentioned by two participants as important but was not expanded upon with any detail. This finding is consistent with Miller et al. (2013), who also showed that balance requirements increased the energy cost of cycling (2.5%; $p = 0.015$) compared to stabilised cycle training methods (i.e. cycling ergometer).

Participants believe that balance and stability are important pre-requisites to allow a triathlete to produce fast and energy efficient forward velocity. While participants recognised that the propelling and stabilising limbs have a relationship in stabilising the body in swimming and running, they did not recognise that this relationship also exists in cycling (Turpin et al., 2017). Turpin et al. (2017) measured upper limb muscle activity during cycling and identified in-phase and coordinated activity of the muscles of the upper limbs to correspond with each pedal stroke, as well as coordinated synergistic contractions of upper limb muscles that play a role in stabilising the bike particularly at high power. As participants did not discuss the relationship of the propelling and stabilising limbs in cycling it is possible that this is overlooked when teaching young triathletes how to cycle.

Navigation and Breathing. Navigation and breathing are swimming-specific invariant features of continuous motor skills that the participants (*n* = 17) deemed important for performance in triathlon. To navigate effectively during the open water swim, the participants believed that triathletes should engage in 'sighting': "Sighting is huge in making sure that you are actually taking the shortest course and not going off on your own tangents" (AT1). Sighting involves inserting a forward lift of the head in place of a head tilt to the side when breathing, which the participants believe may interrupt a triathlete’s stroke cycle and their ability to maintain a hydrodynamic position: "Every time you sight it’s affecting your stroke. So, if you’re sighting every 3rd or 4th stroke, you’re lifting your head and dropping your feet" (AT1). As segmental timing and the inclusion of a head lift to sight are within the swim cycle are different invariant features to pool-swimming it is likely governed by a different GMP (Shea & Wulf, 2005). Practitioners should consider that when training in a pool, teaching a style of swimming that is more effective in open-water conditions is vital, as there is less transfer of learning between similar motor skills with different relative timings (Heuer & Schmidt, 1988).

Coordinated movement of the head and increased roll of the torso was another invariant feature of open-water swimming that participants deemed important, particularly as this is required to breathe: "I think breathing whilst you're swimming is probably a skill in itself that you need to learn […] especially with the ocean because you have the other factors of the waves and breaks of the water in the face" (POT5). In addition to learning to breathe within the stroke, having the ability to do this on both sides of the body was perceived to be a useful tool: "[the] emphasis should be on essentially just building a wide variety of tools that an athlete can deploy if needed" (SS2). While participants discussed how triathletes should navigate and breathe during swimming the relative depth with which this was discussed was low compared to the other invariant features of continuous motor skills. Investigations of the effect of breathing frequency on swimming kinematics have identified swimming velocity to be significantly lower during stroke cycles that include breathing (do Couto et al., 2015). Furthermore, participants overlooked the fact that respiratory and locomotion coordination substantially affects the energy demands of running which can be improved through entrainment (Daley et al., 2013). Currently there have been no scientific investigations into the approach open-water swimmers or triathletes take to navigate through open water conditions to swim the shortest possible distance, therefore guiding triathlon coaches to teach this to young triathletes is difficult.

Parameterization of Absolute Duration of Continuous Motor Skills

To be successful at the elite level in triathlon most participants (*n* = 21) believed the ability to parameterise continuous motor skills by altering the absolute duration with which they are performed (i.e. velocity of movement) is essential: "Stroke rate, cadence on the run and cadence on the bike […] They're all variables of the same thing and to me that's the most important" (C2). Although this was relevant to all triathlon disciplines, the participants emphasised the importance of parameterizing stroke rates in open-water swimming, where high stroke rates and reduced glide distances were believed to propel the body more effectively in the open environment: "We have a medium that's going to affect the glide and reduce the ability to glide without losing speed… so therefore to go to a higher stroke rate or more importantly no lag phase" (C3). The parameterization of the absolute duration of kicking frequency in swimming was seen as less important by participants (*n* = 5):

> The ability to kind of you know, go from a two-beat kick to a four-beat kick, to a six-beat kick […] is it critical for you know, going from the developing athlete to a senior level athlete? Maybe not. But it's something that you know, could be considered. (SS2)

While participants generally discussed their perceived importance of having a variable stroke rate, parameterizing the kick speed to synchronise with changes in arm stroke frequency may play an essential role in maximizing propulsion (Mezêncio et al., 2020). As stroke frequency and kick synchronization has been related to swimming economy (Figueiredo et al., 2013) and propulsion (Mezêncio et al., 2020), further research is required to empirically investigate the most effective way to parameterise swimming technique when transitioning from pool to open-water swimming.

Interestingly, participants beliefs that swimming with a higher stroke rate is necessary to optimise velocity in open-water are similar to Seifert et al. (2004) findings that there are separate distinct arm coordination patterns at high and low swimming velocities. Seifert et al. (2004) identified that as swimming velocity increased the relative timing of stroke phases changed, noting a decrease in non-propulsive phases of the stroke cycle. Seifert et al. (2004) suggested the increase in stroke rate and decrease in glide was required as fluid drag increases substantially as swimming velocity increases. This is congruent with participant suggestions that high stroke rates and minimal glide were needed to maintain higher velocities through turbulent water (due to competitors and ocean tides) where fluid drag is also high. Due to the different relative timings of stroke phases in high velocity pool swimming this would suggest that a different GMP is required for this style of swimming. This indicates that a high velocity pool swimming GMP may be required to swim at lower relative velocities in the open-water and is an important training consideration for triathlon coaches.

In cycling, the participants reported that scaling the pedalling cadence at the same expression of effort was an important motor skill for success in triathlon: "Cadence is a good skill to have because you don't want to have your cadence too low and recruit unnecessary bigger muscle fibres or groups and compromise your ability to run efficiently off the bike" (TRI2). This is consistent with García-López et al. (2016) who showed scaling pedalling cadence was important for power optimization. Additionally, participants believed that pedalling at low compared to high cadences with equated effort was believed to lead to greater build-up of metabolic by-products leading to a faster time to fatigue: "Lactate accumulation, hydrogen ion accumulation and that sort of build-up of by-products, would be a lot less at a higher cadence" (TRI5). Participants also suspected that cycling performance influences subsequent running performance, and that keeping cycling cadence within a particular range would be helpful for the run: "If they're running at say 160-180 their cadence on the bike is going to be around 90-96" (C1), "You maintain the same cadence on the bike as you do when you run, neuromuscularly allows you to get off the bike more efficiently" (C2). However, the effect of different cycling cadences on subsequent running performance has not been investigated in the literature. This is an important consideration for youth triathlon coaches as, these effects are believed to be more substantial in novice triathletes and therefore training prescription should be tailored to account for these changes (Walsh, 2019).

Finally, in running, participants believed that an inability to parameterise the absolute duration of the propulsive cycle resulted in undesirable running biomechanics such as reaching too far in front of the body with each foot contact: "[My son] he's always had a long stride and I think [name coach removed] has been trying to get him to increase that cadence" (POT2). Participants suggested that faster cadences could help prevent over-striding: "Not over-striding. So, you look at stride rate, stride length and stride frequency" (TRI5). Additionally, athletes could be required to parameterise their running cadence up during downhill running:

"Athletes who are very skilled runners actually utilise the downhill", "They go flat out because they can run at 25 km/h" (AT2). The capacity to optimise the absolute duration of running has been related to improved running economy (Moore, 2016) and therefore is important to learn to achieve the performance goal in triathlon.

10.4.2 Discrete Motor Skills

Almost all participants (*n* = 24) believed discrete motor skills were important to be successful at the elite level: "How you approach corners in all the three disciplines [is important] because it is free speed" (TRI2). These discussions centred primarily around cornering in cycling but also included change of direction skills in swimming and running and motor skills required to transition between disciplines. Therefore, 'Cornering and change of direction skills' and 'Transition skills' form the two second order themes under the theme 'discrete motor skills'.

Cornering and Change of Direction Skills

Cornering or changing direction was discussed by most participants (*n* = 24) as an important discrete motor skill required to perform successfully in all triathlon disciplines. The importance of this skill was mentioned most often in relation to cycling (*n* = 23), where forming the correct posture for cornering and learning to steer was deemed essential to performance: "Lower your centre of gravity, (AT4), "Looking at where you’re going", "Steer using their trunk" (TRI5). Participants perceived those triathletes who cannot corner well fall back off the pack, and subsequently must spend energy to re-accelerate to catch up: "It’s sort of easy to get dropped if you’re not going through a corner at the same pace as a group and even if it’s not completely dropped it's having to work harder to get back on" (TRI1). Participants believed it is less energy efficient when triathletes remove an excessive amount of speed before a corner and must re-accelerate afterwards. This belief is consistent with investigations of the energy consumption of steady state compared to shuttle running (Stevens et al., 2015), however, the impact of this may be exacerbated in cycling as wind resistance increases with velocity (Barry et al., 2015). Additionally, abruptly removing large amounts of speed before approaching a corner also results in slower cornering times compared to gradual braking to remove speed (Reijne et al., 2018). Participant's beliefs and the available evidence suggest that coaches should be placing importance on teaching triathletes to corner effectively in cycling not only to minimise time lost in corners, but also as cyclists may be losing additional advantages by not being close enough to the pack to take advantage of drafting.

In relation to swimming, participants (*n* = 9) described the importance of cornering and changing direction in relation to the strategy to getting around the buoy effectively: "Whoever gets to that buoy first is kind of in the best [race] position" (SS1), "Turning at buoys with a massive group of people is usually a disaster" (TRI1). There were two acknowledged methods that participants believed triathletes should use to change direction effectively at the buoy: "If you think about rounding a base in softball, you can go straight to the base and cut hard or you can make this nice arc into it and continue on" (SS4). Furthermore, the optimal line to take in swimming lacks the guidance of road confinements that are present in cycling making it difficult to determine an optimal angle of approach. In addition to this, average swimming velocities are much lower than cycling and running requiring less acceleration and deceleration to approach the corner and return to optimum travelling velocity. Therefore, the optimal path and strategy to use to swim around a buoy is unknown. While the best strategy to adopt is unclear, it is likely to depend on course design, placement and degree of turn and number of competitors trying to turn at the buoy.

A small number of participants (*n* = 4) reported that changing direction in running is an important discrete motor skill required for elite performance in triathlon: "Triathletes don’t execute corners very well. They take these big, weird steps and might be adding extra metres every lap" (SS4). When asked how triathletes might do this better, participants responded: "Not killing too much speed in, then basically accelerating out and settling back into pace" (SS4). Change of direction skill has been investigated in field team sports and may be able to guide change of direction skills for triathletes during races (dos Santos et al., 2019).

Cornering during the cycle leg of a triathlon has been identified by participants as an important motor skill for triathletes to learn to be successful at the elite level. However, investigations of the determinants of cornering performance and the effects of cornering performance on overall cycling performance with representative task design are scarce. Deeper investigations into vehicle handling motor skills have been conducted in motor sports, where some concepts can be transferred from motorcycle handling to bicycle handling due to the similar dynamics of both machines (Zignoli et al., 2021). When travelling through a corner, the maximum speed that can be maintained is based on the friction present between the tyres and the road therefore, motorcycle riders are able to change their body position to influence the tyre-road friction forces that allow higher velocities to be maintained through a corner (Zignoli et al., 2021). Therefore, the ideal posture to form when moving through a corner, should be one that also maximises tyre-road friction and velocity, however, the specific invariant features of this posture are not well understood.

Transition Skills

Participants (*n = 14)* reported that the execution of the transition between triathlon disciplines such as entering and exiting the water on the swim or mounting and dismounting the bike was an important discrete motor skill that contributes to performance in triathlon: "You don't win a triathlon in the transition, but you often lose it" (AT1). While no participants suggested that these motor skills were most critical or expert performance was required to win, this participant group believed that these motor skills could be useful to gain an advantage over other triathletes and therefore were worth learning and practising. Indeed, research indicates that time lost in transitions between triathlon disciplines has a significant small to moderate relationship to final finishing position in major world championships and Olympic games (transition one: $r = 0.34$; transition two: $r = 0.43$) (Cejuela et al., 2013). This evidence further illustrates that while transitions may not entirely decide a race, they deserve some targeted training and with the introduction of shorter distance triathlons (such as the mixed team relay) to the Olympics where transitions occupy a relatively larger proportion of the race, the relative importance of transitioning quickly is increased.

During transitions, participants identified that an important motor skill was being able to quickly mount and dismount the bike using a 'flying' or 'running' mount: "You see some triathletes who almost stop, get on the bike and start cycling. They've lost five seconds. Some of them charge at full pace and leap on the bike and get going really quickly" (POT2). Also, during transition, the design of the racecourse means that several different swim-starts are common, and triathletes should be able to perform all of them: "Some races start on like a bank, like a riverbank type thing. Some off a pontoon" (SS1), "A deep-water start is starting in the water sculling and starting from zero" (TRI1). Pontoon starts require triathletes to dive into the water and this was a point in the race that triathletes could potentially gain an advantage: "The three big areas would be the propulsion, off the pontoon or the starting line. The angle of entry […] then the third one is the underwater control of the body" (C4). Alternatively, triathletes may be required to begin the race on the beach where 'porpoising' or 'dolphin diving' would be required:

> Swim as long as you can until your hand touches the sand or the bottom. And then with porpoise, trying to keep a high knee so that you can lift your legs out of the water until you can make that first dive. (TRI2)

Participants also suggested that 'porpoising' should be performed to exit the water if there is a substantial stretch of beach entering into the first transition.

Aside from performing activities required to transition from one discipline to another there are believed to be additional temporary physiological, kinematic, and coordinative effects of transitioning between one discipline to the other that are not associated with the discrete transition phase. A small number of stakeholders in triathlon (*n* = 3) believed that prior cycling performance causes deleterious effects on subsequent running motor skills: "Early on I worked out that most of the running injuries people had actually been the results of tightness’s they got while biking" (C3), and an equally small group (*n* = 3) considered there to be negative effects of swimming on cycling performance: "I think the most difficult part of any triathlon is the swim to bike transition. Because you've just gone from horizontal to a postural change" (SS2). The primary mechanisms explaining performance reduction have been noted in the literature as disrupted biomechanics, physiology and motor control leading to reduced cycling and running performance (Peeling & Landers, 2009; Walsh, 2019). While these effects are minimal in elite triathletes, they are significant in more novice triathletes (Walsh, 2019). This indicates important considerations for youth triathlon coaches. Firstly, coaches of novice triathletes should tailor their performance expectations and training prescription to account for the associated performance disruptions. Secondly, it is reasonable to suspect that because elite triathletes train the cycle to run transition and perform this regularly in competition, they are more resistant to the deleterious effects of cycling on running performance. This highlights the importance of prescribing deliberate practise of the cycle to run transition.

10.4.3 Adaptability in Continuous and Discrete Motor Skills

In all triathlon disciplines, for both continuous and discrete motor skills, participants ($n = 18$) repeatedly emphasised the importance of athletes being able to adapt skill execution to changing environments around them: "I would say that the elite should really have a bag of skills that if they’ve been taught well enough, they can change the dial slightly" (C3). Participants recognised that the environment within a race could be very dynamic due to the course design, the athletes' position in the race and the presence of other competitors around them: "I: What does a dynamic course look like? C6: Ocean swim, grid style bike course, hilly run with a lot of turns, different surfaces" (C6). The result of this is the belief that triathletes need to practise skills in a variety of different ways to prepare them for the inevitability of change in the environment: "The coach could take them to a surf lifesaving club beach" (C5), "If you implement proprioception training […] running on difficult surfaces, rocks and cross country and so forth. You’ll find an athlete’s ability to handle the rocky grounds improves a lot" (C3). This insight provides a valuable perspective on the importance of adaptable motor skill performance in triathlon that should be considered by coaches to aid the design of effective training prescription.

While participants believe that triathletes need to adapt motor skills to the environment, they discussed this belief in relation to some motor skills more than others. The most discussed motor skill that should be adapted to the environment was swimming stroke: "Some events are a pool swim […] that's going to be a bit different to the ocean swims […] you use your head and arms different compared to what you would in the pool" (POT5). Participants also discussed how athletes had to adapt their posture and cadence to riding up and down hills:

> If I'm climbing a hill, then my body position needs to be more forward in order to apply more torque […] so I've got to have balance from left and right, but also got to have balance and coordination forward to back. (C6)

The relatively open nature of triathlon has impacts on the way that triathlon specific motor skills should be practised to transfer to competition effectively.

One of the goals of sport training is to practise activities that positively transfer motor skill learning to the competitive environment (Magill & Anderson, 2014). The transfer of learning from practise to competition is context dependant (Rosalie & Müller, 2012) and the structure and type of practise have been shown to be important variables when maximising transfer of learning to different competitive contexts (Magill & Anderson, 2014). Participants recognised that triathlon motor skills performance must be transferred to a variety of environmental contexts, therefore motor skills must be practised within the specific learning domain to elicit the desired improvements in triathlon motor skill performance (Rosalie & Müller, 2012). Therefore, if coaches want to promote adaptability of motor skill performance in their athletes varying environmental, task and individual characteristics of the learning domain must be a consideration in training prescription.

10.5 Conclusion

In conclusion, this research has provided a novel and broader understanding of the beliefs, attitudes, and experiences of stakeholders in Australian triathlon regarding important motor skills that are required to succeed at the elite level of the sport. We identified that stakeholders in triathlon believe that continuous motor skill performance is highly important. Further, to ensure young triathletes learn continuous motor skills effectively, the invariant features of swimming, cycling, and running and the ability to parameterise their absolute duration should be trained. Thus, deliberate practise that improves the aforementioned aspects of triathlon locomotion patterns is warranted (Ericsson et al., 1993). A further finding was that coaches need to ensure training prescription includes a focus on teaching the relevant discrete motor skills such as cornering; change of direction skills; diving and porpoising; and mounting the bike with a 'flying mount'. The final key insight in this research is that participants believe that triathletes need to be able to adapt motor skill performances to the variable environment typical to triathlon. Adaptability of learning should be an important consideration for coaches as competition and training may differ in key characteristics such as the environment, variability in the task being completed and internal regulatory conditions which all have an influence on motor skill performance (Müller & Rosalie, 2019; Rosalie & Müller, 2012).

This research clearly indicates that stakeholders in Australian triathlon believe that the acquisition of motor skills is important for expert triathlon performance. However, previous research on triathlon competition readiness has not identified expert motor skill performance as important (Etxebarria et al., 2019). Thus, there is a disconnect between the beliefs of stakeholders within the sport and current evidence. This research also provides a theoretical basis for analysing motor skill performance in triathlon by investigating the subskills that are believed to be important and relating these to Schmidt's schema theory of motor control. The practical implications of this research are administrators can use this research to help guide the content of their education, evaluate how the design of racecourses places emphasis on important motor skills to be learned by young athletes and informs the content of triathlon coaching qualifications. Furthermore, this research also has implications for athletic performance staff who may not have a history of competing in triathlon but require intimate knowledge of the sport to make choices about programming exercises with greater transfer to triathlon performance. Future research should aim to construct an evidence-based skill development pathway to help coaches create intentional and targeted improvements in youth triathletes motor skills performance. The implementation of a seasonal, evidence-based, modified triathlon motor skills program could be an avenue that allows young triathletes to begin participating in triathlon and learning the required motor skills without placing them in a training environment that exposes them to burnout and avoidable overuse injury

The strengths of this research are that it obtains a generalised perspective of a variety of stakeholders within triathlon (Braun et al., 2016; Smith & Sparkes, 2016). By engaging in long duration interviews with participants a large amount of detail was able to be obtained about the important motor skills in triathlon. While this has generated detailed insights into triathlon motor skills from a wide variety of stakeholders in the sport, it was limited to obtaining these insights within Australia, whereas additional and unique insights could be obtained by recruiting participants from other nations. Furthermore, a large proportion of participants were male and recruited from one national sporting organisation, or other allied state sporting organisations and this may present some gender and organisational bias. As with any qualitative investigation, our findings do not allow us to confirm the relative importance of any triathlon motor skills compared to any others and therefore, we are limited to asserting that the motor skills and subskills described by participants are worth some consideration to learn for elite success. As such it is only appropriate to suggest that these motor skills should be considered during an evidence-based triathlon motor skills training program.

To conclude, stakeholders in youth triathlete development should consider the acquisition of proficient motor skills to be an important part of developing elite triathlon performance. However, the scientific literature lacks investigations that help guide the acquisition of proficient triathlon motor skills. Therefore, we recommend that researchers use our investigation as a starting point to begin developing a framework to guide triathlon motor skill acquisition.

