STANDARD DISTANCE TRIATHLON: EXAMINING PARTICIPATION AND SUCCESS, PREDICTIVE PERFORMANCE INSIGHTS AND ENVIRONMENTAL EFFECTS

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Abstract

This thesis examines the success of triathletes in elite standard distance triathlons. Participation and success characteristics, predictive race performance outcomes from race segment placings, and the effect of environmental temperatures (i.e., water and air) on performance times were explored. Study 1 examined and described participation, demographics, and country success in elite standard distance triathlons from 1986 to 2022. World Triathlon standard distance triathlon race data (n = 97,374) were examined, with entries exceeding the world record and misidentification of races removed before analysis. Athlete participation rates were modelled using Bayesian logistic regression. Athlete age and career lengths were summarised as the median and 1st and 3rd quartile, and country success was determined by rank ordering the total wins for each country. There were 3,705 races, 10,161 unique male athletes and 5,139 unique females. Female participation has increased since 2003 from 28.9% to 41.9% in 2022, increasing on average 0.6849% (95% credible interval = 0.6818, 0.6879) each year. The median age of male athletes was 24 years (1st and 3rd quartile = 21 to 28) and females 25 years (21 to 29). The median age of male podium finishers was 26 years (1st and 3rd quartile = 22 to 28) and 26 years for women (22 to 30). The median career length was one year (1st and 3rd quartile = 1 to 3) for men and women, while 3.7% of male and 3.9% of female triathletes had careers of 10 or more years. Australian athletes had the most success with 361 wins, topping both men's and women's categories (173 male, 188 female). Elite female participation is increasing in standard distance triathlon, possibly influenced by the actions of the 2002 World Triathlon's women's committee congress meeting. Further, understanding the reason for the success of Australian standard distance triathletes might be informative for optimising performance and development pathways for both sexes.

Study 2 aimed to provide probabilistic information on achieving a podium finish in an elite standard distance triathlon, focusing on swim and bike position combinations. Five years of World Triathlon race records (2018 to 2022) were analysed. Logistic regression was used to model podium (i.e., 1st, 2nd or 3rd place) and non-podium finishers. The model included the podium outcome, swim and bike position, and the athletes' age and sex. We then imputed the probability of obtaining a podium position of any top 20 swim and bike position combinations. Further, we ran an internal cross-validation method of leave one out (race) to validate the logistic regression model. We modelled data from 211 male and 214 female races. Male triathletes who placed first in the swim and first in the bike had a 59% chance of a podium result. Females in this same position combination had a 79% chance of a podium result. Position off the bike had a greater influence on the overall race result than swim position. Leave-one-race-out cross-validation showed that the model could distinguish podium finishers from non-podium finishers 78% of the time. This study offers insights for athletes and coaches to improve elite standard distance triathlon performances, underlining the importance of the cycle segment positions on overall outcomes. The results supported our hypothesis that position out of the cycling segment is more important than position out of the swim segment for a podium finish. While these findings may be intuitive, our analyses provide empirical support for the change in probability across positions that can better inform race strategies.

Elite triathlon races occur across the globe, exposing athletes to various environmental conditions. However, no research has investigated how race performances of triathletes are affected by differing water and air temperatures. Study 3 aimed to examine the effects of temperature on segment performance times and explore the effects on sex. World Triathlon elite standard distance race entries (n=377) were analysed from 2015 to 2022. Water temperatures were modelled against swim time, air temperatures against cycling time and air temperatures against run times. Fitted models included were polynomial (swim), linear (bike) and second-order polynomial (run) regression models fit in a Bayesian framework. Interaction terms were specified for age, sex and random effects for race and athlete identifiers to account for geographical differences and grouped-level competitiveness. Water temperatures ranged from 14.7 °C to 30.9 °C and air temperatures ranged from 11.0 °C to 38.0 °C across six different continents. Water temperature was determined to affect swimming performances (-0.44, 95% CI -0.62, -0.27), while air temperature to affect running performances (1.11, 95% CI 0.69, 1.55) but not cycling outcomes (0.001 95% CI −0.001, 0.003). There were no differences between men and women on how they were affected by temperatures, swimming (0.166, 95% CI −0.01, 0.34), cycling (0.0005, 95% CI −0.002, 0.003) and running (0.07, 95% CI −0.56, 0.72) Males and females were affected similarly by water temperature for swimming and air temperatures while running. However, air temperature did not affect cycling performance times for either men or women. Swimming also showed no difference in the performance times of men and women.

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List of Abbreviations

ATP	Adenosine tri-phosphate
AUC	Area under the operator receiving curve
AUS	Australia
CI	Confidence interval
Covid-19	Coronavirus Disease
Cr	Creatinine
CrI	Credible interval
df	Degrees of freedom
FD	Full distance
GE	Gross efficiency
Hb	Hemoglobin
Hct	Hematocrit
HD	Half distance
HR	Heart rate
IQR	Inter-quartile range
ITU	International Triathlon Union
La	Lactate
LC	Long course
LDH	Lactate dehydrogenase
M	Male
MAP	Maximal aerobic power
MAV	Maximal aerobic velocity
MTR	Mixed-team relay
PO	Power output
PPO	Peak power output
PT	Pedal torque
PV	Plasma volume
PW	Cycling power
RBC	Red blood cells
RF	Respiratory frequency
RPE	Rate of perceived exertion
RPM	Revolutions per minute
SC	Short course
SD	Standard deviation
UCI	Union Cycliste Internationale
VE	Ventilatory threshold
$\dot{V}O_2$	Oxygen uptake kinetics
$\dot{V}O_{2max}$	Maximal oxygen uptake
$\dot{V}O_{2peak}$	Peak oxygen uptake
VT1	Ventilatory threshold one
VT2	Ventilatory threshold two
WBC	White blood cell

WBGT	Wet bulb globe temperature
W_{peak}	Peak watt
WTO	World Triathlon Organization
β	Beta regression coefficient
Σ	Summation

Units of Measure

≥	Equal to or greater than
≤	Equal to or less than
−	Negative
±	Plus or minus
°C	Degrees Celsius
%	Percentage
+	Plus
<	Less than
=	Equals
>	Greater than
cm	Centimetre
h	Hour
kg	Kilogram
km	Kilometre
km·h^{-1}	Kilometre per hour
m	Metre
m·s^{-1}	Metres per second
mL·kg^{-1}·min^{-1}	Millilitres per kilogram per minute
mm	Millimetre
W	Watts
W·m^{-2}	Watts per metre squared

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Chapter 1: Introduction

This thesis chapter outlines the background (Chapter 1.1), the context of the research thesis (Chapter 1.2), describes the aims and hypotheses of the study chapters (Chapter 1.3) and provides an overview of the remaining chapters of the thesis (Chapter 1.4)

1.1 Background

Triathlon is a relatively young sport, with the first recorded event completed in 1974 and only included in the 2000 Olympic Games. In comparison, endurance sports similar to the modern marathon were part of the 1896 Olympics more than a century earlier. Triathlon research has received increasing attention, with 1,237 articles returned for the search term ‘triathlon’ on MEDLINE (December 2023) and approximately one-third of all articles published in the last five years. These current research findings focus on the physiological, biomechanical, morphological and race analyses of triathlon. Research relating specifically to triathlon has also delved into psychological, nutritional and injury aspects. Findings from these numerous studies have highlighted the importance of specific areas which maximise performance.

The earliest research conducted on triathletes was in 1986 (Holly et al., 1986), exploring the physiological components of triathlon (Long et al., 1990; Mc Naughton, 1989; Schneider et al., 1990; Toussaint, 1990), which have remained the prominent focus of today’s literature (Ambrosini et al., 2022; Rico Bini et al., 2022). Since triathlon was introduced to the Olympic campaign in the early 2000s, performance and prediction of performance, have become particularly emphasised in the literature (Brophy-Williams et al., 2011; Etter et al., 2013; Hausswirth et al., 2001; Hoffmann et al., 2017; Landers et al., 2000; Lepers et al., 2013). While these studies focus on the standard distance triathlon, the research under the context of triathlon is split between the different race distances of triathlon (Table 2.1). Fortunately, increased standard distance triathlon research over the years has amplified more detailed information that can be built upon, leading to many review articles (Ambrosini et al., 2022; Millet, 2000; Rico Bini et al., 2022).

Despite the increasing research attention to triathlon and improvements in the sport over the recent decades, there appears to be a lack of information regarding athlete demographics in the context of elite races. Although research focused on triathlon has examined performance aspects from physiological, morphological, and race analyses, few studies have considered triathlon from the context of a sport. Improved understanding of athlete demographics, participation, and country success in triathlon may highlight areas for improvement or success. Current performance analyses examine time as a performance indicator; as discussed in the thesis, other indicators of race performance have not been considered.

1.2 Context

The history of the current-day triathlon started with the first race in 1974, before the International Triathlon Union (ITU) formed 15 years later in April 1989 (Inside World Triathlon, 2023). Triathlon is a multi-sport event comprising swimming, cycling, and running at various distances, segmented by two transition periods. Notably, there have been two elite racing series that have continued since the inauguration of the ITU. These include the World Cup Series, which started in 1991 and the World Championship Series, which began in 2009. Triathlon was also introduced to the Olympic campaign program, debuting in the 2000 Sydney Olympics. Later, at the 2016 Rio Paralympics, para-triathlon debuted. Most recently, the addition of the mixed team relay was introduced in the 2020 Tokyo Olympics (Inside World Triathlon, 2023). The timeline of these events is depicted in Figure 2.1. This thesis will focus on investigating and discussing the standard Distance triathlon unless otherwise specified.

There have been advancements in the literature on how triathlon has developed since its inception to current-day racing. Furthermore, the current performance of triathlon analyses has, to a lesser extent, not been explored beyond time-based analyses. The scheduling of races across six continents requires athletes to perform further in varied environmental conditions, such as hot air temperatures with high humidity. No research has examined the effects of environmental conditions on triathlon performance in the context of elite races. Developing this understanding may highlight areas of attention for further study.

The importance of athlete positioning during a race and the direct implications on race outcomes from positions have not been modelled in the existing literature. No previous work has also examined the performance of triathletes in various environmental conditions, specifically in the context of elite races. Therefore, research addressing these identified knowledge gaps of race positioning and the effects of environmental temperatures can provide valuable insight into triathlon performance and ultimately improve race outcomes.

1.3 Aims and Hypotheses

This thesis comprises three studies examining elite triathlete characteristics, predicting podium outcomes, and performance times in various environmental conditions. The aims and hypotheses of each study are below.

Study 1: An Overview of Elite Standard Distance Triathlon Between 1986 and 2022.

Aim:

1. Examine the participation rates, athlete demographics, and country success of elite standard distance triathletes between 1986 and 2022.

Hypothesis:

No hypotheses were generated as our aims were only descriptive.

Study 2: Predicting Performance Outcomes in Elite Standard Distance Triathlons.

Aim:

1. Quantify the probability of obtaining a podium position based on swim and cycle segment position combinations.

Hypothesis:

1. An athlete's position finishing the cycle segment would have more influence on final placing than the position finishing the swim segment.

Study 3: The Effect of Water Temperature and Ambient Air Temperature on Elite Standard Distance Triathlon In-Race Performance Outcomes.

Aims:

1. Examine the effect of water temperatures on swimming performance times and air temperatures on cycling and running performance times; and
2. Explore sex differences in the effect of environmental temperatures on performance times.

Hypotheses:

1. Women would be slower across all segments than men; and
2. Men and women would be affected the same by water temperatures swimming, affected the same by air temperatures cycling; however, men would be affected more by air temperatures running.

1.4 Thesis Outline:

The thesis includes six chapters. Chapter 1 contains the introduction to the body of work, while Chapter 2 summarises the relevant literature before the three experimental chapters (Chapter 3–5) are presented. Finally, Chapter 6 offers a collective discussion of these findings while also detailing limitations, practical applications, and recommendations for future research.