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11.0 Chapter 3: A Single Trunk-Mounted Wearable Sensor to Measure Motor Performance in Triathletes During Competition

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11.1 Abstract

The objective of this research was to validate a single, trunk-mounted wearable sensor (Optimeye S5, Catapult Australia, Melbourne) to measure the cadence of swimming strokes, cycling pedals, and running strides in a triathlon. While similar validations have been performed in swimming and running, it is a novel application in cycling, and thus, across a whole triathlon. Seven triathletes were recruited to participate in a sprint distance triathlon which was filmed and simultaneously measured by a single, trunk-mounted wearable sensor. To validate the wearable sensor, individual swimming strokes, cycling pedal strokes and running strides were manually counted by viewing the wearable sensor data and video footage. While analysing cycling data, changes in cycling subtask performances were noticed, thus, a secondary analysis in cycling was conducted to investigate. The 95% limits of agreement analysis indicated the sensor validly measured swimming strokes (mean bias = -0.034 strokes), cycling pedal strokes (mean bias = -0.09 strokes) and running strides (mean bias = 0.00 strides) with minimal to no bias ($p > 0.05$). Further analysis of cycling revealed the wearable sensor is an acceptably valid tool to measure the duration of out of saddle riding (mean bias = 0.08 seconds), however, significant differences in the duration of in saddle riding (mean bias = -0.5 seconds) and coasting were identified (mean bias = 0.39 seconds). A single trunk mounted wearable sensor is a valid tool to measure movement cadence in a triathlon, however, further validation is required to generate a full understanding of cycling subtask performances.

11.2 Introduction

The validity of wearable sensors to measure human movement has been researched extensively (Crang et al., 2021; Hinton-Lewis et al., 2016; Kobsar et al., 2020; Mooney et al., 2016). Wearable sensors provide coaches and sport scientists with the ability to measure human movement in ecologically relevant tasks without the constraints of measuring movement within a laboratory. This flexibility is particularly advantageous when measuring an athletes' performance within competitive situations where movement intensity is high and the task and environmental constraints are difficult, if not impossible to replicate in a laboratory (Dicks et al., 2008). In multi-discipline sports such as the triathlon, wearable sensors may provide a useful way of measuring athletic performance under a unique set of constraints as athletes must effectively utilise multiple different modes of locomotion (swimming, cycling, and running). Additionally, due to the constraints of the racecourse, triathlon coaches find it difficult to gain a comprehensive understanding of their triathlete's performance within a race. Therefore, wearable sensors provide an opportunity for a coach to gain objective performance information (i.e., movement velocity, movement cadence, and power) even when the coaches cannot see their triathletes.

Wearable sensors used in sports commonly contain a combination of micro-sensors, including GPS technology and inertial measurement hardware such as tri-axial accelerometers, gyroscopes, and magnetometers (Crang et al., 2021). While each sensor allows the measurement of unique performance metrics, the integration of these signals provides a rich source of information detailing the sporting performance (Crang et al., 2021). By providing coaches with a tool that gives detailed information about their athlete's performance, one important facet of the coaching process can be improved by enabling better informed decisions regarding training prescriptions. In the individual disciplines of the triathlon, wearable sensors have been validated to objectively analyse swimming stroke kinematics (stroke type, joint position and accelerations) (Ganzevles et al., 2017; Mooney et al., 2016), swimming stroke phase detection (Cortesi et al., 2019; Mooney et al., 2016), swimming stroke count and rate (Ganzevles et al., 2017; Mooney et al., 2016), swimming velocity; and swimming kick count and rate (Mooney et al., 2016). Wearable sensors have also been used to measure running performance metrics like ground contact time and strike patterns; stride rate, length and time; lower leg accelerations; running speed; vertical oscillations; arm movements; stride kinematics (Benson et al., 2018); and running surfaces (Worsey et al., 2021). To measure these performance metrics a variety of sensors and attachment locations such as lower and upper back; wrist; head; wrist and upper back in combination (Ganzevles et al., 2017; López-Belmonte et al., 2023; Mooney et al., 2016); thigh; shank; and foot (Benson et al., 2018) have been used. In contrast, research using wearable sensors in cycling is limited to investigations of activity classification (Ermes et al., 2008), joint kinematics (Cordillet et al., 2019), and kinetics (Millour & Plourde-Couture, 2023). Thus, gaining an understanding of triathlete performance across an entire race is difficult.

The optimisation of swimming stroke rate, cycling pedal and running stride rate was recently identified by triathletes and high performance triathlon coaches as critical to elite performance (Chesher et al., 2022). Furthermore, the ability to maintain swimming stroke, stride and cycling pedal rate during fatigue or modulate these rates according to the environment and race context is believed to be an important aspect of motor skill expertise in the triathlon (Chesher et al., 2022). To date no one has investigated the ability for a single wearable sensor to measure the swimming stroke rate, cycling pedal cadence, and running stride rate consecutively throughout a triathlon. To validly measure these performance metrics in all three modes of locomotion, many common sensor locations may be inappropriate. Thus, a trunk-mounted, multi-sport capable, wearable sensor that collects high frequency inertial and GPS data may enable coaches and other athletic performance staff to draw more detailed and accurate inferences about triathlon motor skills performance.

Therefore, the aim of this research was to extend previous investigations of important motor skills in elite triathlon performance (Chesher et al., 2022) by determining if a single trunk-mounted wearable sensor is a valid method of measuring the frequency of swimming strokes, cycling pedalling cadence, and running strides in a triathlon. We hypothesised that the swimming stroke, cycling pedal stroke, and running stride rate would be validly measurable with a single trunk-mounted wearable sensor during a triathlon.

11.3 Materials and Methods

11.3.1 Participants

A heterogenous sample of seven triathletes were recruited for this study (three females and four males; mean age = 16.29 ± 2.5; competition level: one Tier 4: Elite/International; five Tier 3: Highly Trained/National; and one Tier 2: Trained/Developmental) (McKay et al., 2022). This type of sample was recruited to validate the wearable sensor on triathletes of a variety of skill levels and ages. Participants were included if they were at least 12 years of age, could swim continuously for 200 m, cycle 10 km and run 2 km. Participants were excluded if they had any injury that prevented them from participating in training or competition or prevented them from completing the distances required in the inclusion criteria. Informed consent was sought from all participants aged 18 years and older as well as the parents of participants under the age of 18. Assent was provided by participants who were under 18 years of age. Ethical approval for this research was obtained from the institution's human research ethics committee (HRE2022-0048).

11.3.2 Methodology

A specific triathlon course was constructed, and video footage of the triathlon was used as the gold standard to examine the validity of the wearable sensors (Optimeye S5, Catapult Australia, Melbourne). In this investigation the term "validity" is the psychometric property of the measurement device to provide accurate measurements that truly represent a particular construct as intended (DeVon et al., 2007). The investigation was conducted at a water sports centre and the course used was set in a similar fashion to local races held at the centre (Figure 5). Prior to beginning the triathlon, participants laid out their equipment in a transition area that was constructed with bike racks as per competition rules. Participants then warmed up by completing five to ten minutes of low intensity activity in each mode of locomotion and then performed a sport specific warm-up led by the primary investigator (Jeffreys, 2007). Participants were briefed on the course and instructed to complete the triathlon at competition intensity, however, they should avoid taking unnecessary risks when over taking or cornering whilst cycling. The experiment began with a 'time-trial like' race start where triathletes left the start line 30 seconds apart. They then completed a swimming course consisting of a 400 m swim containing two right angle turns and one U-turn, which started and ended on a shoreline. Participants then entered the transition area and continued to a cycling course of approximately 20 km which consisted of four laps of an elongated rectangle around the water sports centre. At the end of the cycling course, participants once again entered transition and then ran out to a 5 km running course consisting of two laps along a footpath and back to transition. These distances were chosen to represent the length of a junior sprint triathlon (World Triathlon Technical Committee, 2022).

Figure 5. *Course Map.*

Note. An aerial picture of the racecourse showing the swim (400m), cycle (20km) and run (5km) path taken by the participants. Transition was within the circle.

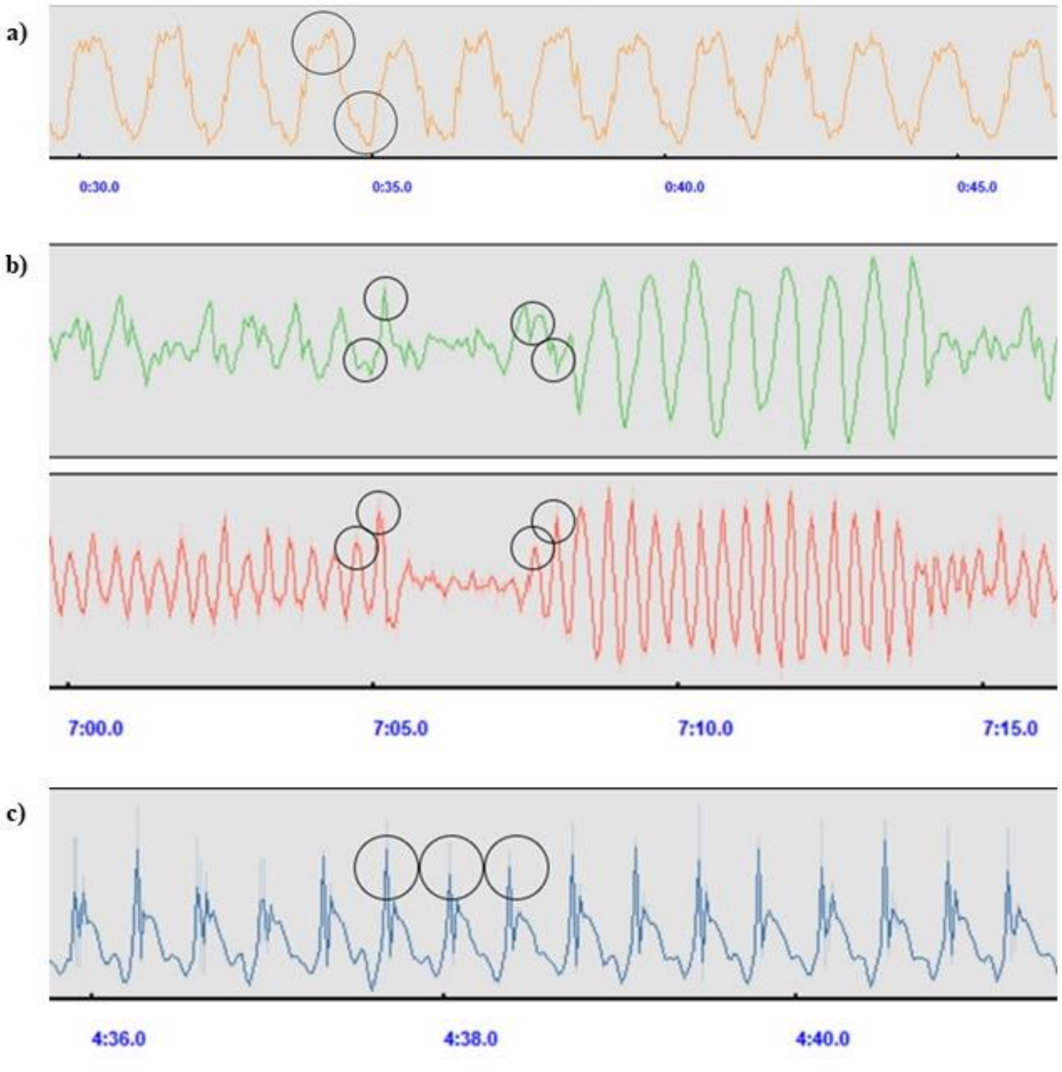
11.3.3 Instruments

Wearable sensors containing a tri-axial accelerometer and gyroscope sampling at 100 Hz were placed in a waterproof covering and secured to the lining of the triathlon suit between participants' shoulder blades and held in place by the suit zip (Appendix C). This location was chosen to gain movement information during each discipline across the triathlon as it is becoming commonplace for triathlon suits to be manufactured with a pouch for a wearable sensor attachment between the shoulder blades. This wearable sensor is able to measure sport specific accelerations in three planes with a maximum mean bias of 0.08 ms^{-2} (Roell et al., 2018). To validate the ability of a single trunk-mounted wearable sensor to measure swimming stroke rate, cycling cadence and stride rate, each participant was paired with a volunteer who filmed the participant throughout the triathlon using two cameras. The first camera (CasioEXZR-800, Exilim, Tokyo, Japan) was attached to a tripod and filmed the swim from a pontoon halfway between the start of the swim and the turnaround buoy. The second camera (Hero Session 5, GoPro, California, USA) was attached to the handlebars of the participant's bike facing towards their legs while cycling. This camera was then transferred to a second bike during transition two that was ridden by the paired volunteer and followed the participants during the run. The volunteers following participants during the run were instructed to remain approximately 5-10 m behind the participant. Both cameras were filming at 30 frames per second. To time synchronize the wearable sensor with the video footage and demarcate the start of each portion of the triathlon, the primary investigator was filmed striking the wearable sensors five times with moderate force to produce distinct antero-posterior accelerations that could be recognised when analysing the data. Participants were stopped briefly (less than 10 seconds) to perform the time synchronization prior to the start of each discipline once the participant had finished their transition.

11.3.4 Wearable Sensor Analysis

To answer the research question, wearable sensor data and video footage were both imported using manufacturer supplied software (Catapult Sprint 5.1.7, Catapult Sports Pty Ltd., Melbourne, Australia; and GoPro Quik 2.7.0.945, GoPro, California, USA). Video footage was analysed in a separate video player that allowed simple and flexible navigation through the video (Avidemux 2.8; Mean, Gruntster & Fahr; Paris, France). Wearable sensor manufacturer software was used to demarcate the three disciplines of the triathlon which were identified from distinct antero-posterior accelerations created by striking the wearable sensor. To identify swimming strokes, medio-lateral accelerations were analysed by counting peaks and troughs in the data (identified by circles in Figure 6a). Gyroscopic 'yaw' measurements were inspected to determine whether a pedal stroke had occurred in cycling. On preliminary inspection of the gyroscope data, coherent patterns that indicate pedal strokes could not be consistently identified. Subsequently, the peaks and troughs of the ‘yaw’ data were coupled with peaks in antero-posterior acceleration to provide a better measurement (identified by circles in Figure 6b). Troughs and peaks in the gyroscope signal occur through rotation of the torso that indicates contralateral pedal strokes are occurring. When they also coincide with a peak in forward acceleration generated by the cyclist pushing the pedals, it can be inferred that a pedal stroke has occurred. Lastly, running strides were identified by counting peaks of vertical acceleration (identified by circles in Figure 6c). Swim strokes, pedals, and strides were counted in ten-second time windows and recorded on a custom spreadsheet (Excel 2019, Microsoft Corporation, Redmond, Washington).

Figure 6. *Sample of Wearable Sensor Manual Identification of a) Swim Strokes, b) Pedals and c) Running Strides.*



Note. Circles in this figure show a) swimming strokes (medio-lateral acceleration), b) cycling pedal strokes (top signal represents 'Yaw' gyroscope, and bottom signal represents antero-posterior acceleration) and c) running strides (vertical acceleration) that were manually counted in the wearable sensor data. Measurements along the x-axis are 'Time' in the format m:ss.0.

11.3.5 Video Footage Analysis

To count swimming strokes the primary investigator viewed the video footage and counted the number of swimming stroke cycles that began in each ten second window. A swimming stroke cycle was determined to have begun if any part of the limb from fingertips to elbows entered the water during the time window. While viewing each cycling video, a pedal stroke was counted if the participant's foot reached the bottom of the revolution during the time window, and this coincided with a peak or trough in the yaw data of the gyroscope. When this pattern was interrupted, the gyroscope data was supplemented with peaks in antero-posterior acceleration to identify where pedal strokes may have occurred. To count running strides from the wearable sensor data, double peak vertical accelerations were identified where the first peak represented the heel strike of the running gait cycle. When viewing running videos, a stride was counted in the current time window if a heel strike occurred. Each video was played through frame by frame, skipping quickly through frames in the middle and slowly at the boundaries of each ten second time window to ensure swimming strokes, pedals and strides were counted in the correct window. Swimming strokes, cycling pedal strokes, and running strides were also recorded on the custom spreadsheet (see Section 11.3.4). A similar validation method has been used by Beanland et al. (2014) and Wundersitz et al. (2014) in swimming and running respectively.

11.3.6 Statistical Analysis

These data were then exported to a statistical analysis program (Statistical Package for the Social Sciences 26.0, IBM, Armonk, New York). A Kolmogorov-Smirnov test of normality was used to check the distribution type of swimming strokes, cycling pedal strokes, and running strides individually. Then a paired samples t-test for swimming and a Wilcoxon Signed-Rank test for cycling and running was used to check for significant differences ($p < 0.05$) in the swim stroke, pedal and stride count between the wearable sensor and video footage. A two-tailed post-hoc power analysis (GPower 3.1.9.7, Heinrich Heine Universität Düsseldorf, Düsseldorf, Germany) with effect size set to 0.8 and alpha level of 0.05 was then performed to determine the statistical power of both parametric and non-parametric differences testing to detect significant differences between the two measurement devices. The mean difference ($\text{mean}_{\text{sensor}}$ - $\text{mean}_{\text{video}}$) and limits of agreement (LoA) between the wearable sensor and video footage to measure swim stroke, pedal and stride count were then calculated. The LoA were calculated according to Bland and Altman (1986) method where there are repeated measures per individual (Bland & Altman, 2007). A one-way ANOVA was performed to determine the mean square regression and error. Next the total variance was calculated, and the standard deviation (SD) was derived from this value. Finally, the 95% LoA were calculated as the mean difference ± (1.96 * SD) and displayed on a scatterplot (Figure 7) of differences between concurrent measurement pairs (y-axis) vs. the mean of concurrent measurement pairs (x-axis).

11.3.7 Secondary Analysis

Following the preliminary analysis of the results, the primary investigator (SC) noticed regular changes in cycling tasks being performed throughout the race and this coincided with interruptions in the wearable sensor signal. To investigate the interruptions in wearable sensor signal, a secondary analysis was conducted to describe changes in cycling subtasks and examine the accuracy of the wearable sensor to measure them. The cycling subtasks performed throughout the race were: ‘in saddle riding’: participant is riding with legs actively turning and gluteus maximus in contact with the bike seat; ‘out of saddle riding’: participant is riding with legs actively turning and gluteus maximum not in contact with the bike seat; and ‘coasting’: participant is riding the bicycle without the active turning of the pedals either in contact with the seat or not, for longer than one second. Therefore, during the secondary analysis the primary investigator counted the occurrences and timed the duration of each task. To count the occurrence and duration of cycling tasks the ‘yaw’ gyroscope and antero-posterior accelerations were re-analysed, however, this time the peaks and troughs of vertical and medio-lateral accelerations were included to improve the delineation of tasks. Subsequently, each piece of video footage was viewed, and the beginning and end timestamp of each cycling task was recorded on two separate customised spreadsheets for each measurement method.

Descriptive statistics such as a count of cycling tasks and the sum of each type of task duration were calculated for each participant. From the descriptive statistics, multiple paired t-tests were performed to check for significant differences between the wearable sensor and video footage for the count of each cycling task and a bias of estimation for the number of cycling tasks recognised by the wearable sensor. Subsequently, to determine the precision of the wearable sensor to measure the duration of each cycling task a Bland Altman LoA analysis (Figure 8) was used to compare all paired measurements of cycling task duration. In this analysis, the difference in duration between concurrent measurement pairs (y-axis) was plotted against the mean duration of the concurrent measurement pairs (x-axis). In any instances where cycling tasks had been incorrectly recognised in the wearable sensor data, this created a single task with no pair from the video footage. In these cases, unpaired measurements (7% of the data set) were excluded from the analysis.

11.4 Results

Video cameras were successful at capturing 100% of the run portion for each triathlete. However, due to technological error the cycle portion of two participants were lost. Further, ten 10-second windows (10/189: 5.3%) from the swim were discarded as the video footage was substantially obstructed. This resulted in a final comparison of 179 concurrent measurement pairs in swimming, 510 concurrent measurements pairs in cycling and 493 concurrent measurement pairs in running data for validity analysis. The two-tailed post-hoc power analysis revealed that at an alpha level of 0.05 a sample of this size has a statistical power of 1.0 and β = 0.0. Additionally, similar participant numbers have been used in other investigations of wearable sensor validity to measure human movement tasks (Akenhead et al., 2014; Worsey et al., 2021). Results of the Kolmogorov-Smirnov test of normality showed swimming was normally distributed (Skewness (SK) = -1.2, Kurtosis (KS) = -2.8), while cycling (SK = -2.0, KS = 8.1) and running (SK = -3.7, KS = 32) were non-parametric.

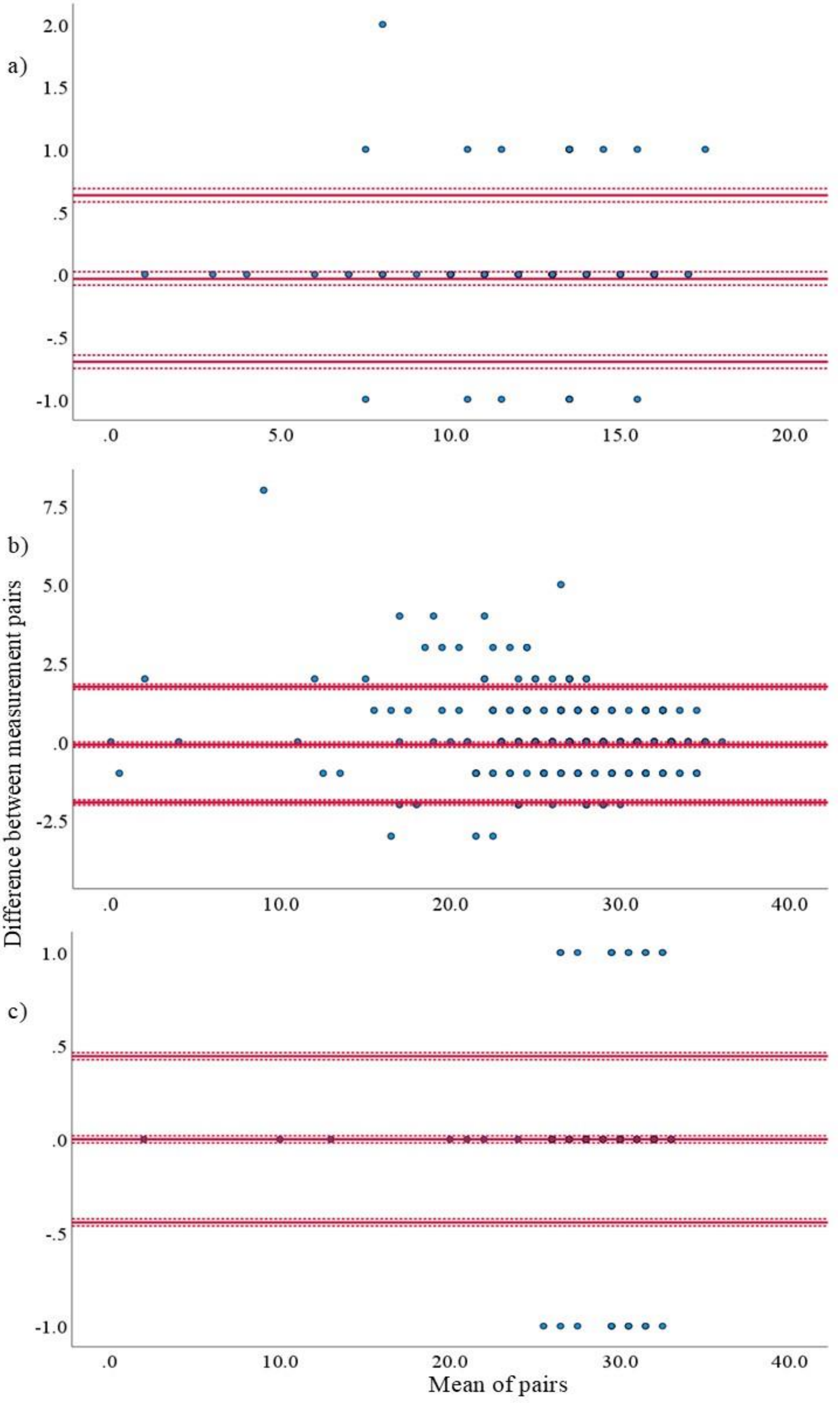
From our initial analysis, results indicated strong agreement for a single trunk-mounted wearable sensor to detect swimming strokes and running strides in a triathlon with a small bias of under-estimation to detect swimming strokes and no bias when detecting running strides (Table 1 and Figure 7). However, there was a statistically significant bias of underestimation when using the wearable sensor to detect the number of pedal revolutions in cycling (Table 1 and Figure 7).

Table 1. *Limits of Agreement (LoA) Analysis of Swim Stroke, Pedal and Stride Count by a Wearable Sensor and Video Footage.*

Discipline	**Mean of Paired Differences (95% CI) (swim strokes, pedals, or strides)**	**p-value**	**95% LoA (95% CI) (swim strokes, pedals, or strides)**
Swim	-0.034 (-0.087 to 0.020)	0.22	-0.70 (-0.75 to -0.65) to 0.63 (0.58 to 0.69)
Cycle	-0.090 (-0.173 to -0.008)	0.08	-1.93 (-2.01 to -1.85) to 1.75 (1.67 to 1.83)
Run	0.000 (-0.019 to 0.019)	1.00	-0.44 (-0.46 to -0.43) to 0.44 (0.43 to 0.46)

Note. The 95% LoA describe the precision of the calculated bias and gives a range that 95% of future measurements will fall between. The mean difference is significant (wearable sensor vs video footage count) at an alpha level of 0.05. CI: confidence interval.

Figure 7. *95% Limits of Agreement (LoA) Scatterplots of Swimming Stroke (a), Pedal (b) and Stride (c) Count by a Wearable Sensor and Video Footage.*



Note. Central solid line represents the mean bias. Outer solid lines represent the 95% LoA. Dashed lines represent 95% confidence interval of the mean bias and 95% LoA.

From our subsequent re-analysis of the cycling portion of the triathlon, participants spent 93.6% (± 1.8%) of their time 'in saddle' riding, 4% (± 2.2%) of their time 'out of saddle' riding, and 2.4% (± 0.6%) coasting. There were no significant differences between the counts of any of the tasks of in saddle, out of saddle and coasting cycling obtained from the video and the wearable sensor (Table 2).

Table 2. *Results of Multiple Paired T-Test of Cycling Task Performance Counts.*

Cycling Task	**Sensor Count**	**Video Count**	**p-value**
Total Task Performed	191	197	0.43
a) In Saddle	88	98	0.13
b) Out of Saddle	52	51	0.32
c) Coasting	49	48	0.62

With errors in cycling task detection removed, this left 85 concurrent measurement pairs of in-saddle riding, 51 concurrent measurement pairs of out-of-saddle riding and 47 concurrent measurement pairs of coasting for analysis. The results of the Bland-Altman 95% LoA analysis of the durations of each cycling task are reported in Table 3 and Bland-Altman 95% LoA plots displayed in Figure 8.

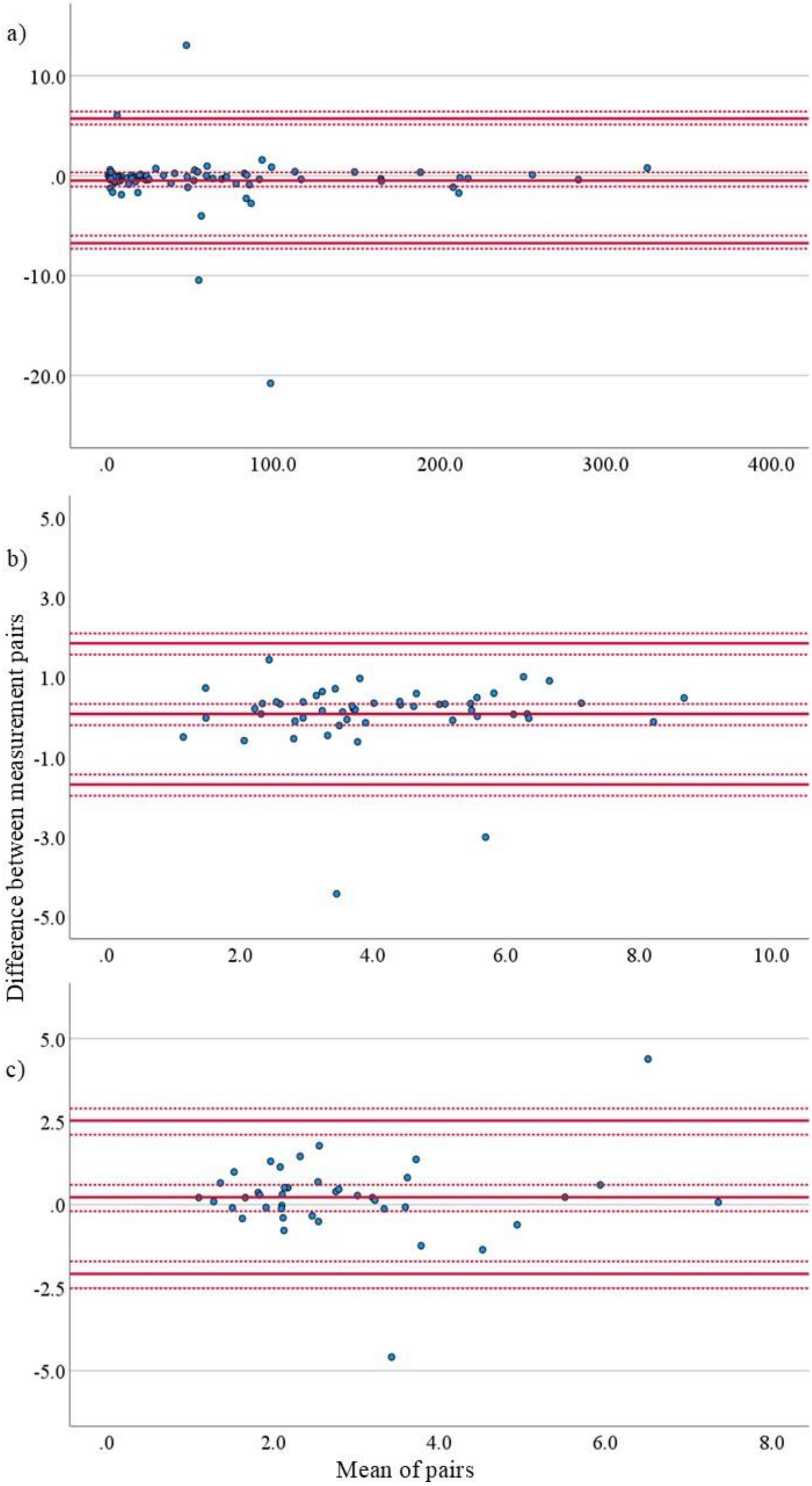
Table 3. *95% Limits of Agreement (LoA) Analysis of Cycling Task Duration for In Saddle Riding, Out of Saddle Riding and Coasting.*

Cycling Task	**Mean Differences (95% CI) (sec)**	**p-value**	**95% LoA (95% CI) (sec)**
In Saddle Riding	-0.45 (-1.11 to 0.19)	< 0.001	-6.71 (-7.31 to -6.01) to 5.71 (5.11 to 6.41)
Out of Saddle Riding	0.08 (-0.2 to 0.33)	0.55	-1.69 (-1.97 to -1.44) to 1.85 (1.57 to 2.10)
Coasting	0.39 (0.19 to 0.58)	< 0.001	-0.93 (-1.13 to -0.73) to 1.71 (1.51 to 1.91)

Note. The mean difference is significant (wearable sensor vs video footage) at an alpha level of 0.05. CI: confidence interval.

There is a lack of significant differences between the video footage and wearable sensors when measuring the duration of out of saddle cycling tasks (Table 3). However, some statistically significant bias of overestimation of the duration of coasting tasks and underestimation of in saddle tasks exist, although, these differences are small.

Figure 8. *Bland Altman 95% Limits of Agreement (LoA) Analysis of Cycling Task Duration. (a) In Saddle Riding, b) Out of Saddle Riding, c) Coasting).*



Note. Central solid line represents the mean bias. Outer solid lines represent the 95% LoA. Dashed lines represent 95% confidence interval of the mean bias and 95% LoA.

11.5 Discussion

This research was conducted to follow on from the Chesher et al. (2022) investigation of important motor skills for elite triathlon performance by validating the measurement of some of the these motor skills in the field. Thus, this is the first investigation to validate a single wearable sensor that can be utilised across an entire triathlon without the combination of multiple incompatible data streams produced by wearable sensors from different manufacturers. Consistent with our hypothesis, our results support the validity of a single trunk-mounted wearable sensor for counting swimming strokes, pedal strokes during ‘in saddle’ and ‘out of saddle’ cycling, and running strides in a triathlon.

The wearable sensor has a trivial bias to underestimate swimming strokes by less than one stroke per minute (-0.20, 95% CI: -0.52 to 0.12) with the limits of agreement indicating that 95% of future measurements by the sensor will fall within 4.2 under and 3.78 over per minute. The wearable sensor also underestimated cycling cadence by approximately one pedal stroke per minute (-0.54, 95% CI: -1.04 to -0.05) and would measure 95% of future cycling strokes per minute by between 11.6 under and 10.5 over. However, this finding was not significant. We also observed no bias of estimation of running cadence (0.00, 95% CI: -0.02 to 0.02) with the limits of agreement indicating that 95% of future measurements by the sensor will fall within 2.6 strides over and 2.6 strides under per minute.

The swimming and running results of this study are consistent with other investigations that have used multiple accelerometers positioned in a variety of locations to measure swimming stroke and running stride cadences (Camomilla et al., 2018; Mooney et al., 2016). However, the validation of a single trunk-mounted wearable sensor to measure cycling cadence is novel. Additionally, using a single wearable sensor with relatively precise GPS and high frequency inertial data capture, that is positioned appropriately to measure motor skills in swimming, cycling, and running allows for a more accurate and nuanced analysis of triathlon performance.

The secondary analysis helps explain interruptions in the wearable sensor signal and describes the cycling task changes that occur during a triathlon. The single trunk mounted sensor was successful at counting the number of cycling task changes that triathletes were performing throughout the triathlon. The approach used was akin to Marsland et al. (2012) who used a similar measurement and analysis method to identify different types of skiing techniques in cross-country skiing. The wearable sensor was also able to detect the number and duration of each out of saddle riding efforts with a trivial mean bias of overestimation (0.08 seconds). Out of saddle riding is useful to produce high amounts of force at the pedal crank and is typically used to accelerate quickly or climb hills (Bouillod & Grappe, 2018). Throughout the triathlon in-saddle riding was the most utilised cycling task and is used to maintain a consistent push-pull pedal stroke while allowing the cyclist to get into an aerodynamic position to reduce the effects of wind resistance (Barry et al., 2015). While the wearable sensor occasionally did not detect when the athlete was riding in saddle, this was not statistically significant. However, there was a statistically significant bias of underestimation (0.45 seconds) of the exact duration triathletes spent in saddle riding.

Similarly, there were statistically significant differences found in the measurement of coasting period duration where the sensor consistently overestimated the length of coasting by 0.4 seconds. Coasting is typically used to traverse a corner or conserve energy (Chesher et al., 2022). There is substantial utility in identifying periods of coasting during the cycle leg of a triathlon. Measuring coasting periods with the higher quality and frequency GPS available from trunk worn sensors, allows accurate analysis of the performance of these tasks in every corner a triathlete traverses during a race. By measuring the path of the cyclist, as well as time-position related characteristics (such as when a triathlete stopped and started pedalling in relation to the corner and the pedalling task employed, in saddle or out of saddle) cornering performance can be described. As noted by Bouillod and Grappe (2018) it is surprising that no investigations exist to characterise the typical time spent performing cycling tasks, perhaps as there has not been a valid tool appropriate for field-based use. The secondary cycling analysis shows that the wearable sensor can measure multiple performance metrics during a race. However, due to the different frequency with which cycling tasks and cycling cadence are performed, the resulting sample size for cycling tasks is small, and a replication of the secondary cycling analysis with greater participant numbers is required.

So far, wearable sensor research in triathlons is uncommon and where it does exist, it focuses on the individual disciplines in isolation and employs wearable sensors (wristwatches, power meters, foot sensors) that are inappropriate to measure motor skills performance in all three disciplines. Therefore, a considerable strength of this study is that it is the first to validate a single wearable sensor to measure triathlon motor skills performance without the combination of multiple data streams from many sensors. In addition, the findings can also be generalized to each of the individual disciplines of the triathlon. When generalising these findings to cycling, it may be beneficial to investigate the validity of counting pedal strokes from an inertial measurement unit attached to the bike instead of the athlete. However, in a triathlon, counting pedal strokes in this way would add additional complexity in performance analysis and undermine one of the primary strengths of this investigation which is measuring movement cadence in all disciplines with a single sensor.

Another strength of the study is that it was conducted in an ecologically valid setting ensuring that the wearable sensor was validated in the environment in which it would be worn. Additionally, triathlon suit manufacturers are beginning to include a similar pouch to the one that was used in this study so that it sits securely and comfortably underneath the suit. When asked if participants were aware of the sensor during the race, they often reported they forgot it was there, thus helping to limit any impact on regular performance. The reference method for validating the wearable sensor was a true gold standard as the swimming strokes, pedals, strides and cycling tasks were directly observable from the video footage. It is also important to note that the statistical methods used to perform a Bland-Altman 95% LoA analysis are a variation of the original method proposed that can accommodate repeated measures on single participants (Bland & Altman, 2007).

A limitation of this validation is that it cannot be extended to cross-triathlons as the uneven surfaces in cycling and running may introduce additional noise in the wearable sensor data and make it more difficult to count cycling pedal strokes and running strides. Additionally, the framework (McKay et al., 2022) used to rate the participant performance level does not provide a direct measurement of performance, thus, without objective performance data, like measurements of maximal oxygen uptake, the real performance level of participants cannot be confirmed. Finally, the processing and analysis of this data is, laborious, time consuming and requires substantial expertise reading accelerometer and gyroscope signals in sport. Therefore, performing a comparable analysis in practice would require a dedicated performance analyst to conduct. Thus, this analysis would benefit from automation with signal processing algorithms and machine learning techniques to improve detection accuracy and reduce resources required.

Future directions for this research should focus on automating the analysis process to save time and improve analysis accuracy. Automatic activity recognition algorithms have been used successfully to detect types of technique in cross country skiing (Marsland et al., 2012; Marsland et al., 2015), recognise jumping and leg lifting tasks in ballet (Hendry et al., 2020), and automatically detect different strokes and tasks in swimming (Delhaye et al., 2022). Thus, there is strong potential for a similar approach here. This investigation has laid the foundation for measuring movement cadence in triathlon. In the future, researchers should use the wearable sensor in question to investigate changes in movement cadence within a triathlon, as well as in response to variables like running shoe and bike tire choice, environmental characteristics of racecourses like hills, and athlete responses to fatigue. Additionally, a similar validation should be performed for cross-triathlon in an environment that is specific to that sport. In cross-triathlon it is even more difficult to obtain performance information from triathletes in a race, thus wearable sensor use could have significant utility in that area. Finally, as this research has established a valid tool to measure swimming stroke rate, cycling pedal rate and task performance and running stride rate at customizable time intervals throughout a race, future research should look to investigate how triathletes typically learn these motor skills over time to understand how to improve rates of motor skill learning among young triathletes.

11.6 Conclusion

In conclusion, this is the first investigation that seeks to validate a single wearable sensor to measure important motor skills across an entire triathlon. Taken together, the findings of this investigation show that a single trunk-mounted wearable sensor is a valid method of manually counting swimming strokes, cycling pedal strokes, and running strides during a triathlon with very high accuracy. Additionally, the secondary analysis in this investigation his highlighted that a single trunk-mounted wearable sensor can detect the occurrence of cycling tasks in triathlon but is not able to accurately determine the duration. This is an important finding as there is no current measurement tool that allows the detection or measurement of cycling tasks, and this could fill that gap by laying the foundation for a time-motion analysis of cycling. While manually measuring the duration of 'in saddle' riding and coasting in cycling could not be validated, it is possible that automatic activity recognition algorithms will be able to detect patterns in the sensor signals that allow for more reliable and valid detection of 'in saddle' riding and 'coasting' tasks.

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12.0 Chapter 4: Automatic Recognition of Motor Skills in Triathlon: Creating a Performance Analysis Tool

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12.1 Abstract

The purpose of this research was to create a peak detection algorithm and machine learning model for use in triathlon. The algorithm and model aimed to automatically measure movement cadence in all three disciplines of a triathlon using data from a single inertial measurement unit and recognise the occurrence and duration of cycling task changes. Seven triathletes were recruited to participate in a triathlon while wearing a single trunk-mounted measurement unit and were filmed throughout. Following an initial analysis, a further six triathletes were recruited to collect additional cycling data to train the machine learning model to more effectively recognise cycling task changes. The peak counting algorithm successfully detected 98.7% of swimming strokes, with a root mean square error of 2.7 swimming strokes. It detected 97.8% of cycling pedal strokes with a root mean square error of 9.1 pedal strokes and 99.4% of running strides with a root mean square error of 1.2 running strides. Additionally, the machine learning model was 94% (± 5%) accurate at distinguishing between 'in-saddle' and 'out-of-saddle' riding, but it was unable to distinguish between 'in-saddle' riding and 'coasting' based on tri-axial acceleration and angular velocity. However, it displayed poor sensitivity to detect 'out-of-saddle' efforts in uncontrolled conditions which improved when conditions were further controlled.