Chapter 2: Literature Review

This literature review covers three main topics:

- The sport of triathlon (Chapter 2.1);
- The physiology of elite triathletes (Chapter 2.2): and
- Current understanding of performance and statistical modelling in triathlon (Chapter 2.3).

2.1 Triathlon

A triathlon is a multisport event of three separate endurance disciplines combined into one race, separated by two short transition periods. Triathlon involves continuous and sequential completion of swimming, cycling, and running segments. The current World Triathlon Organisation (WTO) is the sport's governing body that oversees competition rules for triathlon, duathlon, and other related multisport events. The WTO was founded in 1989, then called the International Triathlon Union (1) before being reformed into the WTO in October 2020. Since the first recorded triathlon on 24 September 1974, various organisations have offered triathlons over different race distances (Table 2.1). The most common format is the Olympic (or standard) distance triathlon. Races are broadly categorised by distance into short- and long-course triathlons. Notably, short-course triathlons are draft-legal at the elite level, while long-course triathlons are non-draft-legal. Drafting reduces the effort to overcome air resistance; therefore, the drafting cyclist can travel at the same relative speed for less power output. The standard distance triathlon is the longest short course at 51.5 km, where drafting is permittable across all race segments (Table 2.1). This standard distance triathlon involves a 1,500 m swim, transition one, 40 km bike, transition two, and a 10 km run.

Table 2.1 Summary of elite-level athletes’ most common triathlon races, segment distances, total distance, and organisation.

Race Name	Swim distance	Cycle distance	Run Distance	Total distance	Course Category	Draft Legal
Super Sprint	400 m	10 km	2.5 km	12.9 km	Short Course	Yes
Sprint	750 m	20 km	5 km	25.75 km	Short Course	Yes
Standard distance	1,500 m	40 km	10 km	51.5 km	Short Course	Yes
100km	2,000 m	80 km	18 km	100 km	Long Course	No
70.3 Half Ironman	1,900 m	90 km	21.1 km	113 km	Long Course	No
140.6 Full Ironman	3,800 m	180 km	42.2 km	226 km	Long Course	No

Figure 2.1 Time series of major events in the standard distance triathlon and current World Triathlon Organization from 1989 to 2020.

Triathlon races typically begin in the early mornings for age group athletes. However, elite athletes can start competition throughout the day. Races always start with the swim segment, transition, cycle segment, transition, and, lastly, the run segment. For elite competitors, these races start from land (e.g., beach), pontoon, or water. This means that for the standard distance triathlon, the swim segment is always completed in an open body of water (i.e., lake, ocean, river). The cycling segment is then completed on closed-off roads, similar to the run segment. Transitioning from swimming to cycling (Transition One) requires triathletes to remove their swimming accessories before un-racking their bike. Triathletes must pass a transition line before mounting their bicycles. Similarly, there is a transition line for Transition Two in which athletes must dismount their bicycles before entering the transition area and commencing the run segment. Given the nature of the race, triathletes currently compete in a one-piece 'triathlon suit' to avoid clothing changing when transitioning between race segments. Before advancements in material technology, triathletes often competed in two-piece attire or separate garments for swimming, cycling and running.

The WTO oversees the rules and regulations that govern the elite standard distance triathlon. To be considered an elite athlete, they must be registered through the World Triathlon online system by their respective National Federation. If an athlete were to compete in an elite race, they would no longer permitted to compete in any non-elite race for the remainder of the calendar year. Further, according to the 2023 World Triathlon Competition Rules, there are regulations regarding the time and equipment allowed during races. In the swim segment, elite triathletes can stay in the water maximally for 30 mins (World Triathlon Competition Rules, 2023). Temperature regulations indicate that the 1,500 m swim will only be completed with water temperatures of 13.0 ºC to 30.9 ºC (World Triathlon Competition Rules, 2023). The water temperature is recorded one hour before the start of the event, 60 cm below the water's surface at the course's midpoint and two other unspecified locations (World Triathlon Competition Rules, 2023). The lowest temperature recorded is considered the reference temperature when the average of the three temperatures is below 27.0 ºC. When the average is above 27.0 ºC, the highest temperature is instead used as the reference temperature. Wetsuit usage is also dictated by the water temperature, with a mandatory requirement that all athletes wear wetsuits when water temperatures are <16.0 ºC, forbidden when temperatures are ≥20.0 ºC, and optional between those given temperatures (World Triathlon Competition Rules, 2023). The thickness of wetsuits also cannot exceed 5 mm. When the water temperature is below 22.0 ºC, and the air temperature is below 15.0 ºC, a separate adjusted water temperature will be used as a final temperature (World Triathlon Competition Rules, 2023). The outline of these adjusted water temperatures can be seen in Appendix A. Recording of air temperature is based on the recommendations of the American College of Sports Medicine using wet bulb globe temperature as the classification method. Measurement is taken at the finish area of the race in direct sunlight, 1.5 m above the ground and every 30 min of the preceding three hours before the start of the competition. Risk categories selected pertain to Low, Moderate, High, Very High, and Extreme for <25.7 ºC, 25.7 ºC to 27.8 ºC, 27.9 ºC to 30.0 ºC, 30.1 ºC to 32.2 ºC, and >32.2 ºC, respective WBGT indexes (World Triathlon Competition Rules, 2023). standard distance triathlons must be re-scheduled or cancelled if temperatures are ‘Extreme’.

From 1 January 2022, the WTO has followed cycling rules imposed by the Union Cycliste Internationale (UCI) (World Triathlon Competition Rules, 2022; World Triathlon Competition Rules, 2023). UCI road race rules apply for draft-legal triathlons like the elite standard distance triathlon. This includes strict regulations on the geometry of the bicycles athletes can race on. For draft-legal races, in any circumstance, athletes are not permitted to draft off an athlete of a different sex, athletes on another course lap, or a motorbike or vehicle. Similar to following rules via the UCI, the WTO also complies with the World Athletics for shoe regulations. Race completion is considered when any part of the athlete’s torso passes the leading edge of a vertical line extending from the leading edge of the finish line.

Since the ITU’s commencement less than 34 years ago, triathlon has become an Olympic sport, containing a world championship series with 172 national federations in competition. Triathlon continues to grow, especially in the research domain. A PubMed search (November 2023) shows 1,231 results with “triathlon” in the title or abstract of articles. Moreover, in the last six years (2018 to 2023), more than one-third (438 articles) of triathlon research has been published. Research can potentially influence competition policy in triathlon, and the ITU has followed research-based recommendations. For example, the then ITU changed its policy on water temperature regulations in 2017 to improve the health and safety of athletes (Saycell et al., 2018).

2.2 Physiology of Triathletes

Triathlon is an endurance sport, with the standard distance triathlon often taking just under two hours for elite athletes to complete. Unlike most sports, a triathlon involves continuously completing three endurance events. Swimming, cycling, and running are three distinct modes of exercise occurring in two separate environmental mediums – water and land. Elite triathletes compete globally, exposing them to various environmental stressors while racing. These factors greatly influence the physiological requirements placed on athletes to perform during races and across the training cycle in preparation for events. This section of the literature review defines elite athletes' morphological and physiological attributes and the unique biomechanical and physiological changes in the transition from swimming to cycling and from cycling to running. Further, environmental stressors are defined in relation to exercise performance, physiological differences, and the impact of environmental conditions between the sexes. Lastly, it will summarise performance analysis in triathlon and the statistical methods implemented in current research.

Physiology

The physiological requirements of triathlon are similar to those in the singular endurance sports of swimming, cycling, and running. A large focus of research has examined the physiology of triathlons to determine correlations with performance outcomes and how performance measures compare to their single-sport counterparts. Endurance performance is mainly determined by maximal oxygen consumption ($\dot{V}O_{2max}$) and economy or efficiency of motion. O'Toole et al. (O'Toole et al., 1989) stated that for a triathlete to be successful, they must "have highly developed oxygen transport and utilisation systems as well as the ability to efficiently produce a high energy output for prolonged periods without creating metabolic acidosis" (O'Toole & Douglas, 1995). A maximal oxygen consumption is the maximal rate at which oxygen can be delivered to the mitochondria to support the oxidative production of ATP to complete physical work (Hill & Lupton, 1923). The absolute $\dot{V}O_{2max}$ is given in $L \cdot min^{-1}$; however, a relative $\dot{V}O_{2max}$ is more common and expressed in $mL \cdot kg^{-1} \cdot min^{-1}$. Athletes, therefore, progressively train to increase their physical work output and overall performance. This results in two main adaptations that drive increased athletic performance: cardiovascular and musculoskeletal adaptations (Blomqvist & Saltin, 1983; Clausen, 1977). With multimodal training in triathlon, cross-training may play a role in developing improved cardiovascular and musculoskeletal performances (Etxebarria et al., 2019).

Triathletes have high aerobic capacities, indicating a high maximal oxygen consumption, similar to their single sport counterparts (i.e., swimmers, cyclists, and runners) (O'Toole & Douglas, 1995). Table 2.2 provides an overview of reported cycling and running $\dot{V}O_{2max}$ values from elite and competitive populations of standard distance triathletes. Given the nature of swimming and difficulties in recording $\dot{V}O_{2max}$ values underwater, there are few reports on swimming $\dot{V}O_{2max}$ values in triathletes (Butts et al., 1991; Roels et al., 2005). While at the elite level, triathletes all possess high $\dot{V}O_{2max}$ values, there are some variations in results (Table 2.2). These miscreances have led to some researchers suggesting that the fractional capacity of $\dot{V}O_{2max}$ (percent of VO_{2max}) may provide a better indicator of performance in triathletes than VO_{2max} (O'Toole & Douglas, 1995). Correlation analyses between $\dot{V}O_{2max}$ and performance in the standard distance triathlon have been conducted, although not in an elite population. Regardless, tethered swim $\dot{V}O_{2max}$, cycling $\dot{V}O_{2max}$ and treadmill $\dot{V}O_{2max}$ were correlated with finish times of $r = –0.49$, $r = –0.78$ and $r = –0.84$, respectively ($p <.01$) (Butts et al., 1991). Again, these values are for recreational athletes and may not reflect an elite population.

The morphology of triathletes in relation to performance was explored in 71 elite triathletes at the 1997 Triathlon World Championships (Landers et al., 2000). This study indicated that four separate distinguishable morphological factors played a role in the success of elite triathletes. These included values of robustness (i.e., total mass, muscle mass, girth and breadth of trunk), adiposity, segmental lengths and skeletal mass (Landers et al., 2000). For success, the importance of low adiposity in male and female triathletes and proportionally longer segmental lengths was noted (Landers et al., 2000). Overall, a low body fat percentage and long limbs are associated with success in triathlon, with longer arms related to swimming success and longer legs to cycling and running success (Ackland et al., 1998; Canda et al., 2014; Landers et al., 2000; Sleivert & Rowlands, 1996). A recent review in talent identification for elite triathletes has reported that elite male triathletes are, on average, ~ 180 cm tall with a weight of ~ 70 kg and a body fat percentage of 8.77 ± 1.62% (Cuba-Dorado et al., 2022). Elite females, smaller, are ~ 167 cm tall and currently ~ 55 kg with a body fat percentage of 19.3 ± 1.94% (Table 2.2) (Cuba-Dorado et al., 2022). Thus, it appears that the anthropometric profile of triathletes can aid in success in the standard distance triathlon, although it is not a requirement for success (Cuba-Dorado et al., 2022).

Table 2.2. Table adapted from **Physiological Attributes of Triathletes** and **Applied Physiology of Triathletes** (O'Toole & Douglas, 1995; Suriano & Bishop, 2010).