12.2 Introduction

Triathlon is a sport where athletes swim, cycle and run sequentially in a highly dynamic environment which requires them to have well developed continuous motor skills (i.e. swimming, cycling, and running) and discrete motor skills (i.e. cornering skills in cycling) to achieve elite performance (Chesher et al., 2022). To gain a detailed analysis of both continuous and discrete motor skills, three-dimensional motion analysis would be the most appropriate method. However, obtaining this level of detail during a race is logistically and feasibly complex to achieve with any certainty. Additionally, there is substantial inter- and intra- race variation, as races are conducted on courses with varying tidal conditions (swim); differing degrees of difficulty in cornering and elevation changes (cycle and run); and congestion caused by varying densities of triathletes (Chesher et al., 2022). Given these challenges, an alternative method for collecting and analysing data that describes motor skill performance in triathlon is required.

Measuring motor skill performance over time is important for identifying changes in triathletes' motor skills so that intentional training strategies can be applied to improve performance. In triathlon, movement cadence refers to the number of propulsive movements performed within a specific time frame (usually one minute) (Moore, 2016; Ribeiro et al., 2017; Turpin & Watier, 2020). In each discipline of triathlon, movement cadence has been identified as a parameter of swimming, cycling, and running motor skills which should be trained to achieve elite success (Chesher et al., 2022). Within an information processing paradigm, the ability to adjust speed of movement to optimally fit the movement goal is a form of parametrisation (Schmidt, 1975). Therefore, longitudinally measuring changes in movement cadence provides a measurement of a triathlete's ability to parameterise the speed of swimming, cycling, and running motor skills, and as this improves, an improvement in motor skill performance can be inferred (Magill & Anderson, 2014).

Wearable inertial measurement units (IMUs) provide a method of measuring aspects of performance where video capture is not feasible. These wearable IMUs typically contain micro-electromechanical systems (MEMS), such as accelerometers, gyroscopes, and magnetometers, which measure along three axes as well as global position system (GPS) components (Crang et al., 2021). By attaching these sensors to a body segment, information is gathered that can be used to infer the movements of the wearer. Wearable IMUs have been validated to analyse a variety of running and swimming performance metrics (Benson et al., 2018; Camomilla et al., 2018; Ganzevles et al., 2017; Mooney et al., 2016). A recent investigation into the use of wearable IMUs in triathlon showed their validity for detecting swimming strokes, cycling pedal strokes, and running strides throughout a triathlon (Chesher et al., 2024). Although there have been several investigations of wearable IMU use in swimming and running, the automation of movement cadence measurement throughout an entire triathlon from a single wearable IMU is novel. Furthermore, it is important to verify that any performance information obtained by using automatic analysis methods are accurate and valid.

These investigators also explored the validity of the IMU to recognise cycling task changes, finding it to be a valid tool for recognising time spent ‘out of saddle riding’. However, there was a bias towards underestimating time spent ‘in saddle riding’ and overestimating time spent ‘coasting’. Although these biases were statistically significant ($p < 0.001$), the practical differences were small (in saddle riding: -0.45 seconds [-1.11 to 0.19 seconds]; coasting: 0.39 seconds [0.19 to 0.58 seconds]) (Chesher et al., 2024). However, the analysis in this investigation was performed visually, using a time and labour-intensive method, without assistance from machine learning or automatic pattern recognition.

Human activity recognition by machine learning has been used in sports performance analysis as a fast and accurate method to describe and quantify important performance metrics (Delhaye et al., 2022; Hendry et al., 2020; Hulin et al., 2017; Jowitt et al., 2020; Murray et al., 2017). To do this, wearable IMU data are analysed using machine learning algorithms to detect patterns that correspond to specific movement signatures. Analysing data in this way makes it possible to recognise complex patterns across multiple data streams and provide an analysis far quicker than manual analysis methods. Therefore, this investigation aims to advance the application of wearable IMUs in a sprint distance triathlon (750m swim, 20km cycle, and 5km run) by developing an automatic activity detection algorithm to detect swimming strokes, cycling pedal strokes and task changes, and running strides performed in a race.

12.3 Materials and Methods

12.3.1 Participants

Six triathletes (participants 1 – 6; three females and three males; mean age = 16.2 yrs. ± 2.7; competition level: one Tier 4: Elite/International; four Tier 3: Highly Trained/National; and one Tier 2: Trained/Developmental (McKay et al., 2022)) were recruited to participate in a mock triathlon on a course constructed for the research study. These participants were selected as they represented a heterogenous sample of triathletes with a variety of skill levels, ages, and statures. Triathletes were eligible to participate if they were at least 12 years of age, could swim continuously for 200 m, cycle 10 km, and run 2 km, and were excluded if they had any injury preventing participation in training or competition. Informed consent was provided by all participants over 18 years old, while parental consent and participant assent was obtained for those under 18 years old. Ethical approval for this research was granted by the institution's human research ethics committee (HRE2022-0048).

12.3.2 Methodology

To collect movement data, participants completed a triathlon on a specifically constructed racecourse. During the triathlon, each participant was filmed by a paired volunteer while wearing a trunk mounted wearable IMU (Optimeye S5, Catapult Innovations, Melbourne, Australia) to collect movement data. Prior to the triathlon, participants set out their equipment (bike, equipment box, and running shoes) as they would in a race, then completed a ten-minute warm up consisting of low intensity sport-specific activities and dynamic stretching. Participants were then briefed on the course, which consisted of a 400 metre swim in a lake containing three turns, a transition area, four laps of a five kilometre elongated rectangular cycling course (20 km), and two laps of a 2.5 km run course along a footpath (5 km); finishing back at the transition area (Chesher et al., 2024). Participants began the triathlon in a time-trial format, each beginning 30 seconds apart to prevent visual obstruction of the video cameras.

To confirm the occurrence of swimming strokes, pedal strokes and task changes, and running strides, participants were filmed using stationary cameras (CasioEXZR-800, Exilim, Tokyo, Japan) attached to tripods and mobile camera's (Hero Session 5, GoPro, California, USA) attached to the handlebars of bikes ridden by paired the volunteers. Camera set-up and filming technique were briefly piloted during a group training session prior to data collection. Sensor data and video footage were time synchronised at the start of each triathlon segment by striking the sensor five times in view of the video camera to create distinct peaks in the forward accelerometer signal. The wearable IMU contained a GPS sensor, tri-axial accelerometer, and gyroscope, measured 96.5 x 52 x 14 mm, weighed approximately 67 grams and was positioned between the shoulder blades in a custom-made pouch within the triathlon suit. The GPS sampled at 10 Hz, while both the accelerometer and gyroscope sampled at 100 Hz along three axes with measurement ranges of +/- 16 g and 2000 °/sec respectively. Following the triathlon, both video and wearable IMU data were analysed to count the swimming strokes, pedal strokes, and running strides, and to record the time stamp and duration of cycling task changes (Chesher et al., 2024).

To obtain a ground truth value for swimming strokes, pedal strokes, and running strides, the video footage was analysed (Avidemux 2.8; Mean, Gruntster & Fahr; Paris, France), and the movement cadence in each discipline was manually counted and recorded on a custom spreadsheet (Excel 2019, Microsoft Corporation, Redmond, Washington). Swimming strokes were counted when any part of the upper limb from fingertips to elbow entered the water, pedal strokes were counted when each of the participant's feet revolved to the bottom of the pedal crank, and running strides were counted at each heel strike (Chesher et al., 2024).

Cycling task changes were identified by viewing the footage, and the start and end times of each task were recorded. 'In-saddle' riding was defined as pedalling while the gluteus maximus was in contact with the bike seat, 'out-of-saddle' riding was defined as pedalling without contact between the gluteus maximus and the seat, and 'coasting' was defined as riding without actively turning the pedals for more than one second, regardless of seat contact.

From the initial analysis, 'in saddle riding' was substantially overrepresented (90 – 94% of the duration) compared to 'out of saddle riding' (1.5 – 7.8%) and 'coasting' (1.8 – 4.5%) throughout the triathlon. To create a valid machine learning algorithm that recognises each cycling task, additional controlled data with clearly demarcated and evenly represented was required. Thus, 217 minutes of additional cycling data was collected from six participants (participants 7 – 12; four female and two male triathletes; mean age = 20.33 yrs. ± 3.3; competition level: two Tier 4:

Elite/International level; two Tier 3: Highly Trained/National level and two Tier 2: Trained/Developmental level (McKay et al., 2022)) who cycled around a closed track, performing 'in-saddle' riding, 'out-of-saddle' riding and 'coasting' in a specific sequence for equal durations. A 180° turn was included at the end of each lap to ensure an even distribution of turn directions. A different track was used for the second round of data collection (Figure 9) to allow for greater control of the conditions, improving the quality of the data for training the machine learning algorithm. Additionally, conducting the second round of data collection on a different track enhanced the model's validity, generalisability, and robustness to noise (Farrahi & Rostami, 2024).

Figure 9. *Map of Course Used for Additional Cycling Data Collection.*

12.3.3 Creating the Performance Analysis Tool

To automate the detection of swimming strokes, cycling pedal strokes, task changes, and running strides, both a ‘peak counting’ and a machine learning model were created. ‘Peak counting’ refers to counting the peaks and troughs in the accelerometer and gyroscope signal that correspond to swimming strokes, pedal strokes, and running strides. To begin, the accelerometer signals were filtered using a sixth order, bandpass Butterworth filter with lower and upper cutoff frequencies of 2 Hz and 3 Hz, respectively, for cycling and running. The Butterworth filter was chosen for its maximally flat passband response and gradual roll-off from the passband to the stopband, which allows it to effectively remove unwanted frequencies while preserving the desired ones (Wang, 2024). For swimming, the same filter was used, but with lower and upper cut-off frequencies of 0.5 Hz and 1.4 Hz due to the slower movement cadence of swimming. Peaks and troughs of the filtered accelerometer signal were counted using SciPy (2022, version 1.9.2, Enthought, Austin, Texas). The minimum peak detection intervals for each movement were set at 0.5 seconds for swimming, 0.3 seconds for cycling, and 0.25 seconds for running.

Next, a machine learning model was built to classify cycling tasks. The accelerometer and gyroscope signals were combined and filtered using the same method as for peak counting. A Short-Time Fourier Transform (STFT) was then applied using SciPy to convert the time-domain signal into the frequency domain. Signal processing by STFT is commonly used to analyse distinct patterns in signal data (Ramos-Aguilar et al., 2019). The frequency content of accelerometer signals generated by physical activity can change over time, making time-frequency domain analysis more appropriate (Mateo & Talavera, 2018). A window size of 250 samples (2.5s) with no overlap was chosen, resulting in 126 frequency bins for each time step, which were used as additional features for model training. Data standardisation was then performed using the ‘standard scaler’ function in Scikit-learn (2023, version 1.2.2, David Cournapeau). Cycling task classification labels were aligned with the original time series, featuring 0.1 second steps, and with the resampled series from the STFT with 2.5s steps. For each longer step, the most frequent label from the 250 shorter steps was assigned to the long step (Mateo & Talavera, 2018). Finally, an XGBClassifier was trained using XGBoost (2023, version 1.7.5, The

XGBoost Contributors) in Python (2023, version 3.12.0b3, Python Software Foundation, Wilmington, Delaware). Since this work serves as a proof of concept rather than a fully optimised model, default parameters were used, and fine-tuning was reserved for future investigations. The resulting data was then exported to Excel (version 2305, Microsoft, Redmond, Washington) for analysis and visualised onto a map using the folium library in Python.

Descriptive statistics were calculated to show the average and standard deviation of the number of swimming strokes, pedal strokes, and running strides for each participant. To evaluate the accuracy of the peak counting algorithm and the machine learning model, the percentage of correctly counted swimming strokes, cycling pedal strokes, running strides (Table 4), and cycling task classifications (Table 5) were calculated (Farrahi & Rostami, 2024). To evaluate the error and provide practical interpretation, the root mean square error (RMSE) and relative error were calculated for the peak counting algorithm. Next, sensitivity and specificity was calculated for the machine learning algorithm to detect the correct labelling of data points as 'out of saddle' riding (Farrahi & Rostami, 2024). To train the cycling task recognition model, 80% of the data was used for training and tested on the remaining 20% from participants one, two, three, eight, nine and eleven. The remaining six participants were entirely excluded from the model training process and used solely for testing. The percentage accuracy of the cycling task recognition model was also reported.

12.4 Results

The peak counting algorithm successfully counted swimming strokes, pedal strokes, and running strides. The ground truth average number of swimming strokes, pedal strokes, and running strides per participant was 341 swimming strokes (± 43); 2,760 cycling pedal strokes (± 171); and 2,036 running strides (± 568) respectively. During cycling, participant five's wearable sensor came loose from the race suit, resulting in a corrupted cycling accelerometer signal. Consequently, this data was removed. The percentage accuracy of the peak counting algorithm is presented in Table 4.

Table 4. *Accuracy of Peak Detection Algorithm in Each Discipline of Triathlon*

	Swimming strokes		**Cycling pedal strokes**		**Running strides**	
	% Accuracy	**RMSE (str/min)**	**% Accuracy**	**RMSE (str/min)**	**% Accuracy**	**RMSE (str/min)**
P1	99.1%	2.0	98.0%	12.0	98.7%	1.0
P2	99.1%	2.9	98.6%	9.5	98.5%	2.6
P3	98.4%	1.3	98.2%	7.3	99.7%	1.5
P4	99.5%	5.4	96.1%	7.9	99.9%	0.7
P5	98.2%	3.7	N/A	N/A	99.9%	0.6
P6	98.2%	1.0	97.9%	8.7	99.8%	0.8
Average	**98.7% (± 0.5%)**	**2.7 (± 1.5)**	**97.8% (± 1.0%)**	**9.1 (± 1.6)**	**99.4% (± 0.6%)**	**1.2 (± 0.7**

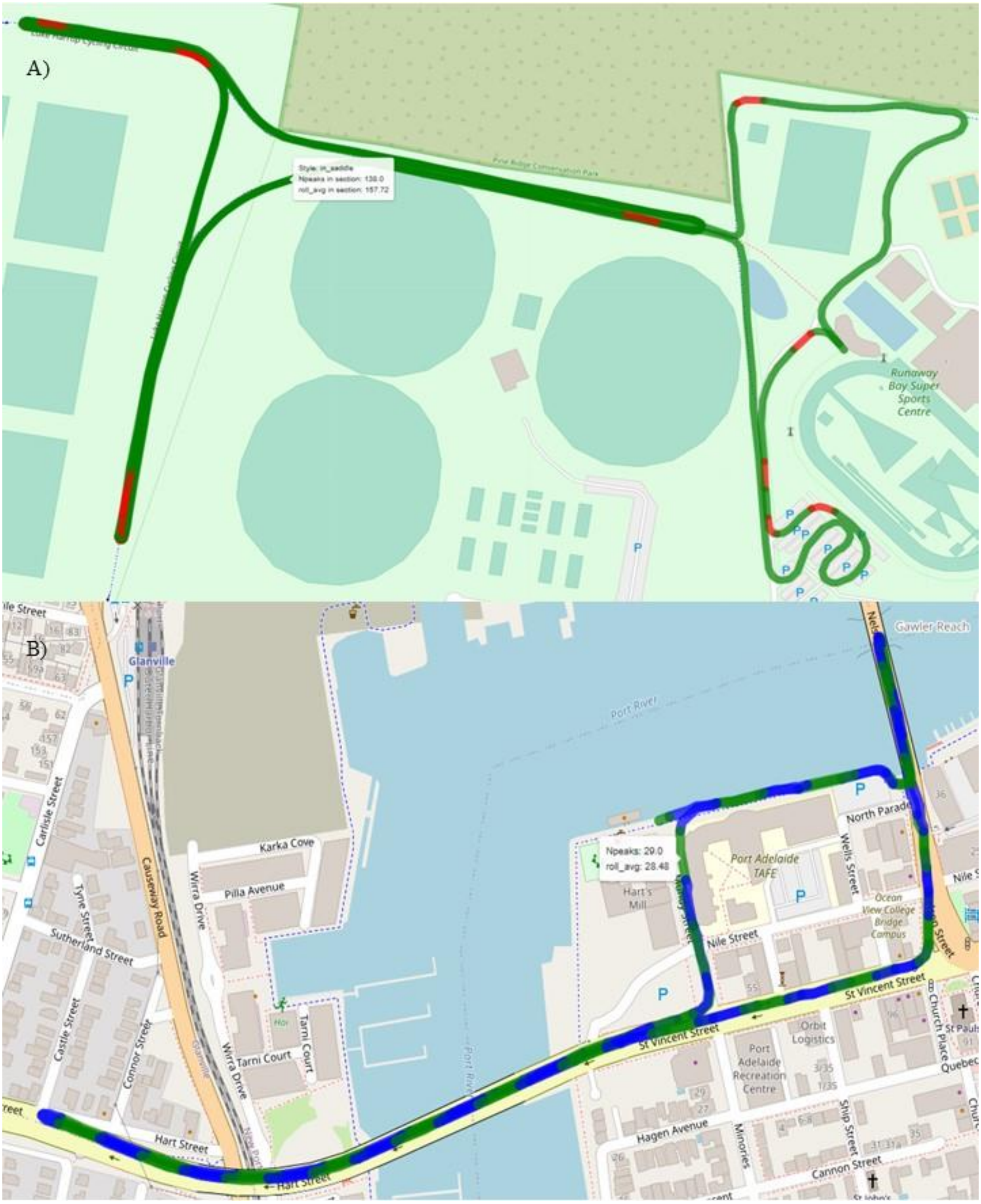
The average swimming cadence across all participants and races was 78.9 (± 8.1) strokes/min with a relative error of 3.4%. The average cycling cadence across all participants and races was 157.5 (± 6.6) pedal strokes/min with a relative error of 5.8% and the average running cadence across all participants and races was 172 (± 5.9) strides/min with a relative error of 0.7%. The average ground truth of cycling task changes for the original data set was 21 (± 5.6) instances of 'in-saddle' riding (16.27 mins ± 13.8 sec), 11 (± 5.2) instances of 'out-of-saddle' riding (37.7 ± 21.0 sec), and 11 (± 2.6) instances of 'coasting' (28.1 ± 10.3 sec). For the additional cycling data collection, the average ground truth was 67 (± 18.3) instances of 'in-saddle' riding (12.6 ± 2.6 mins; 34.9%), 42 (± 8.6) instances of 'out-of-saddle' riding (11.5 ± 2.5 mins; 31.9%), and 60 (± 18.5) instances of 'coasting' (11.7 ± 2.8 mins; 32.3%). The machine learning model was not accurate at distinguishing sections of 'coasting' from 'in-saddle-riding'. Therefore, only the accuracy for distinguishing between 'in-saddle' and 'out-of-saddle' riding has been reported (Table 5) and visualised on the cycling task classification map (Figure 10a).

Table 5. *Accuracy of Machine Learning Model to Recognise Cycling Tasks.*

Participant #	**Percentage Accuracy**	**Sensitivity**	**Specificity**
P1	97.6%	42.2%	95.7%
P2	100%	32.4%	97.6%
P3	98.8%	22.5%	99.6%
P4	98.8%	10.5%	99.5%
P5	N/A	N/A	N/A
P6	91.5%	63.4%	98.5%
P7	94.7%	86.4%	93.5%
P8	97.6%	87.0%	93.9%
P9	91.7%	83.1%	92.6%
P10	91.5%	85.5%	91.9%
P11	83.3%	52.5%	96.9%
P12	88.1%	70.3%	98.3%
Average	94.0% (± 5.0%)	57.8% (± 26.4%)	96.2% (± 2.7%)

Finally, the machine learning model was designed to plot the race performance from participants on a map with changes in cycling tasks and RPM information available for analysis of cycling and a run course with stride rate at customisable intervals available. Examples of the performance of the model are available in Figure 10.

Figure 10. A) *Cycling Task Classification and B) Running Performance Map.*



Note. The red sections of the cycling performance map (Figure 10a) show the location and duration of 'out-of-saddle' riding and the green sections show 'in-saddle' riding. On the running performance map (Figure 10b), the green and blue sections indicate intervals of customisable length where the number of running strides during those intervals are calculated along with a rolling average of stride rate.

12.5 Discussion

This study investigated the accuracy of a peak detection algorithm and a machine learning model to calculate movement cadence across the three disciplines of triathlon, and to classify cycling task changes during the cycling leg of the race. In swimming, comparing the RMSE with the sample standard deviation shows that the expected error range is ± 0.33 standard deviations from the mean, giving an expected range of 74.3 to 79.7 strokes/min for an elite open-water swimmer with a medium cadence (77 strokes/min) (Rodríguez et al., 2021). This indicates a high degree of accuracy. In cycling, comparing the RMSE with the sample standard deviation shows that the expected error range is ± 1.38 standard deviations from the mean. For an elite triathlete cycling at an average cadence (97 RPM), the expected range is 92.5 to 101.5 RPM. Thus, the accuracy is lower than in swimming, but the error range remains practically useful. Finally, in running, comparing the RMSE with the sample standard deviation shows that the expected error range is ± 0.2 standard deviations from the mean, giving an expected range of 180.8 to 183.2 strides/min for an elite triathlete with a cadence of 182 strides/min (Landers et al., 2011b) which can be considered highly accurate.

These findings contrast slightly with previous research which showed lower error rates when using visual inspection of inertial sensor signals to measure triathlon movement cadence (Chesher et al., 2024). Chesher et al. (2024) found that swimming strokes, cycling pedal strokes, and running strides could be detected with very high accuracy (-0.2 swimming strokes, -0.5 cycling pedal strokes, and 0 running strides per minutes) as well as 'out-of-saddle' riding (0.08 seconds respectively). While there has been some reduction in accuracy to automate movement cadence measurement, the ranges for error are still practically useful to use as a tool that enables the assessment of a triathlete's ability to parameterise the speed of swimming, cycling, and running motor skills.

The machine learning model developed to detect transitions between cycling tasks successfully differentiated between 'in-saddle' and 'out-of-saddle' riding but failed to distinguish between ‘in-saddle’ riding and ‘coasting’. While the algorithm exhibited high accuracy in identifying correctly labelled time points, the sensitivity and specificity analysis offers a more nuanced interpretation. Specificity across all participants was high, indicating the model was effective at recognising ‘in-saddle’ riding. However, the low sensitivity revealed its poor performance in detecting ‘out-of-saddle’ riding. Notably, there is a distinct difference in specificity between the first (participants 1–6) and second (participants 7–12) rounds of data collection by 43.4%, contrasting with the algorithm's measured accuracy. Two factors likely explain this discrepancy: 1) In the first round, ‘in-saddle’ riding was overrepresented (90–94% of riding time) compared to ‘out-of-saddle’ riding, meaning the algorithm’s high specificity inflated its overall accuracy, misrepresenting its ability to detect ‘out-of-saddle’ efforts. 2) In the first round of data collection, ‘out of saddle’ riding efforts were short (~ 2-4 seconds), compared to the imposed duration of 20 seconds in the second round of data collection. As the Short-Time Fourier transform used a window size of 2.5 seconds, this blurred shorter ‘out-of-saddle’ efforts, reducing detection accuracy.

The automation of cycling task analysis using the machine learning model had contrasting accuracy compared to previous research (Chesher et al., 2024). However, as in earlier work, the model still failed to distinguish 'coasting' from 'in-saddle' riding, likely due to the small amplitude differences between the two tasks, compounded by the sensor's torso placement, which attenuates reaction forces through the kinetic chain—a finding echoed in running studies (Wundersitz et al., 2014). To improve the accuracy of the model, a more suitable approach for differentiating these tasks may involve using a convolutional neural network (CNN) to analyse the signal's shape or integrating a pedal crank power sensor. However, the current dataset was too small for CNN analysis, a limitation that should be addressed in future research.

Another way to improve cycling task recognition would be to alter the window size of the Short-Time Fourier transform. Selecting an appropriate window size is important to balancing the time and frequency resolution (Banos et al., 2014). When trying to analyse a signal with rapidly changing frequency, a shorter window size can more accurately track these changes, compared to averaging over a longer window (Banos et al., 2014). As the minimum cycling task length in this investigation was one second, a reduced window size may be more accurate to distinguish between rapid changes in cycling task (Banos et al., 2014).

Collecting objective data during triathlons has previously been challenging due to the logistical complexity of video capture and the lack of validated wearable IMU technologies. In some cases, performance analysts manually analyse multiple data streams obtained from multiple sensors attached to various body segments to gain insights. Therefore, this research fills a gap in triathlon performance analysis by quickly generating nuanced performance insights from a single IMU that measures global position more accurately than common alternatives (Gløersen et al., 2018).

At a basic level, this research offers a simple performance analysis tool that measures changes in movement cadence and cycling tasks over time. However, its utility could be extended by combining these measurements with contextual factors like racecourse characteristics, race velocity, and other motor skill metrics (e.g. length of swimming strokes and running strides). Plotting changes in motor skill performance over time can identify changes in the quality, consistency and stability of swimming, cycling, and running motor skills (Magill & Anderson, 2014). Furthermore, combining performance data and contextual information can show persistence of progress, adaptability, and reduced attention demand in motor skill performance (Magill & Anderson, 2014). For example, Bouillod and Grappe (2018) identified that some cyclists alternate between ‘in-saddle’ and ‘out-of-saddle’ riding to maintain speed during a race despite the increased mechanical cost of ‘out-of-saddle’ riding. While this could be influenced by environmental features imposed by the race (hills, over-taking, corners), it may also reflect a cyclist’s difficulty maintaining an efficient in-saddle riding motor pattern (Bouillod & Grappe, 2018; Chesher et al., 2022). This could indicate that these cyclists have not learned stability of the cycling motor pattern at that speed. Thus, measuring time spent in different cycling positions and linking it to racecourse features like elevation could assess motor skill stability.

The high accuracy and relative simplicity, of this method of performance analysis makes it suitable to implement in a practical setting. The peak counting algorithm and map visualisation provides coaches and sport scientists the ability to analyse each discipline in short time intervals and detect performance changes caused by environmental features like hills, corners, competitor congestion and tidal conditions. This nuanced and detailed performance data can inform coaches' training decisions, enabling incremental improvements that are especially valuable at the elite level.

Some limitations should be considered when interpreting this research. First, the machine learning model could not distinguish between efforts of ‘coasting’ and ‘in-saddle-riding’, limiting the strength of the inferences that can be made about cycling motor skills related to cornering or pedalling consistency (Chesher et al., 2022). Second, the peak counting algorithm and cycling task recognition model cannot yet be generalised, as it was developed from a small subset of triathletes and a larger, more diverse dataset is required for generalisation.

Further research should aim to continue developing the cycling task recognition model to distinguish ‘coasting’ from ‘in-saddle’ cycling to deepen the analysis that can be performed. Zignoli and Biral (2020) note that cyclists typically adopt one of two cornering strategies: maintaining a high velocity but also a large radius of curvature (and thus travel a greater distance) or take a shorter path with greater velocity loss. The latter strategy is commonly utilised, but requires a precisely timed late braking point (coasting) and an early high power ‘out-of-saddle’ effort (Zignoli & Biral, 2020). Measuring this could be possible by combining the peak counting algorithm and machine learning model to determine ‘coasting’ as ‘in-saddle’ riding with no pedalling. This proof of concept for trunk-mounted wearable sensors could be integrated with bike computers to combine GPS, power, and inertial data for a comprehensive time-motion analysis of cycling. Additionally, further research should investigate the average changes in movement cadence of youth triathletes over time to inform the training practises.

12.6 Conclusion

Developing a peak counting algorithm to measure cadence at customisable intervals, along with a machine learning model to recognise cycling task changes, is an important step towards improving motor skill analysis and practise design in triathlon. Automating this process also makes the analysis of multiple athletes feasible, given the time and resource constraints faced by many elite sporting organisations. Further refinement of the peak counting algorithm to include additional performance metrics, and enhancement of the machine learning model to recognise ‘coasting’ efforts, can deepen coaches’ and sports scientists’ understanding of their athletes’ performance without requiring additional analysis time.

12.7 Declaration of Interest

There were no recognised conflicts of interest during the completion of this research. The primary researcher is a doctoral student supported by an Australian Government Research Training Program scholarship.

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13.0 Chapter 5: A Longitudinal Analysis of Change in a Motor Skill Parameter of Junior Triathletes

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13.1 Abstract

Purpose: Optimal movement cadence is critical to success in elite triathlon. Therefore, the objective of this research was to investigate longitudinal changes in movement cadence amongst a group of junior triathletes to inform future training design. **Method:** Junior triathletes (n = 12) who were members of the state's talent development pathway wore a single trunk-mounted inertial measurement unit during triathlon races across two triathlon seasons (Oct 2021 to Apr 2023). The sensor data were analysed to identify changes in movement cadence across the three disciplines of triathlon. Additional information was collected from the participants to identify factors that affect changes in movement cadences over time. A custom designed automatic peak detection algorithm was used to process and analyse the movement cadence data for each triathlete in each discipline. **Results:** At the group level a positive non-significant trend was observed in average movement cadence. At the individual level, change in movement cadence over time varied widely. Multi-level modelling showed there were no consistent predictors of movement cadence across all disciplines of triathlon. However, the variable 'coach' was associated with changes in movement cadence in both swimming and cycling. **Conclusion:** Changes in movement cadence and learning are highly individual for youth triathletes, with the coach for training the triathlete influencing the greatest change across both triathlon seasons.

13.2 Introduction

The skilful control of co-ordinated movement is the subject of contemporary and historical scientific investigation. This is particularly relevant in sport, as athletes who demonstrate greater mastery of important motor skills often perform better than lesser skilled counterparts (Farrow & Robertson, 2017). One method of investigating important skills in a sport is to explore the beliefs, attitudes and experiences of stakeholders, including expert coaches and elite athletes (Chesher et al., 2022; Morris-Binelli et al., 2020). Once important skills are established, they can be quantitatively explored to determine how performance changes over time (Morris-Binelli et al., 2021). Taking a similar methodological approach would allow practitioners to understand how triathlon motor skill performance changes over time and provide a foundation to prescribe intentional training strategies to improve motor skill performance if required.

In triathlon, the methodological approach of interviewing experts to identify important skills in short distance triathlons (Olympic distance and sprint distance) was adopted by Chesher et al. (2022), where stakeholders were interviewed about the motor skills that are important for success at the elite level. The investigation identified the kinematics of locomotion, posture, stabilisation, navigation and breathing, and the ability to adapt these skills to situational demands were all important elements of the continuous motor skills required for elite performance (Chesher et al., 2022). When an athlete varies the performance of a motor skill to suit the situational demands it is performed under, one strategy used is known as parameterisation (Schmidt, 1975). Parameterisation can be identified when the features of a skill performance remain relatively the same, but the generalised motor program (GMP) is altered by changing the total speed or force with which it is performed. For continuous motor skills like swimming, cycling, and running, parametrising the speed of movement alters the movement cadence (propulsive movements per unit of time). Performing longitudinal analysis of movement cadence allows for the detection of accelerations, decelerations, and stabilisations of motor skill performance. This can provide a basis for applying appropriate training interventions in response to these trends (Westendorp et al., 2014).

Objectively assessing motor skills in triathlon requires a method of measuring important performance metrics during training and races. Wearable sensors are a valid measurement tool to measure a range of important motor skills in triathlon (Chesher et al., 2024). These sensors function by collecting movement information from the body segments they are attached to, allowing the estimation of gross human movement. Thus, wearable sensor systems can be highly complex, containing multiple integrated sensors on many body parts, or simple, when utilising a single inertial measurement unit (IMU). Additionally, wearable sensor data can be processed automatically by data science techniques to provide timely motor skill analysis of multiple triathletes (section 12.4). While the richness of information provided by multi-sensor wearable systems can be desirable, they require advanced computer processing to integrate the information and are impractical to wear while racing. Therefore, this investigation attempted to answer the question: What is the group and individual change in swimming, cycling, and running cadence in a cohort of junior triathletes across two seasons of triathlon racing?

13.3 Methods

13.3.1 Study Design

A longitudinal, prospective, observational study design was used to measure swimming, cycling, and running movement cadence of 12 triathletes (competition level: nine Tier 3: Highly Trained/National; and three Tier 2: Trained/Developmental (McKay et al., 2022)) during races over two triathlon seasons spanning from October 2021 to April in 2023. A sample of 12 participants represents 32% of the region's junior talent development pathway. Participant recruitment occurred in two cohorts. Before the 2021-2022 triathlon season four junior triathletes (mean age= 16.32 ± 0.57 years; sex = three male and one female; average time in sport = 4.00 ± 0.79 years) were recruited from a single triathlon club. To participate, triathletes had to be at least 12 years old, free from injury and intending to participate in a full competitive triathlon season. Following this, a second round of recruitment occurred before the start of the 2022-2023 triathlon season, recruiting an additional eight triathletes from a different triathlon club (mean age = 15.88 ± 0.98 years; sex = three female and five males; average time in sport = 2.99 ± 1.69 years), while continuing to collect data from the original four triathletes. During the second recruitment period, one participant from the original cohort withdrew from the sport and was removed from data collection, however their data remained in the analysis. Ethical approval was obtained from the university's human research ethics committee (HRE2021-0071).

13.3.2 Procedures

A wearable IMU (Catapult Optimeye S5, Catapult Sports Pty Ltd, Melbourne, Australia) containing a GPS (10 Hz), tri-axial accelerometer, and gyroscope sampling at 100Hz was attached to each participant in a custom-made pouch pinned underneath the triathlon race suit between the shoulder blades. The IMU has been previously validated to measure swimming, cycling, and running cadence in triathlon via an automatic cadence detection program (swimming strokes = 98.7 ± 0.5% accuracy; cycling pedal strokes = 97.8 ± 0.9% accuracy; running strides = 99.4 ± 0.6% accuracy) (section 12.4). Participants wore the IMU during triathlon races throughout two triathlon seasons. On one instance there were multiple races on the same course in the same day. As the intention is to measure longitudinal changes in movement cadence due to improvement in motor skill performance rather than acute changes (i.e. unmeasured fatigue) the performances in these races were averaged to a single result for each participant.

During the investigation, data were collected from 19 triathlons resulting in 83 data points for swimming and cycling, and 86 points for running. As there are observed performance impacts of each discipline on the subsequent one (Chapman et al., 2008; Peeling et al., 2005), data could only be included if the preceding swim or cycle was also included. On one occasion, a last-minute decision was made by the race organiser to change a triathlon to a duathlon (run – cycle – run) due to unsafe water conditions, thus, only the final run could be included from this race. Data was excluded from races for four reasons: when participants raced while ill or were injured during the race, due to improper attachment of the IMU, and GPS failing to connect to satellites. For each race the time taken was recorded along with the GPS distance to calculate the race velocity. Swimming distances were recorded based on the race organiser's directions, as GPS was unavailable when the IMU was submerged. On eight occasions the GPS malfunctioned and was unable to accurately locate the position of the athlete which caused large and rapid changes in global position that were recorded as covering distances outside the racecourse. When this occurred, a close approximation of distance was calculated by averaging the race distance obtained from the functioning GPS sensors attached to the other research participants in the race.

Additional information was collected from each race to check for factors that might cause changes in movement cadence. These factors included chronological age and age category of the race (Garcia et al., 2022); leg and arm lengths (Landers et al., 2011a; Taylor-Haas et al., 2022) measured according to the standards of the International Society for the Advancement of Kinanthropometry (Norton, 2018); years of experience in triathlon and its individual disciplines; current triathlon coach (Ericsson et al., 1993; Werner & Federolf, 2023); whether a wetsuit was worn in addition to the triathlon suit (Gay et al., 2022), and whether the cycling discipline was draft legal (van den Brandt et al., 2023). A rating of racecourse difficulty was also assigned by agreement between two coaches (coach one = Triathlon Australia qualified Performance Coach, > 20 year's coaching experience; coach two = Triathlon Australia qualified Performance Coach, > 10 years' coaching experience), the primary investigator (SC) and co-investigator (KN). Courses were given a rating of ‘low’, ‘medium’, ‘high’, or a halfway rating between the three based on the criteria in Table 6.

Table 6. *Racecourse Difficulty Rating Criteria.*

Difficulty	**Low**	**Medium**	**High**
Swimming	Pool swim	Open water swim	Open water swim
		Low-medium athlete density and turbulence	Medium-high athlete density and turbulence
		Between 1-4 especially 90° or lower	5+ corners, especially greater 90°
Cycling	Flat course	Medium undulation	Substantial undulation
	Few corners (between 1 – 5) especially with cornering angle < 90°	A moderate number of corners (6 – 10) with a variety of cornering angles	A large number of corners (11+) with a variety of cornering angles including while climbing and downhill cornering
	Infrequent re-accelerations out of saddle required.	Occasional re-accelerations out of saddle required.	Frequent re-accelerations out of saddle required.
Running	Flat course	Medium undulation	Substantial undulation
	Few corners (between 1 – 5) especially with cornering angle < 90°	A moderate number of corners (6 – 10) with a variety of cornering angles	A large number of corners (11+) with a variety of cornering angles

Additionally, the perceived importance of each race for each individual triathlete was recorded to act as an indication of the motivation to win and to provide context for their individual season macrocycle training plan. These ratings were decided by consulting both the coach and the triathlete. These ratings were: Low = A race when a win is not expected, and the athlete is not trying to win (e.g. returning from injury and the goal is to 'complete not compete'); Standard = A standard race where the objective is to win; Key = A race designated by the athlete and coach as high importance, which holds greater significance, such as event qualification or accumulating points towards a medal; Very High = A race of extreme importance, such as a championship event where there is no other opportunity to attain this reward.

13.3.3 Statistical Analysis

Data from each IMU were processed using manufacturer supplied software (Catapult Sprint 5.1.7, Catapult Sports Pty Ltd, Melbourne, Australia) and exported to a spreadsheet (Excel 2019, Microsoft Corporation, Redmond, Washington) for further processing. A custom peak counting algorithm was then used to analyse the IMU data (section 12.4). The data were then imported into a statistical analysis program (R, 4.3.3, R Core Team) to analyse changes in performance over time.

To begin, average movement cadence was calculated by using the custom peak counting algorithm to count the total number of swimming strokes, cycling pedal strokes, and running strides throughout each race, and then divide each count by the time taken to complete each discipline. Group and individual average movement cadence (swimming strokes, pedal strokes, or running strides per minute) for each race were then plotted against longitudinal time to visually assess direction of the change in performance. Upon visual inspection of movement cadence graphs, variation in race distance (250 – 750 metres for swimming; 5655 – 21607 metres for cycling; and 1226 – 5275 metres for running) appeared to have a meaningful confounding effect on the change in performance. This was expected due to the relationship between movement cadence, distance, and movement velocity (Anderson, 1996; Mezzaroba & Machado, 2014; Turpin & Watier, 2020). Shorter race distances enable triathletes to race at higher velocities before reaching exhaustion; therefore, increases in either a) movement cadence, b) distance covered per swimming stroke, pedal stroke, or running stride or c) both must occur

(Anderson, 1996; Mezzaroba & Machado, 2014; Turpin & Watier, 2020). To check for the possible influence of race distance, a regression line was fitted, and correlation coefficient (r) for movement cadence and distance was calculated. To determine if a relationship existed between cadence and distance, the following stratifications of correlation coefficient were used: Negligible relationship = 0.00 – 0.10; weak = 0.10 – 0.39; moderate = 0.40 – 0.69; strong = 0.70 – 0.89; very strong = 0.90 – 1.00 (Schober et al., 2018). If a relationship existed, predicted cadences and residuals for each data point were calculated using the fitted regression line equation, and subsequently used to determine changes in performance over time.

To answer the research question, average movement cadence from each discipline was analysed separately, using linear mixed effects models with restricted likelihood estimation to determine the group level change over time. This analysis is appropriate as individual data points are repeated measures taken from the same participants over time, thus, independence cannot be assumed. A two-level generalised linear mixed effects model was used to assess how the predictors affected change in movement cadence. Additionally, random intercepts were included for each participant in the model. To look at changes in movement cadence between races in a season, a variable called “Race_Season” was computed to represent the chronological order of races within one season. This statistical analysis was conducted using the ‘lme4’ package in R (Bates et al., 2015). The distribution type of swimming, cycling and running cadence was checked via Kolmogorov-Smirnov test of normality and linearity was checked by examining scatterplots of residuals and predicted values of movement cadence (Osborne & Waters, 2002). Group level changes in average movement cadence were graphed with 95% confidence intervals shaded.

To determine the predictors that contributed to changes in the dependent variable (movement cadence) the following factors were modelled as fixed effect: age category (as defined by triathlon governing body); age; technical difficulty; race importance; coach; whether a wetsuit was worn during swimming and whether a cycling leg was draft legal; experience in triathlon and its individual disciplines; arm and leg length and ‘Race_Season’. All factors were modelled as main effects to check for significant differences in the dependant variable. The Y-intercept has been reported to describe the average movement cadence (frequency/min) when categorical variables are set to the lowest or base line grouping factor. Parameter estimates for each fixed effect were reported as beta coefficients to show the magnitude of effect on the average movement cadence and were determined to be significant at $\alpha = 0.05$. 95% Confidence intervals for the beta (β) coefficients were calculated as $\beta \pm 1.96*$ Standard Error.