Author	**Subjects**	**Age**	**Sport**	**Level**	**Running**		**Cycling**	
					$\dot{V}O_{2max}$	**MAV (km.h^{-1})**	**$\dot{V}O_{2max}$**	**W_{peak} (W)**
Hue et al., 2000	M = 6	21.8 (2.4)	Triathletes	Members of the French national team	78.5 (3.6)	n/a	75.9 ± (5.2)	n/a
Millet et al., 2003	M = 9	24.8 (2.6)	Triathletes	Senior elite triathletes at world championship level	n/a	n/a	74.3 ± (4.4)	n/a
	F = 9	27.9 (5.0)					61.0 ± (5.0)	
Laurenson et al., 1993	F = 10	27.1 (3.5)	Triathletes	Members of the Great Britain national squad	65.6 (6.0)	n/a	n/a	n/a
Bunc et al., 1996	M = 23	17.7 (2.2)	Triathletes	Young elites	67.9 (5.9)	15.2 (1.4^{a})	n/a	n/a
	F = 13	17.1 (1.4)			56.1 (2.4)	12.7 (0.7^{a})		
Schabort et al., 2000Schabort et al., 2000Schabort et al., Schabort et al., 2000	M = 5	23.0 (4.0)	Triathletes	Elite	74.7 (5.3)	20.9 (0.9)	69.9 ± (4.5)	385 (14) L
	F = 5	25.0 (7.0)			63.2 (3.6)	18.0 (0.9)	61.3 ± (4.6)	282 (19) L
	Group	24.0 (5.5)			68.9 (7.4)	19.5 (1.8)	65.6 ± (6.3)	333 (57) L
Hausswirth et al., 2001	M = 10	25.6 (4.1)	Triathletes	Highly Trained	73.3 (5.0)	20 (1.2)	n/a	n/a
Hue, 2003	M = 8	24.7 (2.1)	Triathletes	Elite	71.8 (7.6)	22.0 (0.7)	70.5 ± (6.5)	389 (38) S
Millet et al., 2003	M = 9	24.8 (2.6)	Triathletes	Senior elite	n/a	n/a	74.3 ± (4.4)	385 (50) O
	M = 7	19.1 (1.5)		Junior elite			74.7 ± (5.7)	354 (21) O
	F = 9	27.9 (5.0)		Senior elite			61.0 ± (5.0)	293 (21) O
	F = 6	19.4 (1.3)		Junior elite			60.1 ± (1.8)	268 (19) O
Bernard et al., 2003	M = 10	25.2 (6.8)	Triathletes	Highly Trained	n/a	n/a	61.9 ± (4.1)	380 (31) S
Bentley et al., 2007	M = 9	25.1 (5.8)	Triathletes	Highly Trained	n/a	n/a	69.3 ± (3.6)	321 (28) O
Brisswalter et al., 2000	M = 10	26 (2)	Triathletes	Highly Trained	n/a	n/a	66.4 ± (3.4)	376.5 (20) S

Schneider et al., 1990	M = 10	27.6 (6.3)	Triathletes	Highly Trained	75.4 (7.3)	n/a	70.3 ± (6.0)	376 (34) M

Note. **F** = female; **M** = male; **n/a** = not available; **L** = Lode electronically-braked cycle ergometer; **M** = Monark mechanically-braked cycle ergometer; **O** = Orion electronically-braked cycle ergometer; **S** = SRM electronically-braked cycle ergometer; $^{\mathbf{a}}$ = treadmill at 5% incline. $\dot{V}O_{2max}$ values are expressed as mL·kg·min^{-1}. Values are presented as the mean and standard deviation (SD).

Table 2.3. Table adapted from **Elite Triathlete Profiles in Draft-Legal Triathlons as a Basis for Talent Identification** (Cuba-Dorado et al., 2022). Summary of the literature examining elite draft-legal triathletes' age, weight, height and body fat percentage.

Author	**N**	**Age (years)**	**Weight (kg)**	**Height (cm)**	**Σ Skin folds (mm)**	**Fat (%)**
González-Parra et al., 2013	F = 2	23.0 (4.2)	54.5 (3.3)	168.5 (9.2)	n/a	16.6 (0.7)
Schabort et al., 2000	F = 5	25 (7)	59.3 (5.8)	167 (4.2)	n/a	19.5 (2.4)
Canda et al., 2014	F = 26	25.6 (4.3)	53.8 (3.8)	163.2 (5.4)	67.7 (17.6) $^{(8)}$	19.8 (3.1)
Millet and Bentley, 2004	F = 9	27.9 (5.0)	60.3 (6.6)	167.2 (5.4)	n/a	21.2 (2.9)
Ackland et al., 1998	F = 19	29.0 (3.0)	59.3 (4.7)	168.3 (4.4)	62.8 (13.4) $^{(8)}$	n/a
Laurenson et al., 1993	F = 10	27.1 (3.5)	56.4 (6.1)	167.0 (6.8)	25.9 (9.4) $^{(4)}$	n/a
Werneck et al., 2014	F = 56	27.7 (4.1)	54.2 (4.5)	167 (6)	n/a	n/a
Olaya-Cuartero & Cejuela, 2021	M = 4	22.5 (1.9)	71.4 (4.2)	184 (41)	34.4 (1.8) $^{(6)}$	6.5 (0.5)
Koury et al., 2004	M = 10	29 (10)	69 (4)	174 (5)	n/a	7 (2)
Zapico A. G. et al., 2014	M = 9	26 (2)	67.8 (2.1)	177 (20)	42.8 (3.9) $^{(6)}$	7.3 (0.4)
Gonzalezharo et al., 2005	M = 6	25.3 (4.2)	69.9 (4.6)	175.2 (4.5)	38.9 (5.7) $^{(6)}$	7.6 (0.6)
González-Parra et al., 2013	M = 4	23.3 (2.9)	66.7 (6.5)	167.8 (4.4)	n/a	7.8 (0.5)
Diaz V et al., 2010	M = 5	24.8 (5.6)	71.9 (6.8)	172 (3)	n/a	8.3 (0.4)
Díaz et al., 2012	M = 6	24.8 (5.6)	71.9 (6.8)	180.2 (8.6)	n/a	8.3 (0.4)
	M = 6	24 (5.6)	71.2 (8.7)	180.0 (8.8)	n/a	8.5 (0.6)
Schabort et al., 2000	M = 5	23 (4)	72.1 (4.7)	181 (1.6)	n/a	9.7 (2.4)
Canda et al., 2014	M = 65	26.0 (4.3)	68.5 (5.0)	178.0 (5.2)	48.4 (9.4) $^{(8)}$	9.9 (2.2)
Chollet et al., 2000	M = 6	24.7 (1.3)	69.3 (1.9)	177.5 (2.0)	n/a	10.1 (0.8)
Millet and Bentley, 2004	M = 9	24.8 (2.6)	70.2 (5.2)	177.9 (4.8)	n/a	10.4 (2.1)
Hoffmann et al., 2017	M = 11	23.4 (2.8)	74.5 (4.3)	187.0 (2.9)	n/a	10.7 (1.4)
Park et al., 2014	M = 8	23.5 (3.6)	66.0 (5.1)	174.4 (4.9)	n/a	11.8 (0.5)
Ackland et al., 1998	M = 19	26.3 (4.4)	72.6 (6.0)	180.1 (5.9)	48.3 (10.2) $^{(8)}$	n/a
Hue, 2003	M = 8	24.8 (2.1)	71.4 (7.3)	180.5 (9.3)	22.3 (0.5) $^{(4)}$	n/a
Werneck et al., 2014	M = 55	28.3 (4.2)	67.6 (5.3)	180 (6)	n/a	n/a

Note. **F** = female and **M** = male. Σ Skin folds $^{(\text{number of folds})}$. n/a = not available. Values are presented as the mean and standard deviation (SD).

Swimming and the Swim-to-Cycle Transition

The nature of triathlon as a multisport event means athletes are undertaking three different sports modalities in sequential completion. This leads to changes in biomechanical, physiological, equipment and body positionings as the athlete transitions between exercise modes (Ambrosini et al., 2022). Specifically, the two transitions, i.e., the swim-to-cycle transition and the cycle-to-run transition, are important in triathlon research. The accumulative load as the athlete passes through each race segment means they start the subsequent segment in a fatigued state (Boussana et al., 2003). Briefly, the impact of the swim-to-cycle transition on cycling physiology and performance has not been fully elucidated (Ambrosini et al., 2022). However, the influence of cycling on subsequent running has shown detrimental effects (Rico Bini et al., 2022) on performance outcomes in elite triathletes. This section of the literature review will examine the physiology of triathletes during the swim, the influence of swimming on the swim-to-cycle transition during the cycle, and the influence of cycling on the run transition and the run.

As previously mentioned, swimming in a triathlon typically occurs in open bodies of water (i.e., oceans, lakes, and rivers). When compared to swimmers, triathletes have been found to swim slower (Toussaint, 1990). Nevertheless, there appears to be no difference in stroke frequency and work per stroke between swimmers and triathletes, indicating that the speed difference is due to an increased distance per stroke (Toussaint, 1990). Moreover, the propelling efficiency of swimmers was 61 ± 6%, but only 44 ± 3% for triathletes (Toussaint, 1990). Similarly, the same finding was reported when comparing French, Italian and Swiss elite triathletes to elite swimmers (Olbrecht, 2011). An Index of Coordination (IdC) quantified the difference in technical performance of triathletes and swimmers. While triathletes and swimmers had similar IdC values, swimmers were always faster at maximal swimming efforts. Swimmers continued to increase their IdC, indicating better technical ability (Olbrecht, 2011). Overall, it has been found that swimmers use 21 to 29% less energy than triathletes and have 36.4% increased propelling efficiency (Bentley et al., 2002), while triathletes have an attenuated pull and propulsive swimming phase compared to swimmers (Olbrecht, 2011).

Drafting during a triathlon facilitates a competitive advantage. For example, drafting behind or beside another athlete while swimming decreases the passive drag following the swimmer by 10 to 26% (J. C. Chatard et al., 1998; Chollet et al., 2000). Additional improvements offer a reduced rating of perceived exertion (RPE) by up to 21% and reduced oxygen uptake ($\dot{V}O_2$) at submaximal velocities, indicating an improvement in efficiency. These improvements can enhance overall swimming performances by between 3.2 to 6% (J. C. Chatard et al., 1998; Troup J, 1990), highlighting the advantage of drafting in the swim segment.

Continuing from swimming to cycling is also important, and considerations to understand the effects of previous swimming have been explored. Most obvious in the transition from swimming to cycling are the postural and environmental changes that occur when athletes go from a supine (in water) to an orthostasis position (on land). Moving from water to land induces physiological and biomechanical changes that can alter performance. Specifically, the higher exercise intensities of previously completed segments during Olympic and sprint distance triathlons affect the transitions more than longer distance triathlons (Ambrosini et al., 2022; Rothschild & Crocker, 2019). It should be noted that this section discusses the swim-to-cycle transition, otherwise referred to as Transition One (Migliorini, 2020). The postural change primarily affects blood plasma volume and fluid shifts in the body; however, this is only expected to be a 1% change in volume (Long et al., 1990; Mc Naughton, 1989). Increased core temperatures, dehydration and exercise intensity throughout swimming are associated with decreased performances from increased heart rate and reduced stroke volume (Coyle, 1998; Coyle & Gonzelez-Alonso, 2001; Peeling & Landers, 2007). Across the standard distance triathlon, the previous 1,500 m swim increased blood lactate, VO_2, heart rate, ventilatory equivalent and respiratory frequency by 56.4%, 5%, 9.3%, 15.7% and 19.9%, respectively, in cycling post swimming compared to control cycling (Delextrat, Brisswalter, et al., 2005). These results suggest that previous swimming at a simulated race pace negatively affects cycling. This study used constant cycling at 75% of maximal aerobic power (MAP), dissimilar to variable power observed during triathlons. Regardless, the evidence remains that swimming may negatively affect cycling physiology and performance.