13.4 Results

Participants who raced in both seasons competed in approximately 13 races each (mean = 12.7 ± 3.3) and participants who raced in one season competed in around five races each (mean = 5.5 ± 1.5). Descriptive information for categorical predictor variables has been reported in Table 7 and continuous predictor variables have been reported in Table 8.

Table 7. *Frequency table for Categorical Predictors*

Predictor Variable	**1**	**2**	**3**	**4**	**5**
Technical Difficulty: Swim	6 (7.2%)	28 (33.7%)	46 (55.4%)	3 (3.6%)	0 (0.0%)
Technical Difficulty: Cycle	12 (14.5%)	33 (39.8%)	30 (36.1%)	0 (0.0%)	8 (9.6%)
Technical Difficulty: Run	73 (84.9%)	6 (7.0%)	4 (4.6%)	3 (3.5%)	0 (0.0%)
Race Importance	9 (10.5%)	33 (38.4%)	38 (44.2%)	6 (7.0%)	
Youth vs. Junior	24 (27.9%)	62 (72.1%)			
Coach 1 vs Coach 2	53 (61.6%)	33 (38.4%)			
Wetsuit (1 = N, 2 = Y, 3 = Unknown)	56 (67.5%)	15 (18.1%)	12 (14.4%)		
Draft Legal (1 = N, 2 = Y)	56 (67.5%)	27 (32.5%)			

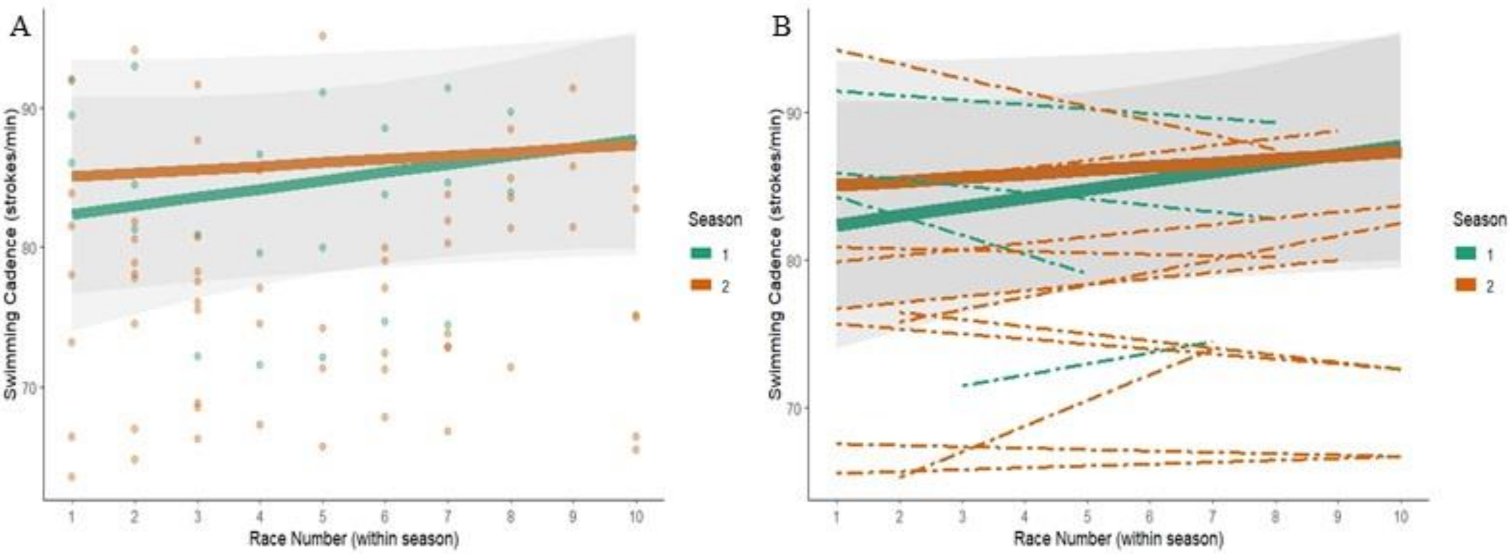
Note. Frequency counts are based on individual participant entries into triathlons and are included with a percentage of the total that the frequency count represents.

Table 8. *Descriptive Statistics for Continuous Predictors*

Predictor Variable	**Mean**	**SD**	**Range**
Arm Length (cm)	78.7	4.0	70.6 – 85.4
Leg Length (cm)	92.7	4.7	85.5 – 103.3
Age (years)	16.4	0.9	14.5 – 18.6
Years in Triathlon	3.7	1.5	1.1 – 6.7
Years in Swimming Sports	5.4	1.7	2.0 – 8.9
Years in Cycling Sports	3.7	1.6	0.5 – 6.7
Years in Running Sports	4.6	2.0	1.3 – 8.7

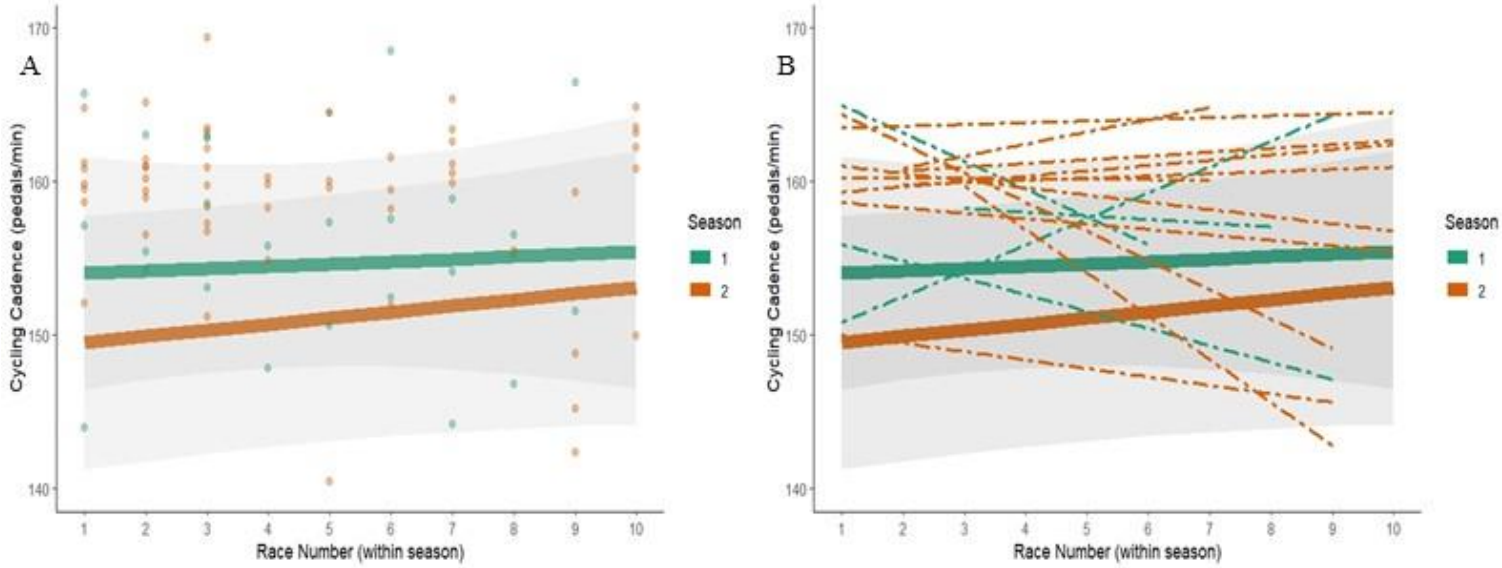
Group and individual change in performance over time for each discipline is reported in Figure 11 – 13.

Figure 11. *Changes in Swimming Cadence over Two Triathlon Seasons.*



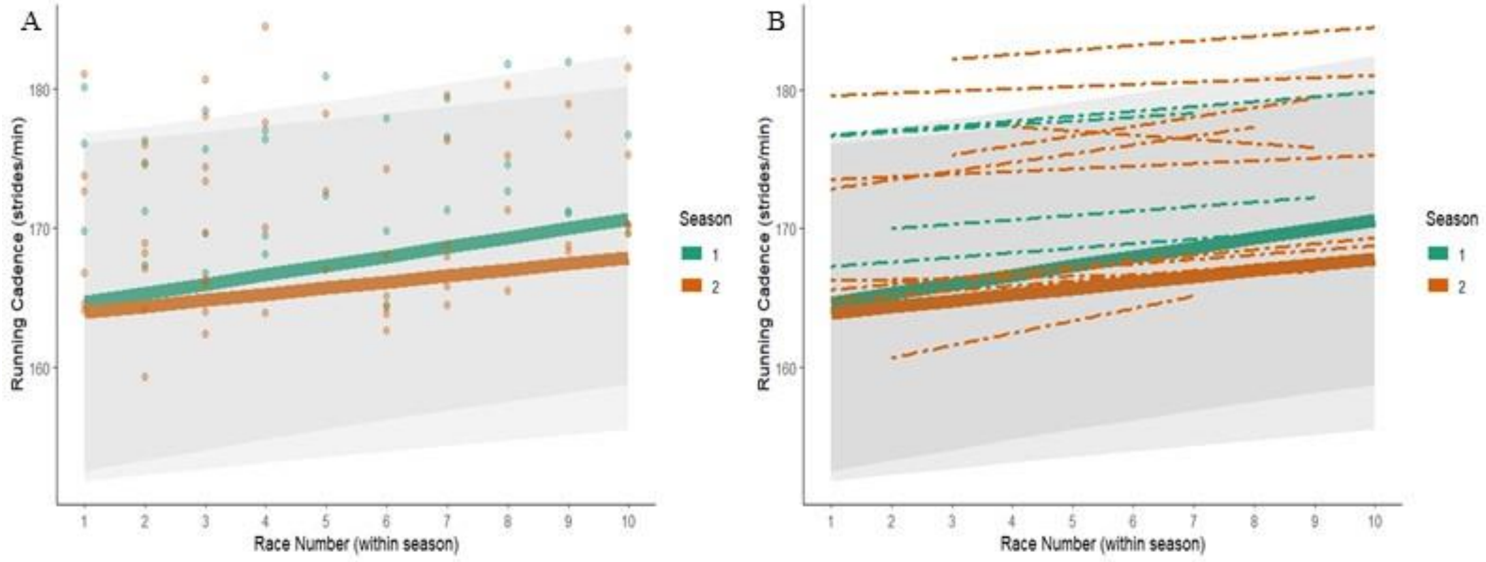
Note. *Figure 11a shows group level change in swimming cadence over two triathlon seasons. In Figure 11b group level change is represented by the enlarged and bolded lines while individual change in swimming cadence is represented by dot-dashed lines. Grey shading on both graphs represents the 95% confidence intervals of group level change.*

Figure 12. *Changes in Cycling Cadence over Two Triathlon Seasons.*



Note. *Figure 12a shows group level change in cycling cadence over two triathlon seasons. In Figure 12b group level change is represented by the enlarged and bolded lines while individual change in cycling cadence is represented by dot-dashed lines. Grey shading on both graphs represents the 95% confidence intervals of group level change.*

Figure 13. *Changes in Running Cadence over Two Triathlon Seasons*



Note. *Figure 13a shows group level change in running cadence over two triathlon seasons. In Figure 13b group level change is represented by the enlarged and bolded lines while individual change in running cadence is represented by dot-dashed lines. Grey shading on both graphs represents the 95% confidence intervals of group level change.*

After plotting the regression line between swimming cadence, cycling cadence, running cadence and distance, no relationship was observed between swimming cadence and distance (r = 0.06). There was a weak relationship between cycling cadence and distance (r = 0.25) and there was no relationship between running cadence and distance (r < 0.01). Therefore, race distance was not accounted for statistically in any of the disciplines.

13.4.1 Main Effects Analysis

The results of linear mixed effect models are reported in Tables 9-11 with significant effects bolded. Modelling for significant main effects demonstrated a variety of outcomes regarding their impact on movement cadence in each discipline. The participants' coach, and time related factors (age, years spent in sport and race progression throughout the season) were most commonly significant. No fixed factors had significant effects across all three disciplines in triathlon. Main effects were explored by reporting β coefficients and the 95% confidence intervals (CI) to estimate the amount of change caused by each factor.

Table 9. *Parameter Estimates of Predictors on Change in Swimming Cadence*

	β	**Std. Error**	**p-value**	**t-value**	**df**	**Lower 95% CI**	**Upper 95% CI**
Intercept	82.84	4.17	**< 0.001***	19.85	41.73	74.66	91.02
Technical Difficulty							
Low vs. Low-Medium	0.92	2.39	0.70	0.38	45.31	-3.76	5.59
Low vs. Medium	0.74	2.50	0.77	0.30	45.43	-4.15	5.62
Race Importance							
Low vs. Standard	1.08	1.25	0.39	0.87	45.95	-1.36	3.53
Low vs. Key	2.62	1.59	0.11	1.65	47.45	-0.50	5.74
Low vs. Very High	3.89	2.87	0.18	1.36	45.51	-1.74	9.51
Youth vs. Junior Race Category	-4.27	2.41	0.08	-1.77	49.90	-9.00	0.46
Races within Seasons (Race_Season)	0.59	0.52	0.26	1.13	47.89	-0.43	1.62
Coach 1 vs. Coach 2	-16.53	3.09	**< 0.01***	-5.35	5.32	-22.59	-10.47
Arm Length (cm)	-1.14	0.44	**0.04***	-2.61	5.71	-1.99	-0.28
Age (yrs)	13.86	2.76	**< 0.001***	5.02	12.27	8.45	19.27
Years in Triathlon	-2.15	0.88	0.06	-2.44	5.31	-3.88	-0.43
Years in Swimming Sports	-3.29	0.97	**0.02***	-3.39	5.67	-5.20	-1.39
Wetsuit No vs. Yes	1.44	0.92	0.12	1.58	46.23	-0.35	3.25
Season 1 vs Season 2	2.68	2.06	0.20	1.30	48.09	-1.36	6.71
Random Effects	**Variance**			**Standard Deviation**			
Intercept	9.86			3.14			
Residual	6.32			2.51			

Table 10. *Parameter Estimates of Predictors on Change in Cycling Cadence*

	β	**Std. Error**	**p-value**	**t-value**	**df**	**Lower 95% CI**	**Upper 95% CI**
Intercept	154.60	4.42	**< 0.001***	35.00	32.41	145.94	163.25
Technical Difficulty							
Low vs. Low-Medium	-2.28	2.15	0.29	-1.06	52.05	-6.50	1.94
Low vs. Medium	-2.12	2.46	0.39	-0.86	51.92	-6.94	2.70
Low vs. High	-5.00	5.20	0.34	-0.96	51.55	-15.19	5.19
Race Importance							
Low vs. Standard	-6.72	2.80	**0.02***	-2.40	51.47	-12.20	-1.23
Low vs. Key	-3.24	3.15	0.31	-1.03	51.93	-9.42	2.94
Low vs. Very High	-3.29	5.63	0.56	-0.59	51.57	-14.33	7.74
Youth vs. Junior Race Category	4.73	3.61	0.19	1.31	54.23	-2.34	11.80
Races within Seasons (Race_Season)	0.53	0.66	0.43	0.80	51.55	-0.77	1.83
Coach 1 vs. Coach 2	8.49	3.96	**0.08**	**2.14**	**5.10**	**0.72***	**16.25***
Leg Length (cm)	0.71	0.45	0.17	1.57	5.92	-0.17	1.59
Age (yrs)	-7.49	4.05	0.08	-1.85	16.39	-15.42	0.45
Years in Triathlon	-12.43	13.05	0.39	-0.95	4.19	-38.02	13.15
Years in Cycling Sports	14.47	12.85	0.32	1.12	4.29	-10.72	39.66
Draft Legal No vs. Yes	5.78	2.30	**0.01***	2.51	51.68	1.27	10.29
Season 1 vs. Season 2	-3.02	3.53	0.40	-0.86	54.05	-9.94	3.90

Random Effects	**Variance**	**Standard Deviation**
Intercept	14.71	3.84
Residual	23.84	4.88

Table 11. *Parameter Estimates of Predictors on Change in Running Cadence*

	β	**Std. Error**	**p-value**	**t-value**	**df**	**Lower 95% CI**	**Upper 95% CI**
Intercept	165.59	5.97	**< 0.001***	27.57	5.14	153.89	177.29
Technical Difficulty							
Low vs. Low-Medium	0.12	1.67	0.94	0.07	55.02	-3.15	3.39
Low vs. Medium	0.93	2.07	0.65	0.45	55.05	-3.12	4.99
Low vs. Medium-High	3.81	2.01	0.06	1.90	55.00	-0.13	7.74
Race Importance							
Low vs. Standard	1.25	1.75	0.48	0.71	55.04	-2.18	4.69
Low vs. Key	2.22	1.62	0.18	1.37	55.07	-0.96	5.40
Low vs. Very High	1.03	1.96	0.60	0.52	55.00	-2.81	4.86
Youth vs. Junior Race Category	0.48	1.32	0.72	55.22	0.36	-2.11	3.07
Races within Seasons (Race_Season)	0.67	0.27	**0.01***	55.11	2.51	0.15	1.19
Coach 1 vs. Coach 2	6.59	9.18	0.51	3.98	0.72	-11.41	24.60
Leg Length (cm)	-0.53	1.03	0.63	4.05	-0.52	-2.55	1.48
Age (yrs)	3.54	5.02	0.52	4.32	0.71	-6.30	13.39
Years in Triathlon	-2.60	6.10	0.69	3.94	-0.43	-14.57	9.36
Years in Running Sports	2.95	5.08	0.59	3.93	0.58	-7.00	12.90
Season 1 vs Season 2	-0.70	1.57	0.66	-0.45	55.35	-3.78	2.38
Random Effects	**Variance**			**Standard Deviation**			
Intercept	56.03			7.49			
Residual	5.72			2.39			

13.5 Discussion

This study measured longitudinal changes in movement cadence of junior elite triathletes over two triathlon seasons to measure changes in movement cadence over time. Multi-level regression analysis showed a non-significant increase in movement cadence across the cohort. However, when individual changes are viewed (Figure

11b, 12b and 13b), substantial variation in the direction and slope of the trajectories was observed. This supports the idea that at the individual level, there is considerable variability in motor skill performance over time (Morris-Binelli et al., 2021).

To address the research question, the analysis of predictors showed that significant changes in swimming cadence were related to the coach who trained the participant, the participant's arm length, chronological age, and years spent in swimming sports. Cycling movement cadence was also significantly related to the coach, in addition to race importance and draft legal race status. Only one significant main interaction was measured in change in running cadence, which indicated that the chronological progression of races throughout a season was related to gradual increases in running cadence.

Swimming mixed models demonstrated that age had a significant and large positive relationship with swimming cadence; however, time spent in swimming sports had a much smaller inverse association. One explanation for how two time-dependant predictors could have inverse effects is that, as triathletes age, they are able to increase their swimming cadence. In contrast, as triathletes spent more time practising swimming, they learn to pull more water with each stroke, requiring fewer strokes to maintain swimming velocity. To be confident in this assertion the collection of intra-cycle velocity data is required, however, it is consistent with investigations of swimming stroke parameters that report swimming cadence remains similar during adolescence, with increases in swimming velocity resulting from increases in stroke length (Dormehl & Osborough, 2015; Mezzaroba & Machado, 2014). Furthermore, stakeholders in triathlon have recognised the greater importance of a higher stroke frequency in open water swimming to maintain swimming velocity when turbulent water reduces the gliding phase of the stroke cycle (Chesher et al., 2022). Therefore, this finding requires further investigation.

For cycling, the relationship between temporal factors and cycling cadence was not statistically significant, although the relationship with age related changes approached significance. Initially, this might suggest that as triathletes spend more time in the sport, they do not learn to cycle with higher cadences. However, measuring, and interpreting cycling cadence is confounded by the fact that movement during cycling is possible without direct propulsion, which is not the case in swimming and running. In both swimming and running, velocity (m/s) (the performance outcome) is equal to movement frequency (Hz) multiplied by length of each stride or stroke (in metres) (Moore, 2016; Ribeiro et al., 2017). In cycling, gearing systems allow cyclists to produce a large range of velocities at the same cadence, and the significant movement available while coasting (cycling without pedalling) makes evaluating the quality of cycling cadence more difficult. To understand changes in cycling cadence more accurately, information about a cyclist's gearing is required.

In this study, a significant relationship was observed between the draft legal status of a race and cycling cadence. This aligns with a systematic review of drafting investigations performed in the field, where significant effects on biomechanical, physiological and psychobiological factors were identified (van den Brandt et al., 2023). The significant relationship with cycling cadence is likely due to a few factors. First, a decrease in the drag experienced by drafting cyclists allows higher cadences to be achieved for the same work performed (van den Brandt et al., 2023). Second, cyclists can cycle in a lower gear and increase cycling cadence while maintaining similar velocities due to reduced drag. Third, the cyclists exercise intensity is regulated based on the cycling intensity of the peloton, and therefore, cadence differences may be influenced by the pacing behaviour of the entire peloton (van den Brandt et al., 2023). Without additional sensors such as bike computers that measure power input or electronic gearing information, it is difficult to discern the reasons for this relationship. Thus, future investigations of drafting should collect this information during races using additional sensors to help explain this finding.

Mixed modelling of running cadence only highlighted one significant factor which was a significant relationship with chronological race progression. This suggests that triathletes were able to progressively increase running cadence from race to race throughout a season. However, without significant interactions of any temporal variables or coach, it is unclear if these changes are related to maturation or learning. Maturation can cause improvements in cardiovascular fitness, strength, and motor control via physiological, musculoskeletal and neurological development (Haibach-Beach et al., 2023). Thus, measuring maturation is required to delineate the associated variables identified from race to race.

A large interaction between movement cadence and coach in swimming and cycling was observed. This relationship was significant in swimming cadence, yet, approached significance in cycling (p = 0.08). However, as the confidence intervals measuring the association with coaching in cycling do not include zero (95% CI: 0.72 – 16.25), it cannot be confidently stated that this association is spurious. Without additional descriptions of the differences between the coaches' practices (i.e. training prescription) and their coaching strategies, philosophies and instructions, it is challenging to attribute an exact reason for the significant relationship between movement cadence and coach. For example, it has been documented that movement cadence changes in response to specific programming with auditory feedback (Hafer et al., 2015), and the focus of attention directed by the type of instruction a coach gives can change the motor coordination and performance outcomes of a variety of sporting motor skills (Werner & Federolf, 2023). Therefore, changes in movement cadence attributed to the coach could be due to the training prescription and coaching style of each coach, whereby deliberate practice aimed at improving movement cadence with attention directed by specific coaching cues may help to increase movement cadence (Ericsson et al., 1993).

Technical difficulty had no significant relationship with movement cadence in any discipline. This is interesting, as increasing course difficulty was expected to disrupt motor skill performance by challenging the stability and attention demands of the motor skill (Magill & Anderson, 2014). It is possible that the swimming, cycling, and running motor skills of the participants were not sufficiently challenged by the characteristics of the racecourses to cause changes in movement cadence. Alternatively, the motor skill improvements achieved through practise by triathletes in this sample may be sufficient for motor skills to resist the external performance perturbations and divided attention allocation imposed by the higher difficulty courses (Magill & Anderson, 2014). In future, more objective descriptions of course difficulty should be provided by measuring characteristics of the racecourse rather than relying on expert opinion.

The findings relating to arm length and cadence in swimming are consistent with previous research indicating that greater heights and limb lengths are associated with lower cadences (Landers et al., 2011a; Taylor-Haas et al., 2022). This was an expected finding and has been reported previously, showing that longer limbs can be advantageous for generating higher velocities, provided each individual is strong enough to utilise their longer levers (Landers et al., 2009).

Changes in movement cadence over time were related to coach, age, time spent practising, and race progression throughout the season. Changes in movement cadence could also partly be attributed to maturation, increases in physiological fitness and strength, or learning. If any improvements are due to learning, they are expected to be due to an improved ability to parameterise the GMP of swimming, cycling, and running by scaling the speed that the GMP is executed (Schmidt, 1975). One explanation for improvements in parametrisation of the GMP related to temporal factors such as age, race progression and time spent practising could be a result of improvements in motor skill adaptability. After races, participants update the parameters within the motor response schema that should be applied to scale the GMP correctly for optimal performance (Magill & Anderson, 2014; Schmidt, 1975). This updating occurs through self-evaluation from intrinsic feedback and sensory information collected during the race, as well as feedback from the coach and information from the wearable IMU (Salmoni et al., 1984; Schmidt, 1975). Improvements in motor skill adaptability are inferred if this results in improved performance from race to race over time.

The strengths of this research are that this is the first longitudinal analysis of the change of swimming, cycling, and running movement cadence in triathlon. This research used commercially available IMUs and established data processing techniques to collect and analyse data, resulting in a process that could be implemented in any professional sports setting. Importantly, this investigation acts as a proof of concept for monitoring the changes of a specific motor skill over time. The participant sample represents a substantial portion of the state's development athletes which allows more confidence when inferring results to the population it was drawn from.

The length of time the triathletes were followed provides a 6 – 18 month 'snapshot' of their training careers. However, the average time spent competing in triathlon by participants in this sample is 3.77 (± 1.53) years, and training careers in total are likely to span more than a decade. Thus, caution is advised when extrapolating changes in performance taken from this period and making assumptions about the entire training career. Therefore, a much larger timescale might be required to gain a true picture of the overall performance changes of each participant. Individual changes in movement cadence in this investigation take on a variety of slopes, and for the majority, there appears to be no discernible pattern.

A limitation of this model is the relative subjectivity of some descriptors of racecourse technical difficulty. For example, objective measurements of tidal and weather conditions of the swim should have been collected, as well as measurements of athlete density and total elevation gain and loss to objectively describe the undulation of a course. Additionally, training diaries detailing the total time spent practising in each discipline may provide better discrimination than simply recording the years spent practising in each discipline. Future research should seek to collect additional fixed factors and covariates such as acute and chronic training load, and long-term training diaries, which could strengthen the statistical modelling of the dataset.

This investigation is the first to use a single wearable IMU to analyse the cadence of each leg of the triathlon in sequence, without the need for multiple wearable IMUs. Every additional IMU used to capture data increases the complexity of synchronisation and analysis. The single wearable IMU used in this investigation was able to elicit sufficient movement information to make inferences about motor skill performance on its own. The method of motor skill performance analysis used in this investigation could be applied in the field allowing practitioners and coaches to respond to changing motor skill performance over time by implementing highly specific training. For example, a coach could measure movement cadence of a triathlete across races to create a performance curve of changes over time (Harlow, 1949). Based on this performance curve triathlon coaches could implement strategies like auditory feedback training for improving gait characteristics to promote a positive change in performance (Agresta & Brown, 2015).

The present investigation has shown there is substantial individual variance in change in movement cadence over two triathlon seasons, particularly in swimming and cycling (Figure 11b, 12b, and 13b). What remains to be understood is the contribution of maturation, learning, and improvements in physiological fitness and strength to individual differences in movement cadence over a triathlon season.

Further investigations should also validate the measurement of other important triathlon motor skills, such coasting during cycling (Chesher et al., 2024), and posture in each discipline (Chesher et al., 2022). Additionally, future research could use the inferences from statistical modelling to conduct randomised controlled trials aimed at experimentally testing the hypotheses that are generated from this work. Finally, to address the difficulties in evaluating cycling cadence, integration of this wearable sensor with an electronic gearing system would enable the combination of gearing information with cadence, providing more informative performance metrics.

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14.0 Chapter 6: General Discussion and Conclusion

14.1 General Discussion

The aim of this thesis was, first, to generate a comprehensive overview of important motor skills required for elite triathlon success by interview stakeholders in elite triathlon. Secondly, validate a tool to measure important triathlon motor skills in the field, and finally, use this tool to analyse the changes in performance of an important motor skill longitudinally. After interviewing stakeholders in Australian triathlon (Chapter Two), participant perceptions were categorised into three main themes: 1) Continuous motor skills, 2) Discrete motor skills, and 3) Adaptability of continuous and discrete motor skills. Participants in this investigation identified the imprtance of training the invariant features of the motor skills required for each discipline, whch could be divided into the kinematics of locomotion, forming and maintaining posture, stabilising the body, and navigation and breathing. Additionally, participants recognised that discrete skills, such as cornering, change of direction skills, and transition skills also need specific training. Finally, participants acknowledged that the highly variable nature of triathlon means that any motor skill needs to be adaptable to a variety of contexts.

The second and third studies successfully validated a single trunk-mounted wearable IMU to detect movement cadence in all three triathlon disciplines (Chapter Three) and automated the counting of movement cadence, allowing results to be made available quickly, with a high degree of accuracy, and without the need for manual data processing (Chapter Four). An additional and novel finding from this research was that the wearable IMU can also be used to classify the number of tasks performed while cycling, contributing to a comprehensive motion analysis of cycling in triathlon. However, more work needs to be done to improve the automatic detection of ‘out of saddle’ riding by fine tuning the paramters of the machine learning model.

In the final study (Chapter Five), individual and group trajectories of change in movement cadence for each of the three disciplines of triathlon were described. The findings indicated that patterns of change in movement cadence are highly individual; however, when combined, a general positive trend is observed.

Furthermore, movement cadence was primarily influenced by temporal factors such as age, time spent in the sport, and the coach who trained the participants.

14.2 Interpretation and Contextualisation of Findings

Taken together, the findings highlight an individual approach is required to train a highly adaptable triathlete who is proficient in three modes of locomotion and the relevant discrete motor skills (Chesher et al., 2022). This should be driven by applying practise over extended periods, guided by coaching and training prescription that focusses on motor skill learning, while also achieves the required physiological adaptations for success. Therefore, the required learning and physical adaptations should be obtained by completing training specific to the desired adaptations (Reilly et al., 2009). Surveying the literature reveals a dearth of investigations into triathlon training that are guided by motor learning principles and informed by monitoring motor skill performance over time. Triathletes would benefit from such investigations, given that research comparing motor skills between triathletes and single discipline endurance athletes repeatedly shows that single discipline athletes exhibit superior motor skills than triathletes (Candotti et al., 2009; Chapman et al., 2007; Swinnen et al., 2018; Toussaint, 1990).

To understand this, hypotheses regarding how learning is transferred may provide valuable insights. Rosalie and Müller (2012) state that learning transfer occurs according to the characteristics of the learning and performance domains. Some differences between the learning and performance domains of sports include the absence of crowds (Otte et al., 2021) and the absence of perceived pressure (Savage & Torgler, 2012). However, triathlon training also lacks similarities like water conditions (pool versus open water) and cognitive demands imposed by course difficulty (number and degree of corners in cycling). Based on the experiences, attitudes and opinions of stakeholders, training in a manner that teaches adaptability to cope with the wide variety of performance contexts is important and may be overlooked in many training squads (Chesher et al., 2022).

The research contained in this thesis is impactful for triathlon as it provides an ecologically valid and practically useful tool for measuring changes in motor skill performance in triathlon. This research fills a gap in triathlon, where performance in competition is currently measured by wrist worn sensors and bike computers. The former device does not have the sufficiently accurate GPS to contextualise changes in motor skill performance over small time scales and does not allow for the exportation of data into customisable spreadsheets for advanced analysis. Furthermore, this research fills a gap in the industry by providing a measurement tool that does not require the combination of multiple data streams from several wearable IMUs to evaluate movement cadence concurrently throughout an entire triathlon.

The validation of a single measurement device to measure the parameterisation of a motor skill throughout a triathlon in this research is important. While other validations of measuring movement cadence with the same measurement device have been conducted in the individual disciplines of triathlon, this is the first investigation to do so concurrently throughout an entire triathlon. In swimming, previous Bland-Altman analyses have revealed a similar mean percentage error for stroke frequency (-0.25%) (Callaway, 2015). Other investigations have shown higher error rates, however, the wearable IMU used was attached to the lower back. In running, a systematic review and meta-analysis of wearable IMU use showed wearable IMU's have excellent validity (ICC = 0.93) when measuring step frequency in running speed ranges of 8 – 21 km/h (Zeng et al., 2022). In the present thesis, the accuracy was also high reporting 95% of running stride measurements would lie between ± 0.44 strides from the true value. As this is the first investigation to use a wearable IMU to measure movement cadence in cycling, there is no comparative validity literature.

In contrast, the reliability of this measurement unit has not been discussed thus far. The reliability of wearable IMU devices has been extensively researched (Crang et al., 2021). Intra-device reliability is high, with only small within device variations detected when measuring acceleration magnitude (coefficient of variation (CV) = 5.0 – 5.2%) (Crang et al., 2021). Additionally, when acceleration magnitudes are low (i.e. continuous long slow distance running versus sprinting) the reliability improves (CV = 4.7%) (Crang et al., 2021). Furthermore, stride frequency measurements have high test-retest reliability (ICC = 0.90) (Zeng et al., 2022). In contrast, unfortunately the most recent systematic review of inertial measurement technology in swimming did not include any measurement of reliability when analysing accelerations, or stroke frequency from a trunk worn sensor (Mooney et al., 2016).

Creating a tool for this analysis, allows for the development of an evidence-based framework to monitor and improve motor skill performance. For example, the research in this thesis has shown that an important motor skill parameter (movement cadence) can be measured and tracked over time. Subsequently, a coach could measure the consistency of performance improvements by assessing the movement cadence of an triathlete during training sessions and races to determine whether performance improvements are persistenting across subsequent performances (Magill & Anderson, 2014). If the trajectory of change in performance over time does not demonstrate persistence, the coach could provide intentional coaching strategies like using a metronome for auditory feedback to guide the desired movement cadence and create changes in the gait cycle (Agresta & Brown, 2015).

The espistemological process in this study can also be applied more widely to other sports. For example, the same strategy of measuring change in motor skill performance could be used with fast bowlers in cricket. Machine learning algorithms have been validated in cricket to automatically detect and classify bowling events to help monitor bowling workload and reduce injury risk (Jowitt et al., 2020). The run-up speed, deceleration, and amount of trunk rotation of a fast bowler are all performance qualities that are important for effective fast bowling in cricket and have been measured using the same IMU that was used in this research (Jowitt et al., 2020). By measuring run-up speed, deceleration, and trunk rotation over time and identifying the relative permanence of performance improvements, cricket coaches and performance scientists could measure the performance of fast bowlers and apply appropriate training drills to enhance performance when required.

Having a framework through which to deliberately train triathletes is important due to the relatively low number of potential talented athletes that participate in the sport compared to the many athletes paricipating in invasion team sports (Bottoni et al., 2011). With fewer athletes participating and limited resources to invest in them, effective talent identification is paramount to ensure optimal use of the resouces that are available. Therefore, this research not only guides motor skill development but can also guide talent identification by measuring individual motor skill performances of triathletes. Additionally, combining prospective motor skill measurements with expert coach subjective assessments may help begin to quantify ‘the coach’s eye’, a term used to describe how coaches are able to distinguish talented individuals from expert subjective assessment and ‘gut instinct’ (Roberts et al., 2021).

Cuba-Dorado et al. (2022, p. 17) identified the need for research to “provide greater knowledge in the field and better tools for coaches” when identifying talented individuals. This thesis begins to fill this gap by providing specific knowledge about what motor skills to identify in talented triathletes and a method to measure these motor skills in the field. Gulbin et al. (2013) have identified that progressing through the FTEM framework from the Foundation to Talent stage and then from Talent to Elite requires the identification of individuals who possess superior motor skills rather than superior morphological or physiological features (a common criticism of talent identification programmes) (Gulbin et al., 2013). This thesis has demonstrated that wearable sensors can measure the timing and rate of performance changes, allowing the assessment of an athlete’s motor skills over time. Thus, it is plausible that triathletes with accelerated improvements in motor skill performance may excel through talent programmes and achieve senior elite representation and success (stage E1 and E2 of the FTEM framework) by spending more time at a higher level of motor skill mastery (Gulbin et al., 2013).

The third aim of this thesis was to identify if any common milestones of motor skill performance existed. Observing the changes in movement cadence across each discipline of triathlon, there do not appear to be any identifiable milestones of motor skill performance, as the trajectories of change in movement cadence is highly individual. After exploring the motor skills required for success in triathlon (Chesher et al., 2022), stakeholders in Australian triathlon did not report believing that any milestones of triathlon motor skills existed. Instead, these stakeholders highlighted the importance of continuous motor skills for success. Therefore, the direction of this research was guided by these findings, specifically investigating how triathletes control movement cadence, a common parameter of the continuous motor skills performed across all disciplines in triathlon.

Investigating one parameter of a motor skill is unlikely to provide enough insight into the existence of milestones of motor skill performance. In previous milestone models of motor skill performance, investigators highlight the achievement of a performance goal while satisfying performance criteria (Wijnhoven et al., 2004). For example, when Wijnhoven et al. (2004) investigated the achievement of unassisted walking as a milestone of infant motor skill development, the milestone required that the "child takes at least five steps independently" (performance goal), "in an upright position with the back straight. One leg moves forward while the other supports most of the body weight. There is no contact with a person or object" (performance criteria) (Wijnhoven et al. 2004, p. S38). When considering what a milestone of swimming, cycling, and running motor skills would entail, achieving a particular stable or optimum movement cadence could serve as a criterion, but would not constitute a performance goal. A hypothetical example of a milestone of triathlon motor skills has been added to the Recommendations for Future Research section of the amended thesis (section 14.7).

14.3 Existing Theories and Models

In this thesis, I made a deliberate choice to operate within the schema paradigm of motor control suggested by Schmidt (1975). This hypothesis has provided a paradigm through which to interpret the experiences, attitudes, and beliefs of stakeholders in triathlon regarding the important motor skills required to develop an elite triathlete. Interpreting our findings using this paradigm has created a theoretically sound interpretation of the data obtained from interviews, with the generated themes forming a coherent picture of motor skills in triathlon. Furthermore, findings from previous research highlight the importance of effective learning transfer from practise to competition (Rosalie & Müller, 2012). Based on participant's experiences, attitudes, and opinions about motor skill development in triathlon, the characteristics of practice domains differ from the competition domain in key areas such as physical, temporal, and social qualities (Barnett & Ceci, 2002; Chesher et al., 2022; Rosalie & Müller, 2012).

Additionally, findings from this thesis align with ideas about practising to achieve mastery of motor skill performance. Ericsson et al. (1993) proposal for the attaining expertise stipulated that large amounts of 'deliberate practise' was necessary. Notably, such practise be: 1) motivated, with specific attention and effort directed towards improvement under the guidance of a suitably qualified teacher, 2) accompanied by immediate feedback and knowledge of performance results, and 3) involve considerable repetition of the same or similar tasks. However, it has been noted that in sport, the conditions for deliberate practice are not always met, yet mastery is still attained. Over 25 years later, Ericsson and Harwell (2019) proposed ‘purposeful practice’ and ‘naïve practice’ as additional forms of practice through which performance improvements can be obtained. It is appears that most triathlon training falls under the categories of deliberate or purposeful practise, both of which are characterised by specific attention towards improvement and repetition (Ericsson & Harwell, 2019). The findings from the final study of this thesis suggest that the specific coach is responsible for a signficiant and substantial amount of variation in motor skill performance, potentially due to how attention and motivation is directed in training, as well as the specific training tasks set by the coach (Ericsson et al., 1993; Hafer et al., 2015; Werner & Federolf, 2023).

14.3.1 Critique of Motor Skill Investigation in Sport

In sports coaching, passing knowledge from coach to athlete and through generations of coaches is a common method of teaching (Leeder, 2019). This transfer of knowledge through experience and collaboration is important, as it is currently the primary way of teaching athletes and other coaches how to perform sport specific motor skills in the absence of an evidence-based pathway. Scientific investigations have not yet advanced the field by identifying important motor skills in a sport and evaluating them longitudinally (Williams & Hodges, 2023). As a result, the body of literature on motor skill performance in sport lacks an applied framework that can objectively describe or guide improvement in sport specific motor skills.

The current state of the motor control and skill acquisition literature can be summarised as primarily focussed on debating the processes behind the central control of movement and learning, while lacking a sport specific or longitudinal focus (Phillips et al., 2010; Schmidt, 2003). Additionally, numerous studies investigate the types of practice that are performed (Choo et al., 2024; Magill & Anderson, 2014) and the type of feedback that should be received (knowledge of results and/or knowledge of performance) (Magill & Anderson, 2014). However, no investigations exist that measure motor skill performance changes in athletes longitudinally. The closest approximations are: 1) longitudinal investigations of fundamental motor skill development in infants and children (de Onis, 2006; Pfeiffer et al., 2020; Wijnhoven et al., 2004), 2) short term investigations (approx. 10 days to

10 weeks) (Agresta & Brown, 2015; di Cagno et al., 2014; Ildikó et al., 2019), and 3) investigations of motor skill development in individuals living with disabilities (Azar et al., 2016; Bishop & Pangelinan, 2018) and injuries (Agresta & Brown, 2015). Therefore, subjective assessments of motor skill performance and development, guided by coaches' experience, remain the most reliable approach available.

To gain further insight into sport specific motor skill performance, more objective and longitudinal investigations are required. These would complement the experience-based ideations that guide expert coaches to understand how motor skill performance changes over time. For this to happen, the skill acquisition and motor control field must focus on investigating sport specific motor skills in ecologically valid settings with participants who actively compete in sport. This thesis applied the design thinking process (Carlgren et al., 2016) to triathlon, offering an innovative example that could guide longitudinal investigations of motor skill performance in other sports. With further replication of this approach and an increased understanding of changes in sport specific motor skill performance, the fields of motor control and skill acquisition will advance, without the need to wait for a complete understanding of central movement control or learning processes.