Biomechanically, the change from swimming, an upper body-driven exercise, to cycling, a lower body-driven exercise, is considerable. During the swim segment, blood flow from the lower extremities is redirected to the working musculature of the upper extremities (Ambrosini et al., 2022). Therefore, across the last ~ 200 m of the swim segment, triathletes supposedly increase the use of their legs (Ambrosini et al., 2022). Noted, they increase from a 2-beat kick to a 6-beat kick to stay within the approximation of other athletes and re-direct blood flow to the lower extremities for cycling. However, further information is needed to provide clear statements on the prevalence and effect increasing kicking has on outcomes. These changes indicate that the previous swimming segment in a standard distance triathlon can decrease cycling gross efficiency by 13% (Gonzalezharo et al., 2005). High-intensity swimming may decrease lower limb muscular capacity from accumulated fatigue. This results in triathletes adopting a cycling cadence that is more optimal for reducing neuromuscular fatigue, which may not be appropriate for performance (Delextrat, Tricot, et al., 2005). In a review by Ambrosini et al. (Ambrosini et al., 2022), cycling performances varied in exercise methodologies involving constant or fixed rate power, not typical of elite standard distance triathlon racing. Regardless, the accumulative fatigue from swimming, changes in blood plasma volume, and blood redistribution indicate that swimming would negatively impact cycling (Ambrosini et al., 2022).

Cycling, Running and the Cycle to Run Transition

Cycling in the standard distance triathlon has been described as stochastic with high variability in power output. Power distributions in elite-level races have reported the majority (51%) of power output to be in Zone 1 (PO at V_{T1}), 17% in Zone 2 (PO between V_{T1} and V_{T2}), 15% in Zone 3 (MAP) and 17% in Zone 4 (above MAP))(Bernard et al., 2009. As the Olympic distance distance triathlon is draft-legal at the elite level, athletes surge to try and break away to create an advantage. Similarly, this was seen across seven elite male races, with 34 peaks in power output above 600 W in an elite male race and 18% of cycling spent above MAP (Etxebarria et al., 2014).

A recent systematic review examined 40 studies exploring the cycle-to-run transition in triathlon (Rico Bini et al., 2022). The review suggests it is impossible to determine the effect of cycling on subsequent running physiology, and it was unclear regarding mechanical changes (Rico Bini et al., 2022). However, anecdotal evidence strongly suggests it has detrimental effects. Conflicting evidence was seen in stride length, running velocities either decreased or remained the same, VO_2 either increased or stayed the same, and blood lactate, heart rate, and ventilation also increased. At the same time, other trials found similar results in controlled running or running post-cycling (Rico Bini et al., 2022). However, clear evidence suggests that running RPE post-cycling increases compared to controlling running RPE. This may be indicative of anecdotal evidence suggesting running post-cycling is harder. This review found some evidence of the detrimental effects of cycling pre-running, with most studies observing detrimental effects and no studies showing improvements in running post-cycling. Some articles examined did not include a pre-swim and varied greatly in the methodologies used. A flaw in these studies was the varied methodology, including different cycling durations and intensities (e.g., 15 minutes to 3 hours) and other running durations and intensities (e.g., 4 minutes to 45 minutes) (Rico Bini et al., 2022).

Table 2.4. Table adapted from **Interlink between Physiological and Biomechanical Changes in the Swim-to-Cycle Transition in Triathlon Events: A Narrative Review** (Ambrosini et al., 2022). The physiological and biomechanical changes in athletes cycling during the transition from swimming to cycling in triathlon.

Type	**Physiological Changes**					**Biomechanical Changes**			
	VO_2/VE/RF during cycling	**La/HR after swim/during cycling**	**Hct/Hb/WBC after swim**	**RPE / T° after swim**	**PV after swim**	**GE during cycling**	**PW during cycling**	**SSF/RPM**	**PT**
FD, Laursen et al., 2000	+ 5% VO_2 + 6.7% VE	+ 2% HR					− 4.7%		
HD, Rothschild & Crocker, 2019	+ 4% VO_2	+ 4% HR					− 3.8% PW mean		
HD, Rothschild et al., 2022		HR No Change							
OD, Long et al., 1990		+ 21.2%LDH + 25% Cr	+ 39% WBC + 3.8% RBC		− 9.6%		− 6%		
OD, Delextrat, Brisswalter, et al., 2005	+ 5% VO_2 + 15.7% VE + 19.9% RF	+ 9.3% HR + 32.2% La				− 13%			
OD, Gonzalezharo et al., 2005	No change	High to low HR no change					No change		
SD, Kreider et al., 1988)	+ 5.6% VO_2 + 5.3% VE			+ 0.8% T°		− 17%			
SD, Mc Naughton, 1989					− 3.8% to 4.3%		No change		
SD, Delextrat, Bernard, Hausswirth, et al., 2003	+ 4.5% VO_2 + 14.4% VE + 15.6% RF	+ 11% HR + 47% La				− 12.1%		+ 14% SSR	
SD, Delextrat et al., 2003	+ 4.4% VO_2 + 6.6% VE + 9.4% RF	+ 7% HR + 29.3% La		High RPE		− 4.8%		+ 5.6% RPM	
SD, Delextrat, Bernard,	+ 5% VO_2 + 19% VE + 24.8% RF	+ 7% HR + 42.9% La				− 15.5%			

Vercruyssen, et al., 2003							
SD, Delextrat, Tricot, et al., 2005	+ 5% VO_2	+ 6.4% HR + 16.7% La	High RPE	− 5.4%		+ 5.8% RPM	− 2.9% Pk − 3.9% Mn
SD, P. D. Peeling et al., 2005	No change	+ 75% La	High RPE	− 4.2%	− 9.6%	+ 20.5% SSF	
SD, P. Peeling & Landers, 2007		+ 1.8% HR + 1.2% La	+ 2.4%T°		No change		
SD, Wu et al., 2016			High RPE		− 6.5%		
SD, Barragán et al., 2020		+ 59% La			No change	No change RPM	
MTR, Bentley et al., 2007	No change	+ 3.5% HR ~ + 87% La			− 11% PW mean	+ 18.4% SSF	

Note. C° Celsius; **Cr**: Creatinine; **FD** Full distance; **GE** Gross efficiency; **Hb** Hemoglobin, **Hct** Hematocrit; **HD** Half distance; **HR** Heart rate; **La** Lactate; **LDH** Lactate dehydrogenase; **MTR** Mixed-team relay distance; **OD** Olympic distance; **PT** Pedal torque; **PV** Plasma volume; **PW** Cycling power; **RBC** Red blood cell; **RF** Respiratory frequency; **RPE** Rate of perceived exertion; **RPM** Revolution per minute; **SD** Sprint distance; **SSF** Swim stroke frequency; **SSL** Swim stroke length; **VE** Ventilatory equivalent; **VO_2** Oxygen uptake kinetics; **WBC** White blood cell

An earlier review indicated the detrimental effects of cycling preceding running in standard distance triathlons, noting the adverse effects were more apparent in age group athletes than elite-level athletes. Millet (2000) reported that $\dot{V}O_2$, respiratory frequency, ventilation rate and heart rate increased in running post-cycling (Millet, 2000). A possible reason for this change in physiological parameters may be glycogen depletion, decreased ventilatory efficiency from respiratory fatigue and decreased pulmonary compliance (68). Increased heart rate may also be attributed to dehydration (reduction in blood plasma volume) and an increase in core temperature (Guezennec et al., 1996; Hausswirth et al., 1996, 1997). Moreover, muscular fatigue is typical and contributes to increased energy costs for running (Danner & Plowman, 1995; Hausswirth et al., 1997; Marino G.W & Goegan J, 1993). Reports have shown that the energy cost of running is 1.6% to 11.6% higher than control running (Danner & Plowman, 1995; Guezennec et al., 1996; Hausswirth et al., 1996; Hue et al., 1997; Kreider et al., 1988). Overall, this evidence appears to suggest that cycling has a negative impact on running.

Environmental Physiology

Specific to triathlon is the changing from different sports and environmental conditions – water to land. For performance, the regulation of body temperature is required so that temperatures do not decrease or increase, which will reduce performance. Swimming in triathlons can occur in water temperatures as low as 13.0 ºC and as high as 30.9 ºC (*World Triathlon Competition Rules*, 2023). Cycling and running can occur in air temperatures up to 32.2 ºC as recorded by WBGT (e.g., 38 ºC, 50 % relative humidity). The regulation of human core body temperature is internally controlled at roughly 36.6 ºC (95% CI 35.7 to 37.3) (Fortney & Vroman, 1985; Périard et al., 2021). During exercise, the relative workload of the individual influences the change in core body temperature (Saltin & Hermansen, 1966). This section of the literature review will cover the swim portion, water temperature and its effect on human physiology and performance during exercise. As well as the cycle and run segment and the influence air temperatures have on human physiology and performance during exercise.

Swimming occurs in different mediums (i.e., water) to cycling and running (i.e., air). Water is ~ 830 times more dense than air, increasing its ability to transfer heat from the human body. The heat transfer coefficient of air is around 4.5 $W{\cdot}m^{-2}$ (de Dear et al., 1997), while the coefficient of heat transfer for water ranges from 125-130 $W \cdot m^{-2}$ (Nadel et al., 1974) to 230 $W{\cdot}m^{-2}$ (Boutelier et al., 1977). Accordingly, for any given unit change in water temperature, the immersion of the human body will have a greater physiological response than the same given change in air temperature (Nielsen & Davies, 1976). When swimming, the water temperature is the most imminent threat to the health and safety of triathletes, with an elevated risk of hypothermia (a core temperature < 35 ºC) and hyperthermia (a core temperature > 40 ºC) (Dallam et al., 2005). The rate at which a swimmer loses heat depends on the time spent immersed, the relative metabolic workload and the athlete's body composition (82).Therefore, the scheduling of races in different environmental conditions, especially water temperatures, is important for the health and safety of athletes.

The response to swimming in cold water (< 20 ºC) sees vasomotor tone changes in skin blood vessels due to skin thermoreceptor stimulation, resulting in vasoconstriction (Holmér, 1979) that re-directs blood flow away from the peripheries. More severe complications can arise from immersion in cold water, such as loss of consciousness, decreased muscular contractile force and loss of coordination (Alexiou, 2014). Competitive triathletes are some of the leanest athletes (Sleivert & Rowlands, 1996), disproportionately increasing their risk of hypothermia as risk is associated with time immersed and body composition (Alexiou, 2014). Cardiovascular changes initially result in cold-shock-induced tachycardia before bradycardia, increased arterial blood pressure and cardiac output (Shattock & Tipton, 2012). These changes can also lead to an increased risk of heart arrhythmia, potentially due to an autonomic conflict of increased sympathetic (cold shock response) and parasympathetic (mammalian dive response) tone (Shattock & Tipton, 2012). More generally, there are decreased peripheral and core temperatures of 20 ºC to 25 ºC, reducing performance (Alexiou, 2014). From 16 ºC to 20 ºC, there is marked vasoconstriction, a decrease in $\dot{V}O_2$, a risk of hypothermia and a further reduction in performance (Alexiou, 2014). Between 12 ºC and 16 ºC, there is a continued risk of hypothermia, marked decreases in core and peripheral temperatures leading to a potential inability to swim (Alexiou, 2014). While below 12 ºC, there is a rapid cooling of the body temperature, which can eventuate to the death of the swimmer if left unaddressed (Alexiou, 2014).

Optimal water temperatures for endurance swimming performance are between 25 ºC and 27 ºC (Alexiou, 2014). However, once water temperatures increase to >28 ºC, there is a vasodilatory response and a small decrease in arterial blood pressure and heart rate (Alexiou, 2014). Specifically examining triathletes swimming in warm water (32.1 ± 0.04 ºC) for 20-, 60- and 120-minute conditions, only modest increases in rectal temperatures were observed (Carl D, 2013). Given that elite triathletes complete the swim in a duration of ~ 20 minutes at a maximum temperature of 30.9 ºC (*World Triathlon Competition Rules*, 2023) there is unlikely a great risk of adverse effects from warm water swimming or a great risk of hyperthermia for elite triathletes. While the previous paragraph highlighted the increased risk of hyperthermia, the reduced immersion time (~20 minutes) again reduces this risk.

Most notable concerning water temperature and triathlon races is a study by Saycell et al. (Saycell et al., 2018) examining 20-minute flume swimming in 10 ºC, 12 ºC and 14 ºC with wet suits as well as 14 ºC and 16 ºC without wet suits in elite and sub-elite triathletes (Saycell et al., 2018). Prior, wetsuit regulations for 1,500 m swims were forbidden above 20.0 ºC and optional between 14.0 ºC and 20.0 ºC, with 14.0 ºC being the minimum temperature allowed for 1,500 m swims (ITU Competition Rules, 2014). The study states that the ITU adopted water temperature regulation changes in 2017, decreasing the water temperature minimum to 12.0 ºC, which was changed in November 2015 (ITU Competition Rules, 2015). Temperature regulations have not changed since November 2015, so it is unclear whether the ITU implemented the claimed changes in 2017 (Saycell et al., 2018). Regardless, the minimum temperature for wetsuit swimming is 12.0 ºC for 750 m swims and 13.0 ºC for 1,500 m swims. It is further unclear how the temperature of 13.0 ºC was determined for 1,500 m swims. This is especially problematic as 10% of elite triathletes who commenced 12.0 ºC wetsuit swimming for 20 minutes failed to complete the trial. As previously mentioned, hypothermia in cold water swimming is dictated by immersion time and rate of work. For elite triathletes, 20 minutes of swimming is reasonable as this is an expected completion time within a 30-minute swim cut-off for elites. However, age-group triathletes have a swim cut-off time of 70 minutes (*World Triathlon Competition Rules*, 2023), potentially placing athletes at a high risk of hypothermia and risk of injury or death. Further understanding of how performances changed in athletes upon different water temperatures could provide helpful information in determining areas for further research.

Triathlon cycling is draft-legal and power output has been described as stochastic (Etxebarria et al., 2014). Studies examining cycling in the heat are typically laboratory-based; however, outdoor cycling can achieve speeds that aid in evaporative and convective cooling (Nybo, 2010). This also suggests that if high-velocity speeds can be maintained, the environment does not become a limiting factor for cycling. Moreover, drafting can reduce $\dot{V}O_2$ by up to 39 ± 6%, reducing metabolic heat production (Kyle, 1979; McCole et al., 1990). It appears that cycling at high speeds, which occurs in draft legal triathlon, would not greatly affect the performance of triathletes and that drafting will further reduce endothermic heat production, which can improve performance.

Running occurs at slower speeds, and there is subsequently a decrease in the evaporative and convective cooling when compared to cycling. Land-based exercise does not benefit from the increased heat transfer of the swimming medium. A more prominent requirement for running is modulating pacing to limit metabolic heat production and balance external heat transfer to avoid heat injury and illness (heat stroke). When environmental air temperatures are below skin temperatures, the heat production of a runner is proportional to body mass (Dennis & Noakes, 1999). Increased muscle activation – as seen in running compared to cycling − subsequently increased metabolic heat production and $\dot{V}O_2$ (Table 2.2) (Millet et al., 2009). One physiological response to running in hot environments is a decrease in blood pressure from a vasodilatory response releasing heat externally and increased heart rate, RPE and $\dot{V}O_2$ at the same relative workload.

Sex Differences

In 2009, only one study had examined sex-based differences in elite triathletes (Le Meur et al., 2009). Since then, there have been advancements in the literature surrounding sex-based differences in the elite triathlete population, though it is still lacking. Men and women adopt similar positive pacing strategies across the swim and run segments (Le Meur et al., 2009). However, this positive pacing strategy is less effective than a negative pacing strategy in improving running performance times. (Hausswirth et al., 2010). Analysis from 2009 to 2012 further found that sex differences in performance times of men were 14.3% faster in running, 9.5% in cycling, and 9.1% in swimming (Lepers, 2019).

Some of these differences may be explained by morphological and physiological (Table 2.3) components. Considering the swimming portion of a triathlon, increased buoyancy can improve swimming performance. Women typically have 7 − 12% more body fat than men (Heydenreich et al., 2017), and adipose tissue provides buoyancy in water, which may explain why the performance gap is least pronounced in the swimming segment. Increased muscle mass and reduced body fat (B. Knechtle et al., 2010) for elite males may further reduce the differences in physiological performance between men and women.

Extensive research explores the physiological demands of triathletes (Ambrosini et al., 2022; Bunc et al., 1996; Hausswirth & Lehenaff, 2001; Laurenson et al., 1993; Millet, 2000; Millet et al., 2003, 2009; Sleivert & Rowlands, 1996; Sleivert & Wenger, 1993; Suriano & Bishop, 2010; Millet & Bently, 2004). However, there is little regarding the physiological differences between male and female triathletes. The largest differences observed between men and women relate to $\dot{V}O_{2max}$ values for running and cycling. Given the nature of swimming, there is little data on swimming $\dot{V}O_{2max}$ for triathletes, as previously mentioned. Females tend to have lower $\dot{V}O_{2max}$ values than males, cycling and running (Lepers, 2019). There also is an apparent further discrepancy between cycling and running $\dot{V}O_{2max}$ in females than males (Lepers, 2019). Millet and Bentley (2004) found the elite junior and senior triathletes to have a sex difference of 22% for relative $\dot{V}O_{2max}$ results (74 compared to 61 $mL \cdot kg^{-1} \cdot min^{-1}$) Millet & Bently, 2004).

Women are underrepresented in thermoregulatory research (Hutchins et al., 2021), though the effects of sex on thermoregulation in a sports performance context have been explored in other athletic disciplines (Cheuvront & Haymes, 2001; Lewis et al., 1986). Females tend to have reduced body mass and size, making them fare better in hot and humid racing conditions than men (Dennis & Noakes, 1999; Marino et al., 2000). Smaller runners will have a higher surface area to body mass ratio, so they are more equipped to dissipate heat, leaving them less susceptible than males to overheating and reduced performance (Lepers, 2019).

Injuries

The sport's high training loads and physiological demands place triathletes at an increased risk of injury. Triathlon injury rates have been reported to affect 37% (Burns et al., 2003) to 91% (O'Toole et al., 1989) of surveyed triathletes. 75% to 83% of injuries have been reported from training rather than competition injuries (Cipriani et al., 1998; Wilk et al., 1995). Of triathlon-related injuries, the lower limb contributes from 36% to 85% of all injuries (Gosling et al., 2008). The back and shoulders have also been reported to be common sites of injuries in triathletes. This is unsurprising as most training involves running and cycling, with swimming attributed to back and shoulder injuries. In elite male triathletes competing in training for a standard distance triathlon, overuse injury occurred in 75% of athletes (Vleck & Garbutt, 1998).

These results have been further confirmed in a recent systematic review on injury and illness in short-course triathletes. A total of 42 studies were included in the systemic review. Across all the studies, the most common injury and illness problems in triathletes were lower limb overuse injuries, gastrointestinal illness, and cardiovascular and respiratory illnesses. While injury rates are high in triathletes, when comparing the 2012 London Olympics, 15% (Engebretsen et al., 2013) of triathletes reported an injury, whereas the majority 79% to 83%

of injuries result from training (Bertola et al., 2014; Cipriani et al., 1998; Gosling et al., 2008). Further, lower limb injuries of the knee, ankle and foot are most common, with 50% to 75% (Collins et al., 1989; Vleck & Garbutt, 1998) being associated with overuse and 54 to 92% associated with running (Bertola et al., 2014; Collins et al., 1989; Gosling et al., 2010; Vleck et al., 2010; Vleck & Garbutt, 1998).

Training Loads

Large training loads are not uncommon for elite standard distance triathletes. Two case studies of a male triathlete competing at the 2020 Tokyo Olympic Triathlon and a female triathlete competing at the 2012 London Olympic Triathlon depict the size of the training load. Over 50 weeks, the female triathlete completed 796 training sessions (303 swims, 194 bikes, 254 runs, and 45 strength), averaging 16 ± 4 sessions per week. This was 25 ± 8 km/week swimming, 9 ± 3 h / week cycling and 5 ± 2 h / week running (Mujika, 2014). Similarly, the male triathlete, across 43 weeks on average, completed 14.74 ±3.01 h/week of training, peaking at roughly 19 h / week of training (Cejuela & Sellés-Pérez, 2022). An important factor for elite triathletes is the volume of races each year. The elite female triathletes undertook 18 events in one year, while the male triathletes competed in just five races. With many athletes competing in multiple World Triathlon Championship Series races yearly, training loads and cycles must align with events for optimal performance.

Triathlon training has been noted to potentially benefit from a non-traditional periodisation strategy. Given the need to compete at a high level across many months of the year and races, athletes have reduced opportunities to taper (Issurin, 2010). Block periodisation has been proposed as a possible alternative to the traditional approach (Etxebarria et al., 2019). This includes specialised accumulation, transmutation, and realisation mesocycle blocks to improve the quality and quantity of peak performances in a triathlon season (Issurin, 2010). Flexible and integrated periodisation are two further concepts that may provide suitable training for triathletes. Regardless of the training program, the training intensity of triathletes typically follows a polarised training distribution (Cejuela & Selles-Perez, 2023). The aforementioned elite female triathlete completed 74% of swimming, 88% of cycling and 85% of running at intensities below her lactate threshold (Mujika, 2014). This is typical, with endurance athletes showing great improvements in performance from more polarized training distributions (Esteve-Lanao et al., 2007; Ingham et al., 2012; Neal et al., 2013; Stöggl & Sperlich, 2014).

Quantifying the training load of triathletes is another step to optimise an athlete's performance. Monitoring and understanding the physiological or psychological impacts of training can be viewed from internal and external stimuli. Internal workload is the physiological stress response to the external workload (e.g., heart rate, time, and power). A triathlon-specific load quantification method has been derived, but not validated (Cejuela & Esteve-Lanao, 2011). The load quantification involves subjective and objective measures and relative values specific to standard distance triathlons. Further training load quantification in triathlon is beyond this thesis's scope and can be read elsewhere (Cejuela & Esteve-Lanao, 2011, 2020).

2.3 Performance and statistical modelling in triathlon

Performance in triathlon has been a broad focus area, leading to extensive research efforts to maximise race results. There have been two main approaches to determining performance in the standard distance triathlon. The first is the correlation between laboratory-based physiological values and analyses of race performances. As will be examined in this section of the literature review, there are insufficient and varying results to determine if swimming, cycling, or running is the best determinant of success in the standard distance triathlon. Appropriate methodologies and analyses are needed for results to apply to coaches and athletes. Thus, an emphasis will be placed on the statistical methods for appropriate analyses of data.

Laboratory-based performance

Laboratory-based performance has measured physiological indicators of performance times in each triathlon segment and overall performance. $\dot{V}O_{2max}$ has previously been shown to be a good indicator of overall triathlon times in amateur and recreational athletes, but for homogenous elite athlete populations, it fails to accurately predict performance (Sleivert & Rowlands, 1996). For elite-level triathletes, predictors of overall performance times in the standard distance triathlon have been examined from maximal and submaximal measures. Scharbort et al. (Schabort et al., 2000) were the first to predict overall performance times from elite triathletes with 400 m maximal swimming time, maximal and submaximal cycling and running tests. Maximal 400 m swimming, stroke distance, and stroke index did not predict overall triathlon time. Cycling peak power output (PPO) had the best prediction of the cycle and overall time of $r = -0.91$ and $r = -0.86$, respectively (Schabort et al., 2000). Scharbort et al. also found that the % $\dot{V}O_{2peak}$ in both submaximal running and cycling tests was related, r = 0.77 for the 10 km segment and r = 0.76 for overall time. The authors do note that these correlations may be due to the higher relative proportion segment time to time of the overall triathlon.

A recent study examined similar measurements concerning draft legal triathlons with elite athletes (Hue, 2003). This study found that 400 m maximal swimming was correlated with 1,500 m swim segment time but similarly not to overall race time (Hue, 2003). No correlations existed between maximal cycling measures ($\dot{V}O_{2max}$, PPO, P:W and power output at thresholds). Drafting may explain this finding, however, as it is possible to conserve energy through drafting in races and that intensity during group riding is lower than that of time trial cycling (Palmer et al., 1999). Maximal running measures of $\dot{V}O_{2peak}$, and velocity at $\dot{V}O_{2peak}$ were correlated with running time in triathlons of r = −0.84 and r = −0.89, indicating a higher $\dot{V}O_{2peak}$ is associated with faster running times (Hue, 2003). Therefore, it is suggested that for standard distance triathlons, physiological variables in swimming and running are related to overall performance times and that physiological cycling variables do not well predict overall performance (Sleivert & Wenger, 1993).