14.4 Unexpected Findings

It was unexpected that adaptability would be a focus of stakeholders in triathlon. According to Gentile's Taxonomy of Motor Skills, pool swimming, cycling without drafting, and running on an athletics track would typically be categorised as closed skills (swimming and running: 1C - body transport, with no object in stationary regulatory conditions and no intertrial variability; Cycling: 1D - including object manipulation) (Gentile, 2000; Magill & Anderson, 2014). Therefore, adaptability of motor skill performances would not typically be considered important. However, within the context of triathlon, changing regulatory conditions such as running and cycling surfaces, tides, proximity to competitors, hills and corners demand adaptability in skill execution. Additionally, to respond to factors like waves, the pacing strategy of a peloton, and matching competitiors running pace near the finish line, requires intertrial variability (Chesher et al., 2022), making swimming, cycling, and running more open (4C and 4D) (Gentile, 2000; Magill & Anderson, 2014). Consequently, training these motor skills as closed skills (1C and 1D) does not account for the adaptability needed during race performance. Coaches should therefore seek opportunities to train under varied environmental and task contexts, such as open-water or group pool swimming, cycling in a group over variable terrain, and running in a close group where contact with other triathletes may occur.

It was also unexpected to find that a single trunk mounted wearable IMU may have the capacity to fully describe the tasks that a cyclist performs during a race. By describing the tasks and relating them to course features (such as hills and corners), the IMU provides rich detail to evaluate the motor skills of cyclists (Zignoli & Biral, 2020). To date, the wearable IMU can detect 'in-saddle' and 'out-of-saddle' riding, offering some insight into the stability of the cyclists GMP. In Chapter 4, it was noted that some cyclists alternate repeatedly between 'in-saddle' and 'out-of-saddle' cycling. While this could result from environmental factors imposed by the race (hills, over-taking, corners), it could also occur from poor stability of the cycling GMP and an inability to maintain an efficient cycling motor pattern at a constant speed (Bouillod & Grappe, 2018; Chesher et al., 2022).

14.5 Conclusions

This thesis aimed to identify and measure the performance of important motor skills in triathlon over time, with the objective of providing practitioners with information to guide training to maximise motor skill performance. Upon completing the individual investigations and compiling them to form this thesis, several important questions have been addressed:

1) *What are the important motor skills for elite success in triathlon?*
   Interviewing stakeholders in triathlon generated rich and novel insights into important motor skills for elite success in triathlon. Stakeholders tended to primarily discuss continuous motor skills and the ability to paramterise the invariant features of these motor skills. Additionally, this investigation highlighted a disconnect between practitioners in triathlon and sport science research, as motor skill development is scarcely discussed alongside determinants of performance. Consequently, this thesis will advance the application of performance analysis in triathlon.

2) *How can important triathlon motor skills be measured in the field?* A single trunk-mounted wearable IMU is a valid method of measuring movement cadence across all disciplines of triathlon and can be automated using custom peak counting algorithms. This investigation demonstrated how a measurement system with high ecological validity can accurately measure motor skill performance in a natural setting, as opposed to abstract environments. Furthermore, the custom peak-counting algorithm enables rapid data analysis with minimal technical expertise, making it feasible for use by practitioners in professional settings. This further underscores the utility of the measurement system in ecologically valid contexts, rather than abstract ones.
3) *Are there typical patterns of change in performance of an important motor skill parameter (movement cadence) in triathlon over time, and what factors affect this?* Patterns of change in movement cadence over time are highly individual, with different predictors influencing each discipline. The most significant factors affecting movement cadence were age, time spent practising in the sport and the specific coach responsible for coaching the triathlete. Given the influence of these factors, training drills should be designed to intentionally improve movement cadence over time. Coaches should direct attentional focus towards improving cadence during training in order to enhance athletes' ability to parameterise each motor skill.

Each investigation in this thesis builds upon the previous one to create a framework for analysing motor skills in triathlon. This framework can be applied to other motor skills in triathlon as well as in other sports. This is important because athletes with greater mastery of key motor skills often outperform their less skilled counterparts. Additionally, this information is important to direct the significant time and resources that are devoted to identifying individuals with superior motor abilities and fostering these over time.

14.6 Limitations of the Research

As with all research, the findings contained within this thesis are not without limitations. Primarily, this research aimed to understand the typical patterns of change in performance of important motor skills in triathlon. To do this, it was necessary to use a paradigm of motor control to interpret how motor skills might be performed (Kelso & Tuller, 1984; Schmidt, 1975). It is therefore important to acknowledge that an alternative paradigm of motor control could also have been used. The intention of this thesis was not to investigate how motor skills are centrally controlled or learned and therefore we are not participating in the debate of which motor skill paradigm is most likely to be accurate.

The primary objective of this thesis was to conduct a longitudinal analysis of motor skill performance prospectively over an extended period to understand how motor skills performances change over time. While this has provided some insights into individual and group changes in performance, the measurement window may not have been of sufficient duration to capture performance changes for all participants. For participants who did not demonstrate individual changes in motor skill performance, the duration of this research may have been insufficient, or race-to-race variations in performance may have obscured observable changes. In the final study, participants had been competing for periods ranging from six months and seven years; thus, the one- or two-years observation period may have coincided with a plateau in performance rather than the culmination of skill mastery, and longer periods of analysis are required. Despite participants being of a similar age, there was considerable variation of time spent in triathlon. This may suggest that, rather than the absence of a common change in motor skill performance, changes could be confounded by maturation, or participants' skill might exist at different points along the learning process.

In Chapter 5, it was assumed that the training environment was sufficient to elicit a change in motor skill performance. However, as there is no established evidence on how much training is required to create changes in movement cadence for swimming, cycling, and running, it is difficult to assess whether the participants' training was adequate. Additionally, ratings of course difficulty were decided subjectively, as no established guidelines from Triathlon Australia or World Triathlon exist to objectively rate the difficulty of a racecourse. These ratings were decided by an expert panel of raters, which included coaches with over 20 years coaching experience, who have also competed at international competitions and produced athletes who have ranked in the world top 50 in Olympic triathlon and world #2 in duathlon.

The changes in motor skill performance observed in this research were identified exclusively among triathletes. Caution should be exercised when extrapolating these results to athletes in the individual sports of triathlon as these athletes spend considerably more time training a single motor skill, and there are documented interference effects when training multiple different modes of locomotion concurrently (Chapman et al., 2007). This has been shown to restrain the amount of motor learning that occurs, meaning athletes in the individual disciplines are likely to achieve greater levels of motor skill mastery than triathletes (Chapman et al., 2007).

Throughout this thesis, the focus has been on performing research with practical application to triathlon competition. In Chapter 3 (section 11.5 Discussion), it was noted that participants often reported forgetting the wearable IMU was attached, indicating that there was unlikely to have impacted regular performance. However, qualitative data gathering was not reported in the methodology of Chapter 3. Given the applied nature of this research, collecting additional qualitative data about the participants' experiences with wearable technology during racing would have provided valuable insight to the practical application of this technology.

14.7 Recommendations for Future Research

The investigations in this thesis lay the foundation for several avenues of future research. Primarily, this research acts as a proof of concept to identify important motor skills for a sport, validating a measurement tool for field use, automating the analysis and processing, then measuring changes in motor skill performance over time. This is particularly relevant for any sport where motor skill performance is not commonly explored. Additionally, as the participants recruited in Chapter 5 were relatively homogenous, this conceptual process should be further tested across a wider spectrum of triathlete abilities. As there is a lack of supporting research, a speculative position must be taken as to whether replicating this investigation with different participants would yield different results. As stated in Unexpected Findings (section 14.4), as swimming, cycling, and running motor skills are performed in triathlon races, they become more open (4C and 4D) (Gentile, 2000). It is therefore possible that elite triathletes may perform to a higher standard compared to more novice triathletes where there is increased inter-trial variability imposed by the features of the racecourse (Komar et al., 2015). The applicability of this conceptual process should be investigated, considering that the performance of these motor skills may change in the more difficult environments encountered by elite triathletes.

By monitoring changes in motor skill performance over time, appropriate training can be prescribed in response to accelerations, decelerations or stabilisations in the performance of a motor skill. This process could be further developed in triathlon by analysing performance concurrently with data collection, enabling training to be prospectively adjusted. This would also provide an objective measure of a coach's effectiveness by assessing how well intentional coaching strategies produce the desired performance changes in athletes over time. Thus, a performance trajectory for coaches could also be established.

Another avenue for future research is in the identification of talented triathletes. Firstly, measuring the ability of triathletes to parameterise the speed of swimming, cycling, and running motor skills, could provide insights into which triathletes have better developed motor skills, aligning with the processes of identifying talent (T1) in the FTEM framework (Gulbin et al., 2013). Gulbin et al. (2013) recognised that identifying potential in a skill domain is important to distinguish individuals from those who may also be physically gifted.

Secondly, motor skill performance measurements could be used to identify how changes in motor skill performance relate to subjective assessments made by coaches. Roberts et al. (2021) described the 'coach's eye' as a coach's instinctive ability to rate athlete performance and identify sporting talent. Coach' use mental models of performance built over years, and often rely on 'gut instinct' to make talent identification decisions. Another way to conceptualise the 'coach's eye' is the subconcious creation of mental models of performance through experience, by repeatedly watching athletes perform and creating associations between certain performance, anthropometric or training characteristics with success. Therefore, quantifying motor skill performance and tracking changes over time could be useful to further explain exactly what expert coaches see when they observe talented athletes. This may help to quantify the 'coach's eye' and allow other practitioners to employ the same mental talent identification models as expert coaches and could improve coach development by making these models more transparent.

A novel finding of this thesis is the ability of a single-trunk mounted wearable sensor to count the cyclists transition between in-saddle, out-of-saddle, and coasting cycling tasks. Further, it was encouraging that a machine learning algorithm could automatically detect when a cyclist was riding in-saddle and out-of-saddle under controlled conditions. However, more work is required to improve the automated measurements of the exact duration of these tasks. Unfortunately, coasting could not be determined with accuracy, though this may be possible by using a convolutional neural network to analyse the shape of the accelerometer signal, but this would require a much larger data set. Validating an IMU to automatically detect coasting efforts would enable a comprehensive time motion analysis of a cycling course, providing information about cyclists pedalling, whether they are in-saddle or out-of-saddle, and the path taken through the corner.

To gain insight into the cycling task performances of triathletes in races, a preliminary analysis was conducted to describe the amount of time triathletes spent 'in saddle' and 'out of saddle' riding. These results varied widely and there was no discernible pattern identified when compared with average race velocity. Additionally, the sensitivity and specificity of the machine learning algorithm that was used to detect cycling task changes lacks sufficient sensitivity to provide an accurate measurement of time spent riding 'out of saddle' in a race. A formal analysis was not reported as the focus of this thesis is to measure changes in movement cadence, however, further development of the short time fourier transform and parameters of the machine learning algorithm should be undertaken to improve the utility of this tool in the field.

Regarding the third aim of the thesis, while no common milestones of triathlon motor skill performance were identified, future research should investigate the existence of such milestones. Previous milestone models have been used in infant (Wijnhoven et al., 2004) and in gymnastics motor skill development (Gymnastics Australia, 2022). In artistic gymnastics in Australia, gymnasts progress through ‘levels’ by demonstrating proficiency in motor skills that satisfy specific performance criteria (Gymnastics Australia, 2022). For example, a ‘level three’ gymnast is expected to perform a single leg vertical hop (motor skill) during a beam routine, with a 45° leg lift and land on the same leg (performance criteria). As the gymnast advances, they must perform a split leap (motor skill), with 135° between the legs at level five and 180° between the legs (performance criteria) at level six (Gymnastics Australia, 2022). This illustrates a milestone model of sport performance, where a gymnast advances by demonstrating competence in specific motor skills, allowing progression through the sport.

In triathlon, a milestone model could be applied by identifying important performance goals of swimming, cycling, and running and establish performance criteria that must be achieved before increasing in race difficulty (see Chesher et al. (2022) for the beginnings of this process). For example, a triathlon motor skill milestone framework might require achieving a performance goal (average speed throughout a race), benchmarked by age group distance national records, while meeting specific performance criteria (movement cadence). An example of a milestone in swimming could be completing a particular distance in a benchmarked time, while maintaining specific stroke and kick rates with qualitative assessments of technique (McLean et al., 2010). In cycling, a milestone might involve completing a time trial in a benchmarked time while maintaining a stable average power output and associated optimum movement cadence (Foss & Hallén, 2005; Leirdal & Ettema, 2011). In running, it could involve completing a specific distance in a benchmarked time while focussing performance criteria on stride rates and lengths with qualitative assessments of running form (de Ruiter et al., 2014).

To expand on the motor skill milestone in cycling, investigations have demonstrated that as average power output increases, so too does optimal movement cadence (Ettema & Lorås, 2009). For example, maintaining approximately 350 watts at 80-100 RPM has been associated with improved finish times, oxygen efficiency and energy turnover (Foss & Hallén, 2005; Leirdal & Ettema, 2011) compared to cycling at the same average power with lower cadences (Ettema & Lorås, 2009). Thus, this milestone could also be linked to physiological and biomechanical determinants of triathlon performance. Such milestones could be tracked during junior triathlete development to ensure progression in motor skills such as optimising cycling cadence as power output increases. A milestone model for progressing young triathletes in race distance and difficulty based on motor skill performance could encourage skill development over high training volumes focused solely on attaining physiological adaptation.

In summary, this thesis lays an important foundation for measuring changes in motor skill performance over time to inform training and promote motor skill mastery in triathlon. Firstly, by establishing current opinions on key motor skills for elite triathlon, a targeted approach was adopted for validating measurement tools for field use. Secondly, the validation of the wearable sensor enables continuous measurement of triathlon motor skills in both training and competition—an important advancement in motor skills analysis for the sport. Finally, this thesis offers critical insights into the changes in performance of key motor skill parameter in triathlon and provides a methodology that practitioners can replicate to improve motor skills in other sports.

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15.0 Appendices

15.1 Supplementary Material

15.1.1 Appendix A – Online Eligibility Survey

- Please fill in relevant personal details.

Name: _______________________________ DOB: ______/______/______

Gender: ______________________________

- In what state do you currently reside?

____

- Which of the following roles best describes your role in youth triathlon development or elite triathlon performance? (Circle multiple if more than one applies).

a). Triathlete

b). Parent of a triathlete

c). Triathlon coach

d). Administrator/Technical official within a triathlon organization

e). Athletic preparation or supporting staff working with triathletes

- Can you provide some more detail about your selection in Q3? (Length, specific title, role)

- Depending on answer to Q3.
  a. Triathlete:
    i. Are you licenced to race by Triathlon Australia?
    ii. Please list the coaches you have had during your time as a competitive triathlete.

  b. Parent:
    i. How old is your child triathlete?
    ii. How long have they been competing in triathlon?
    iii. Is your child licenced to race by Triathlon Australia?
    iv. Please list the coaches your child has had as a competitive triathlete.

c. Coach: Do you hold or have you held a coaching qualification issued by Triathlon Australia? Provide information (level of qualification, length held)

d. Administrator/Technical Official:
    i. What triathlon organization are you currently employed by?
    ii. Have you been employed by any other triathlon organizations in an administrator/technical official role? Please list.

e. Athletic Preparation/Support Staff:
    i. What triathlon organization are you currently employed by?

Have you been employed by any other triathlon organizations in an Athletic Preparation/Support Staff role? Please list.

15.1.2 Appendix B – Interview Guide

Personal Background/Icebreaker questions:

1. How did you get involved in triathlon?
2. What role(s) have you fulfilled in relation to triathlon?
    i. How would you describe your role(s) in relation to the development of youth triathlete(s)?

Experience:

3. What is your understanding of the pathways available to talented youth triathletes to develop into successful senior athletes? (so that the next questions have some context)
4. In your experience, at what age do talented triathletes begin training for competitive events (seriously)?
5. In your opinion, what is an appropriate age for talent triathletes to begin training for competitive events (seriously)? Why?
6. How do/did youth triathletes/you/your child gain recognition as a talented triathlete?
   (Prompt if required only: Do they begin as triathletes or transfer in as a sub discipline?)
    i. What is your opinion on the effectiveness of this method of talent identification?

Development:

7. What discipline of triathlon do you believe to be the most important predictor of high performance in triathlon?
8. How important are the transition phases between each discipline of the triathlon to achieving a fast time? Prompt: explain why

So that main thing we would like to discuss today is the motor skills that are important for success in elite triathlon racing. What is your current understanding of the term "motor skills"?

(If the participant is unable to articulate their understanding or have no idea the following definition can be provided: "activities or tasks that require voluntary control over movements of the joints and body segments to achieve a goal")

I can provide an analogy to a ball sport. In football, passing and receiving the ball would be classed as a motor skill, but not making a decision about who or where to pass it.

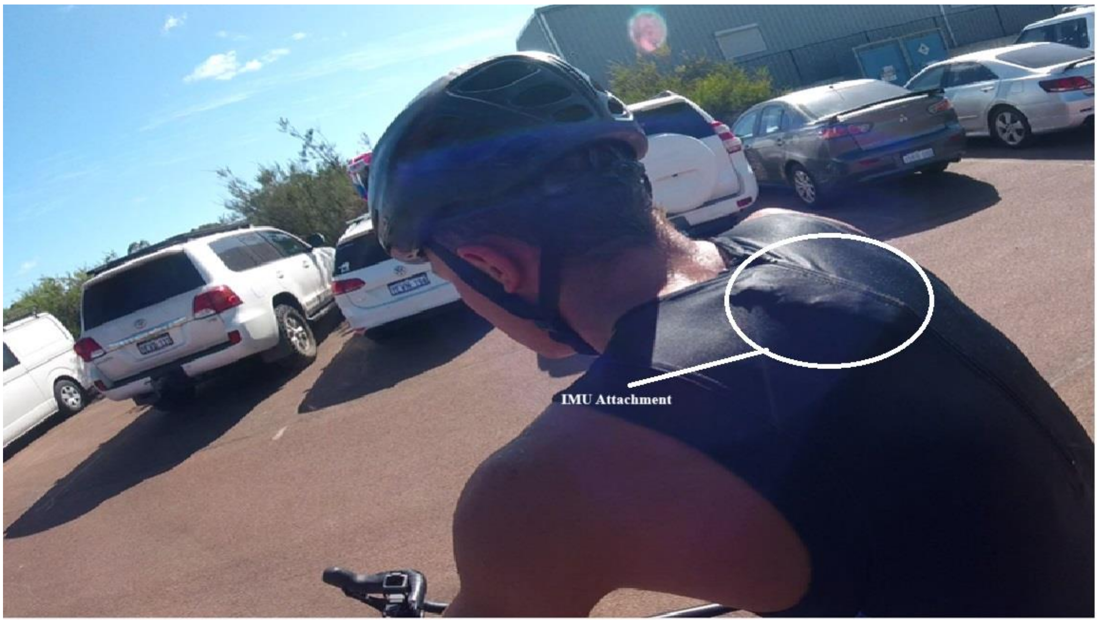
9. What motor skills do you believe are important for success in triathlon racing? Prompt for each skill mentioned:
    i. Explain what it is and why.
    ii. What part or component of this skill is most important?
    iii. Why you think this is the most important component of the skill?
    iv. By what age do you think this skill should be mastered? Prompt: why
    v. How do you think this skill typically develops over different age groups?

vi. For what age categories is this skill most important?
vii. What might it look like when a triathlete has mastered this particular skill? (Prompt: What are the characteristics of it? What are the outcomes of the skill that demonstrates this? i.e. when someone kicks a ball and the ball accurately reaches the target)

At the end of this line of questioning: Are there any other physical skills you believe are important for success in triathlon? Then, start the list of skills mentioned in question 9.

10. In your opinion, how does the length of a race change the importance of each skill?
11. In your opinion, how does the course set at an event change the importance of each skill? (i.e. Depending on the number and degree of corners required during the bike etc)
    If they mention change: Why do you think this change occurs?
12. Which of the skills that you mentioned do you think is most important to achieving fast race times?
    i. Why do you believe this one is most important?
13. What are the milestones that you/your coach/coaches look for to determine that youth triathletes are making acceptable improvements with their physical skill development?
    i. In your experience, what milestones are commonly tracked among many coaches?
    ii. In your experience, how do coaches use the achievement of the milestones you identified to inform their training practises?
    iii. What is your opinion of the effectiveness of tracking these milestones?
14. What would, in your opinion, be the best way to identify triathlon talent based on physical skill development?
15. Are there any other areas of physical skill development in youth triathletes that we haven’t explored, but you think are important?
16. Any further questions/comments?

15.1.3 Appendix C – Picture of wearable IMU attachment



Note. the wearable IMU is attached between the shoulder blades and pinned into the lining of the triathlon suit to ensure it does not move.