In-Race Performance

In-race performance in triathlons has been examined through various statistical methods and data. Given that such research has been explored in this area of triathlon, overlaps in methodologies and similar data sets are present, which, surprisingly, has resulted in contrasting results. Specifically, seven research articles examine performance from race segments in elite-level standard distance triathlons (Table 2.5). Each segment in the triathlon has been determined to be the most influential for overall race performances. For example, Sousa et al. reported that swimming was the best predictor for standard distance triathlons (Sousa et al., 2021). This is further supported by Vleck et al., who determined that swimming position over the first 222 m of the swim of a triathlon best predicted overall performance (Vleck et al., 2006). However, this conflicts with Barbosa et al., who examined U23 triathlon results from the ITU and determined that cycling had the greatest influence on overall performance in triathlon (Barbosa et al., 2022), as well as a concordance study which found good agreement between cycling performance and overall performance (Olaya-Cuartero et al., 2022). Again, further conflicted by another three studies indicating that running is the most important segment of overall performance in triathlon (Figueiredo et al., 2016; Gadelha et al., 2020; Ofoghi et al., 2016).

More surprisingly, four of these studies utilised the same methodologies: a Kolmogorov-Smirnov test or Levens test before applying linear regression. However, many assumptions about the data apply to linear regression as an appropriate statistical method. Assumptions include independence, linearity, homoscedasticity, normality and without multicollinearity (Schmidt & Finan, 2018). With an understanding of the regression assumptions, it can be possible that several of these studies may have potentially violated some of these assumptions during analyses. When examining segment time to overall time, the assumption of independence fails, with the proportion of triathlon segments representing swimming at ~15%, cycling at 55% and running at 30% of total race time (Hausswirth et al., 1999; Landers et al., 2008). As cycling maintains the largest relative proportion of triathlon and running is the second largest and last segment of the triathlon, this likely explains the results in the literature regarding collinearity. In other words, these analyses examine how 55% of race time predicts overall race time or the last 35% of race time predicts overall race time. This may indicate why running and cycling are primarily reported as the most influential.

One of the more robust analyses undertaken on triathlon performance is by Ofoghi et al., who examined the likelihood of finish positions from time differentials between athletes (Ofoghi et al., 2016). Compared to linear regression, these researchers used Bayesian networks to determine the likelihood of categorical outcomes (positions). This supports the suggestion that linear regression of swim, cycle, and run time to overall time may be inappropriate for triathlon performance. As stated, “this complexity means that intuition alone and individual component analyses may not be sufficient for determining the strategies required to maximise the chances of success” (Ofoghi et al., 2016).

Thus far, triathlon performance analyses have all been time-based. However, some studies have indicated that positioning across the triathlon may be more critical. Positional analyses have been implemented in other sports (i.e., 800 m running) with strong results of the area under the operator receiving curve of 0.96, representing it can predict outcomes correctly 96% of the time (González-Mohíno et al., 2020). One study from 2000 mentioned that “it would appear that the most important determining factor of finishing place is the position of the athlete at the end of the cycle leg” (Landers et al., 2000). Similarly, Vleck et al. found evidence that swim positioning could be a determining factor for the outcome of triathletes in elite races (Vleck et al., 2006). Overall, the current literature suggests that the positioning of triathletes during the swim and cycle segments may be a better-determining factor for success. Further, the methodologies with current time-based performance analyses leave room for improvement, with statistical assumptions needing to be carefully managed.

Table 2.5 An Overview of studies predicting triathlon performance.

Author	**Segment Prediction**	**Method**	**Approach**
Olaya-Cuartero et al., 2022	Cycling	Concordance study using interclass correlation. Kolmogorov-smirnov test	Segment time to overall time.
Barbosa et al., 2022	Cycling	Linear regression. Kolmogorov-smirnov test	Segment time to overall time.
Sousa et al., 2021	Swimming	Automatic linear regression. Kolmogorov-smirnov test and levenes test	Segment time to overall time.
Gadelha et al., 2020	Running	Linear regression. Kolmogorov-smirnov and levenes test	Segment time to overall time.
Figueiredo et al., 2016	Running	Linear regression and one-way ANOVA	Segment times to overall time.
Vleck et al., 2006	Swimming and running	One-way ANOVA	Segment velocities to segment position.
Ofoghi et al., 2016	Running	Bayesian Networks	Time differentials to overall positioning.

2.4 Literature Review Summary

Chapter 2 summarised the relevant literature surrounding triathlon (Chapter 2.1), the physiology and biomechanics of triathlon, the swim–to–cycle transition, cycle–to–run transition and exercising in environmental temperatures (Chapter 2.2), as well as the literature surrounding the predictive analyses of performance in elite triathlon (Chapter 2.3).

The standard distance triathlon consists of a 1,500 m swim, 40 km cycle, and 10 km run separated by two short transition periods: transition one and transition two. Physiological and biomechanical alterations occur during the transition from swimming to cycling and cycling to running. The effect of temperature on the performance of triathletes has briefly been explored; however, these are laboratory-based protocols and have not included all three segments. Performance prediction in triathlon has also used inappropriate methods, which has left outcomes conflicting with little agreement between studies. A positional approach to triathlon performance may provide unique insights into improving the outcomes of elite triathletes.

This thesis aimed to complete three study chapters: (1) Examine the participation rates, athlete demographics, and country success of elite standard distance triathletes between the years of 1986 and 2022; (2) quantify the probability of obtaining a podium position based on combinations of swim and cycle segment positions; (3) examine the effect of water temperatures on swimming performance times and air temperatures on cycling and running performance times; (4) Explore sex differences in the effect of environmental temperatures on performance times.

Chapter 3: An Overview of Elite Standard Distance Triathlon Between 1986 and 2022

3.1 Abstract

Introduction and aims: Past studies on elite standard distance triathlon have focused on the event's physiological and biomechanical characteristics rather than participation and demographic trends. This study aimed to describe participation, athlete demographics, and country success in elite standard distance triathlons from 1986 to 2022. **Methods**: World Triathlon standard distance triathlon race data (n = 97,374) were examined, with entries exceeding the world record and misidentification of races removed before analysis. Athlete participation rates were modelled using Bayesian logistic regression. Athlete age and career lengths were summarised as the median and 1st and 3rd quartile, and country success was determined by rank ordering the total wins for each country. **Results**: There were 3,705 races, 10,161 unique male athletes and 5,139 unique females. Female participation has increased since 2003 from 28.9% to 41.9% in 2022, increasing on average 0.6849% (95% credible interval = 0.6818, 0.6879) each year. The median age of male athletes was 24 years (1st and 3rd quartile = 21 to 28) and females 25 years (21 to 29). The median age of male podium finishers was 26 years (1st and 3rd quartile = 22 to 28) and 26 years for women (22 to 30). The median career length was one year (1st and 3rd quartile = 1 to 3) for men and women, while 3.7% of male and 3.9% of female triathletes had careers of 10 or more years. Australian athletes had the most success with 361 wins, topping both men’s and women’s categories (173 male, 188 female). **Conclusion:** Elite female participation is increasing in standard distance triathlon, possibly influenced by the actions of the 2002 World Triathlon’s women’s committee congress meeting. Further, understanding the reason for the success of Australian standard distance triathletes might be informative for optimising performance and development pathways for both sexes.

3.2 Introduction

Triathlon is a multi-sport race involving the continuous and sequential completion of three endurance disciplines—swimming, cycling, and running. The most common race distance is the ‘Olympic’ (standard) distance triathlon, which comprises a 1.5 km swim, 40 km cycle, and 10 km run. In elite standard distance races, triathlon involves a mass start, commencing either from land, a pontoon, or in water. Since 2022, wetsuit use has been governed by water temperatures and is mandatory from temperatures ≤15.9 °C, forbidden at temperatures ≥20 °C and optional between (World Triathlon Competition Rules, 2022). During races, athletes are permitted to draft on all segments, a policy introduced at the 1995 ITU World Championships (Figueiredo et al., 2016). Drafting involves sheltering behind another athlete, reducing drag, and conserving energy, most effective during the cycling segment due to the higher speeds.

Previous triathlon studies have primarily focused on the morphology of athletes (Brunkhorst & Kielstein, 2013; Puccinelli et al., 2022) or the physiological (Hausswirth & Lehenaff, 2001; Millet et al., 2003; O’Toole & Douglas, 1995) and/or biomechanical aspects of simulated triathlon performance (Millet, 2000; Millour et al., 2020; Rico Bini et al., 2022). For example, laboratory running and cycling measures have been associated with triathlon finish times (Schabort et al., 2000). While endurance sports have seen improvements in female participation (Etter et al., 2013; Hoffman & Wegelin, 2009; Leyk et al., 2007)few studies have reported on participation rates and athlete demographics in elite triathlon. Etter et al. reported participation of age categories from the Zurich triathlon from 2000 to 2010, finding no changes in male participation and increased female participation for 40- to 54-year-olds (Etter et al., 2013). A decade ago, time-based performance trends in elite triathlon were described for 44 races from 2003 to 2013 (R. Knechtle et al., 2014), showing total race times for men and women were slowing. Studies have also examined age-related performance for elite-level triathletes, suggesting a performance age of 27 years old (R. Knechtle et al., 2014; Malcata et al., 2014; Villaroel et al., 2011). Other sports, such as the marathon, have explored and identified such issues as country success, age, and sex differences (Hunter & Stevens, 2013; Hunter et al., 2011; Wilber & Pitsiladis, 2012).

No study has investigated athlete or country demographics, specifically in elite standard distance triathlon. Such insights could help evaluate gender participation inequality, benchmark triathlete characteristics, and determine the country’s success and support for athletes. This study aimed to describe participation, athlete demographics, and country success in elite standard distance triathlon between 1986 and 2022. No hypotheses were generated as our aims were only descriptive in nature.

3.3 Methods

This study used publicly available data published on the World Triathlon Organization (WTO) website (World Triathlon API.; World Triathlon Organisation). The dataset contained 15 variables, including a unique identifier for each athlete and race, the sex of each athlete, each athlete's year of birth and country of representation. Swim, bike, run, both transition times, total race time, finish position and race location (i.e., longitude, latitude) were present. The dataset also contained a race status variable indicating whether athletes 1) did not finish the race, 2) were disqualified, 3) were lapped on the bike segment, 4) were assigned to the race but did not start, or 5) did not complete at least two segments. There were 97,374 race records (men = 61,099; women = 36,275) before data cleaning procedures were undertaken. Ethical approval for this study was not required as the data were publicly available. These data and R code are available at https://github.com/alexdgibson/mphil_triathlon (alexdgibson, 2024).

All data cleaning procedures and analyses were undertaken R (Version 4.0.3) (R Core Team, 2022) using the RStudio environment (RStudio Team, 2022), and the *tidyverse* (Wickham et al., 2019), *brms* (Bürkner, 2017) and *lme4* (Bates et al., 2015) packages. Men's and women's data were analysed separately, and identical cleaning processes were applied. Supplement 1 provides an overview of the data cleaning process.

An initial correlation matrix was visualised for each segment time and finish time for men and women. Apparent misidentification of standard distance races was present in both the men's and women's data sets. Any clustering of segment and race times faster than expected values were manually examined. A cut-off time value was determined for each segment. This cut-off was the world's best time for the fastest race with a reported standard distance triathlon swim, bike, and run distances of 1.5 km, 40 km, and 10 km; all races with faster times were removed.

Athlete participation included all unique athletes in any given year that started a race regardless of the finishing result. Participation was visualised using bar charts for males and females separately. The percentage of unique female athletes for each year was determined by calculating the proportion of female triathletes to total athletes (i.e., men and women). The change in the percentage of unique female athletes over time was determined by modelling sex (levels: male, female) using a logistic regression model, including year as a fixed effect. Data from 2003 to 2022 were included in this analysis. All other statistics are reported from the period 1986 to 2022. The model was fit in a Bayesian framework. Weakly informative prior distributions were specified for the regression coefficients (*t*-distribution (3, 0, 2.5)). Monte Carlo Markov Chain (MCMC) methods were used to generate posterior estimates (20,000 iterations, 8 chains, 50% iteration burn-in). The convergence of MCMC to the posterior distribution was visually assessed via trace plots.

Each athlete's age was determined as the age they turned in the competition year. Repeat measures of athletes competing multiple times a year were removed. We described age as the median and interquartile range (1st and 3rd quartile) of podium athletes and all athletes who started a race. This included all years in the data set.

Athlete career lengths were determined as the total years of competition in which they raced. As such, career length may be a total of non-consecutive years. Only records of athletes who started a race were included in this analysis. We plotted the distribution of career lengths and indicated the 90% central interval, such that the career length of 90% of all athletes fell in this region. Career lengths were descriptively summarised as the median and interquartile range (1st and 3rd quartile). All years of competition were included in this analysis.

Country success was summarised as the total race wins for each represented country. The success of each country was determined by both male and female country representation and individual countries. The top 10 ranked countries for men and women were visualised. The relative success of each country was also determined. Calculated as the total wins to the total race starts for each country, expressed as a percentage.

3.4 Results

After cleaning procedures, there were 57,929 male and 34,845 female records, corresponding to 10,161 unique male and 5,139 unique female athletes. Total races included 3,705, of which 1,650 were male and 1,655 races were female. A total of 290 races (144 male races, 146 female races) were removed, identified as not standard distance races.

The median age of triathletes competing across all years was 24 years old (1st and 3rd quartile = 21 to 28) for men and 25 years old (1st and 3rd quartile = 21 to 29) for women. The median age of male podium finishers across all years was 26 years old (1st and 3rd quartile = 23 to 29) and the median age of female podium finishers was 26 years old (1st and 3rd quartile = 22 to 30).

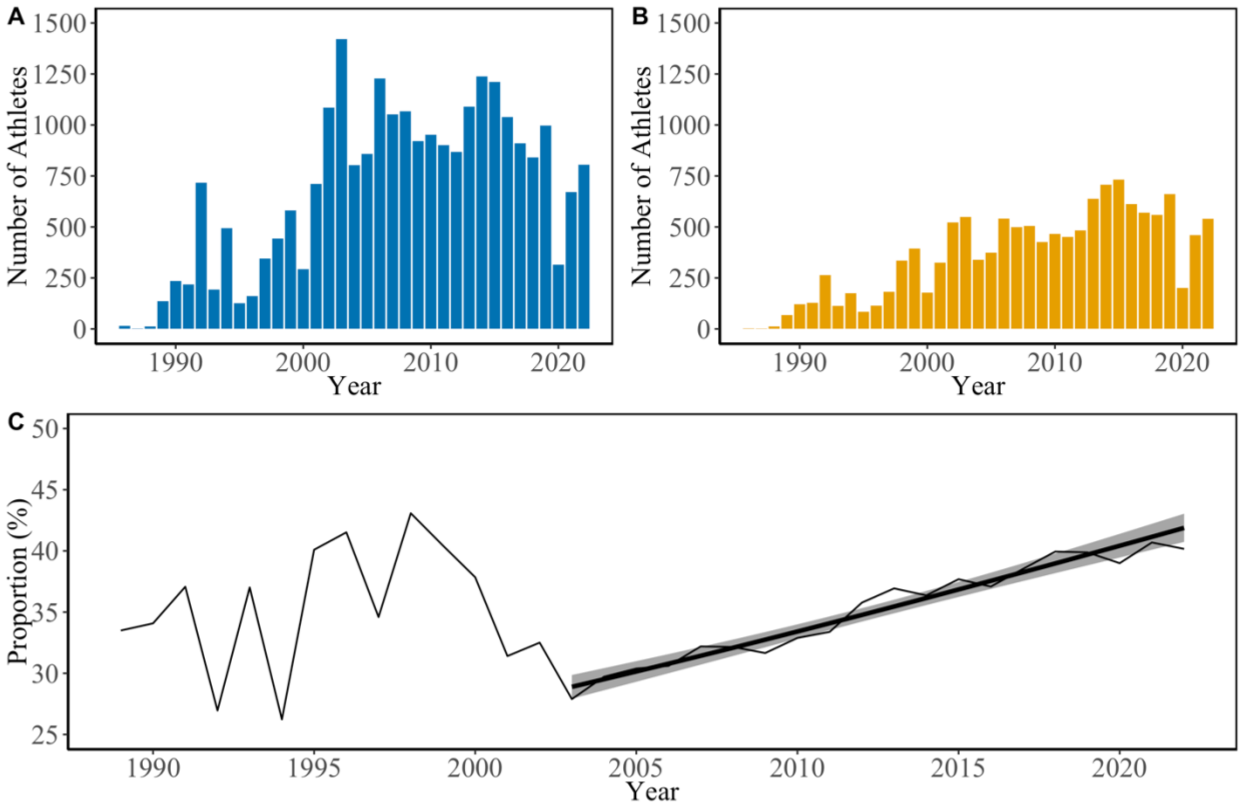

Figure 3.1. Unique male (panel A) and female (panel B) athletes between 1986 and 2022. The proportion of female athletes between 1989 and 2022 (panel C). The thin black line represents the observed proportion of females for each year, while the solid black line represents the modelled posterior mean. The grey ribbon indicates the 95% credible interval of the modelled data.

The total number of unique male participants across all years was 10,161 and 5,139 for females. Male participation peaked in 2003 at 1,422 unique athletes, while females peaked in 2015 at 733 unique athletes. The lowest participation since 2000 for men was 294 athletes (panel A) and 179 for women (panel B) in 2020. The proportion of female participants modelled between 2003 and 2022 increased by, on average, 0.685 percentage points (95% CI = 0.682, 0.6878 each year, from 28.9% in 2003 to 41.9% in 2022.

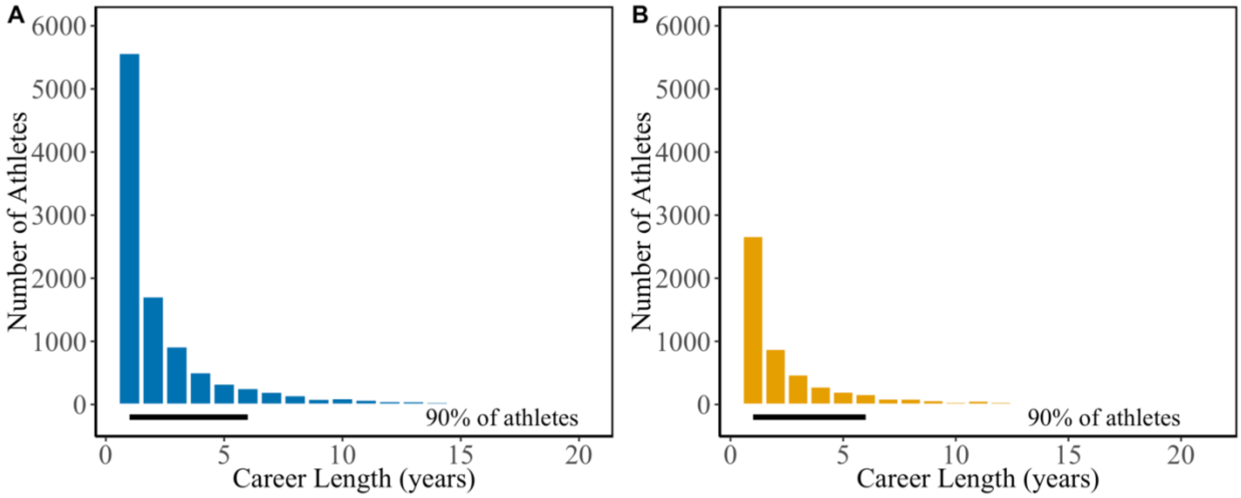

Figure 3.2. The distribution of career lengths in elite standard distance triathlon for men (panel A) and women (panel B). The horizontal black line indicates the 90% central interval, such that career lengths from 90% of athletes fall in this region.

There were 5,568 (55.1%) male athletes and 2,667 (52.1%) female athletes who competed in one race. The highest number of unique years a male athlete raced in was 20 (n = 2), while the most unique years a female raced in was 21 (n = 1). There were 376 (3.7%) male triathletes and 198 (3.9%) female triathletes who competed in 10 or more years. Males had a median career length or 1 year (1st and 3rd quartile = 1 to 3) and females had a median career length of 1 year (1st and 3rd quartile = 1 to 3).

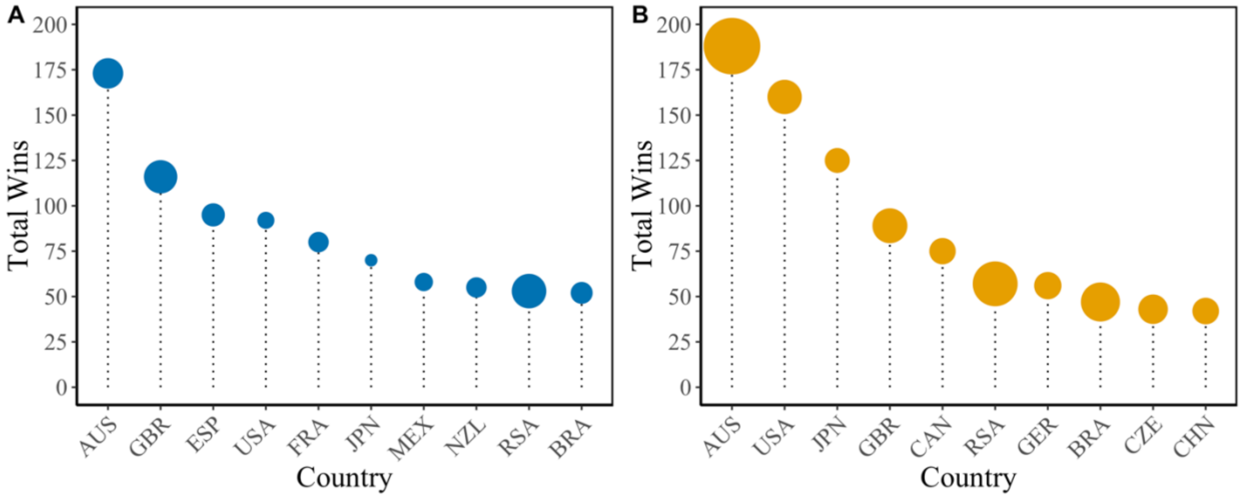

Figure 3.3. The top 10 countries with the most wins for men (panel A) and women (panel B) for all years. The size of each point is the relative success rate of each country and sex. AUS = Australia, GBR = Great Britain, ESP = Spain, USA = United States of America, FRA = France, JPN = Japan, MEX = Mexico, NZL = New Zealand, RSA = Russia, BRA = Brazil, CAN = Canada, CZE = Czech Republic, CHN = China.

There were 163 unique countries represented across all years (men = 158, women = 123). Australia won the most races overall, for men and women, with 361 wins (male wins = 173, male athletes = 49, female wins = 188, female athletes = 39). The United States of America has won the second most amount overall with 252 wins (male wins = 92, male athletes = 44, female wins = 160, female athletes = 51). Great Britain has the third most wins, with 205 total (male wins = 116 men, male athletes = 26, female wins = 89, female athletes = 31). Russia had the most success for men, with 5.8% of athletes starting winning, followed by Great Britain at 5.6% and Australia at 5.1%. Australian females had the most success, with 9.8% of starting athletes winning, followed by Russia at 7.7% and Brazil at 6.6%.

Men		Women	
Event Classification	**Total**	**Event Classification**	**Total**
Continental Cup	753	Continental Cup	754
World Cup	266	World Cup	270
Continental Championship	132	Continental Championship	135
World Championship Series	75	World Championship Series	75
Regional Championships	59	Regional Championships	60
World Championships	31	World Championships	32
Recognised event	24	Recognised event	24
Recognised Games	21	Recognised Games	21
Major Games	17	Major Games	18
World Championship Finals	2	World Championship Finals	2
Qualification Event	1	Qualification Event	1
N/A	408	N/A	400

Table 3.1 The total of sub-categorisation events of the elite level races analysed for men and women across all years.

3.5 Discussion

This study examined participation, athlete demographics, and country success in the elite standard distance triathlon between 1986 and 2022. Key insights were: 1) female participation has increased since 2003 by an average of 0.685 percentage points per year; 2) the median age of all male triathletes was 24 years old, and all female triathletes were 25 years old, while podium age was 26 years old for men and women; 3) men and women on average compete for only one year and those who compete in 10 or more years represent only 3.7% of men and 3.9% of women; and 4) Australia has had the most wins of any country overall and individually for men and women.

The lowest participation since 2000 was observed in 2020 for men and women (Figure 3.1) due to the COVID-19 pandemic suspending international events and travel (Onyeaka et al., 2021). While male participation peaked at 1,422 athletes, females have peaked recently with only 733 athletes, just more than half of the men. The discrepancy between male and female participation has been of concern. The WTO (then known as the International Triathlon Union) noted a decline in female participation, highlighting it during their 2002 congress meeting (International Triathlon Union (ITU) Minutes of Congress, 2002). Since 2003, female participation has substantially increased (Figure 3.1). The WTO Women’s Committee aims to develop and implement policies promoting equal opportunity for women in triathlon and paratriathlon (Women’s Committee). This observed improvement in female participation may be supported by increased opportunities for women in triathlon from the Women’s Committee's efforts. The decrease in female participation from 1998 to 2003 (Figure 3.1C) may have been influenced by the announcement of the introduction to the Olympic Program in 2000. As total male participation increased more than female participation over these years (Figure 3.1A and Figure 3.1B). Female participation in triathlon is higher than the rates reported by the Union Cycliste Internationale (UCI) and World Athletics. For example, female participation rates in triathlon during 2022 were nearly double that of elite road cycling, with only 22% of all UCI World and Continental ranked riders being female (Current UCI world champions – road). According to World Athletics, females are better represented at 47% for the marathon but not for 10 km running at 39% in 2022 (World Rankings, 2022) compared to triathlon at 41.9%. While parity is yet to be reached, triathlon demonstrates notable improvements in female participation, among some of the highest in endurance sports.

The age of maximum performance in elite standard distance triathletes was previously suggested to be around 27 years old for men and women (Cuba-Dorado et al., 2022). Our results support this proposal. While a median podium age of 26 for men and women was found across all years, there was a sizeable interquartile range. Half of all male podium finishers were aged between 23 and 29 and female podium finishers were aged between 22 and 30. This large variance has been documented in previous age-related triathlon literature. An age-related correlation to finish position was examined for elite triathlon races from 2007 to 2010 (Villaroel et al., 2011). Finding an optimal age range of 26 to 32 suggests that race experience is an important performance component. Peak age trajectories in the 2012 London Olympics triathlete career were modelled and determined to be approximately 26 to 28 years old (Malcata et al., 2014). Further, the top 10 elite men and women from 2003 to 2013 saw a male performance age of 27.1 ± 4.9 (mean ± SD) years old, while females were 26.6 ± 4.4 (mean ± SD) years old (R. Knechtle et al., 2014). The common theme of older performance ages supports the suggestion that race experience is likely important for success in triathlon. However, the large variability may indicate that age is not an essential factor.

Most typically, elite triathletes competed for only one year (Figure 3.2). Triathletes will rely heavily on sponsorships, prize money, and (possibly) salaries from their national federations. This makes it a competitive environment where livelihoods can be based on race performances. The difficulty of maintaining a professional career is demonstrated by only 3.7% of men and 3.9% of women having a career of 10 years or longer. In a previous study on an Olympic-level male triathlete, an average of 15 hours of endurance training was completed each week over nearly a year, peaking at 20 hours (Cejuela & Sellés-Pérez, 2022). These reports did not include time for other commitments such as travel, strength training, recovery, or nutrition. Further, the financial prizes are relatively low, for example, $18,000 (Championship Series), $30,000 (Championship Final), and $80,000 (Bonus pool) (Prize Money Breakdown for the 2022 Triathlon Events, 2022) first-place finishers. Consequently, triathletes who sustain an athletic career probably need to earn money through other avenues. Domestic funding to elite sports and athletes is essential for the success of national federations in sport (De Bosscher et al., 2009). Further, injury rates have been reported from 37% to 91% of surveyed triathletes (Gosling et al., 2008). With one Olympic-level female triathlete having just 21 days of complete rest over a 50-week training cycle (Mujika, 2014), athlete injuries may be career-ending. The combination of high injury rates, relatively low monetary return, and median career length of one year highlight the difficulties and challenges in sustaining a successful and prolonged career as a triathlete.

Country success for triathletes has seen Australia with the most wins for the country and individual wins for men and women. The relative country success for Australian females is the highest at 9.8%, and Australian men had the third-highest relative success rate, with 5.1%. The top three female countries appear to be winning races at just under double the success rate of male triathletes. This may be partly due to the reduced total female participants (Figure 3.1) while competing across relatively the same number of races—reducing race field size. One study examined elite triathlon development in the USA and AUS, the two leading countries by wins (Figure 3.3). While the delivery of triathlon was similar, the development process and setting were vastly different. The USA ‘poaches’ athletes from the single sport equivalents, while AUS has implemented triathlon-specific pathways. This difference increases opportunities in AUS for athletes, coaches, facilities, and financial development, while the USA falls comparatively short as triathlon is not considered an individual sport (Newland & Kellett, 2012). This view of triathlon as an individual sport in AUS likely constitutes its lead with 109 more wins than the USA. Further, the large amount of continental races analysed (Table 3.1) may inflate AUS overall race count if they competed in more continental races inaccessible to other countries.

3.6 Conclusion

This study examined participation, age-related performance, triathlete careers and country performance for elite standard distance triathlons. Our results showed that female participation rates have improved yearly since 2003. Podium ages for triathletes across all years was 26 for men and women, similar to previously reported performance ages. Triathletes likely have to rely heavily on sponsorship and their national federations to sustain performance at the elite level. Lastly, country success based on historical wins from 1986 to 2022 has shown Australia has been the most successful overall and for both men and women. Not directly examined, the large proportion of continental championship races (Table 3.1) may inflate Australia’s overall wins if it participated in more continental championship races. More recently, this success could be attributed to their ability to support athletes, coaches, and facilities.

Chapter 4: Predicting Performance Outcomes in Elite Standard Distance Triathlons

4.1 Abstract

Introduction and aims: Previous analyses of standard distance triathlon segments and their influence on overall race position have focused mainly on correlation analysis of performance times. This study aimed to provide probabilistic information on achieving a podium finish in elite standard distance triathlon, focusing on swim and bike position combinations. **Methods**: Five years of World Triathlon race records (2018 to 2022) were analysed. Logistic regression was used to model podium (i.e., 1st, 2nd or 3rd place) and non-podium finishers. The model included the podium outcome, swim and bike position, and the athletes' age and sex. We then imputed the probability of obtaining a podium position of any top 20 swim and bike position combinations. Further, we ran an internal cross-validation method of leave one out (race) to validate the logistic regression model. **Results**: We modelled data from 211 male and 214 female races. Male triathletes who placed first in the swim and first in the bike had a 59% chance of a podium result. Females in this same position combination had a 79% chance of a podium result. Position off the bike had a greater influence on the overall race result than swim position. Leave-one-race-out cross-validation showed that the model could distinguish podium finishers from non-podium finishers 78% of the time. **Conclusion**: This study offers insights for athletes and coaches to improve elite standard distance triathlon performances, underlining the importance of the cycle segment positions on overall outcomes. The results supported our hypothesis that position out of the cycling segment is more important than position out of the swim segment for a podium finish. While these findings may be intuitive, our analyses provide empirical support for the change in probability across positions that can better inform race strategies.

4.2 Introduction

The standard distance triathlon incorporates a 1,500 m swim, 40 km cycle and 10 km run, with segments separated by a short transition period. Triathlons can be complex to analyse compared to single sport events, as each successive segment is impacted by the previous. However, with appropriate methodologies, analyses can provide valuable information to coaches and athletes to optimise race strategies. Elite triathlons see athletes finishing segments and overall races within remarkably close times (Ofoghi et al., 2016). For example, the 2020 Tokyo Olympic male podium finished within 20 seconds of each other, equivalent to 0.3% of race time. Therefore, with such brief time margins, any competitive advantage accessible to improve the overall finish position is constantly sought.

Improving triathlon race performances has received considerable attention. Previous research has focused on improving the transition from swimming to cycling (2,3) and the cycle-to-run transition (Hausswirth et al., 1999; Millet, 2000; Millour et al., 2020; Rico Bini et al., 2022; Vercruyssen et al., 2002; Viker & Richardson, 2013) as well as biomechanical and pacing strategies. A popular analytical approach of previous studies has been to investigate the relationship between segment time and overall race time. Conflicting results are found in the conclusions of these studies, with the swim (Sousa et al., 2021; Vleck et al., 2006), cycle (Barbosa et al., 2022; Olaya-Cuartero et al., 2022) and run (Figueiredo et al., 2016; Landers et al., 2008; Ofoghi et al., 2016; Vleck et al., 2006) segments each identified as the most important. Using a different analytical approach with Bayesian networks, a recent study quantified the likelihood of race finish position according to time differentials from the leader at each race segment (Ofoghi et al., 2016). However, it is stated that this "does not indicate the probabilistic relationship between in-race performance and final placing" (Ofoghi et al., 2016). Further, the importance of positions has been noted: "it would appear that the most important determining factor of finishing place is the position of the athlete at the end of the cycle leg" (Landers et al., 2000) and that "90% of male and 70% of females winners came from the first pack of swimmers" (Landers et al., 2008). No other study has quantified finish positions using probabilistic modelling approaches or segment positions. Understanding the dispersion of probabilities between segment positions can allow athletes to focus efforts to maximise overall performance.

Considering the swim segment position only, Landers et al. (Landers et al., 2008) saw most race winners exit the swim within the first pack. Triathletes with strong running abilities are also suggested to position themselves in the first cycling pack (Piacentini et al., 2019), indicating that positioning in triathlon segments could be a vital determinant for overall success. Considering that all relevant segments in the analysis will improve the understanding of elite triathlon performance, we sought to determine probabilistic information from all segment position combinations to provide athletes and coaches with quantifiable measures to inform race strategies. This study aimed to quantify the probability of obtaining a podium finish in an elite standard distance triathlon, considering both swim and bike positions. We hypothesised that an athlete's position finishing the cycle segment would be more important than the position finishing the swim segment.

4.3 Methods

Data for this study was obtained from the World Triathlon Organization website (World Triathlon API, 2023). Segment times for swim, transition one, bike, transition two and run were used to determine each athlete's position on completing the swim and bike segments. Overall race positions were categorised as a podium (first to third position) or non-podium (fourth position or lower) finish. We used this categorisation for interpretability, as such information is useful for athletes and coaches interested in creating positional performance targets. Ethical approval for the study was not required as the data were publicly available to be downloaded and examined. These data and R code are available at https://github.com/alexdgibson/mphil_triathlon (alexdgibson, 2024).

The data set comprised five complete years of elite racing from 2018 to 2022. This period contains recent years of elite competition to be modelled off potential current race strategies, most applicable to current races. There were 425 unique races categorised as elite-level competitions and 8,922 race records. There were 12 variables in the dataset, including a unique athlete and race identifier, segment, transition and overall times, the year of competition, sex, finish position and athletes' year of birth.

Races were included in the analysis if all six time variables were present, which made it possible to determine segment position. Segment position was determined by rank ordering cumulative race times at each corresponding segment. Athletes who did not finish a race were used to assess segment positions until they dropped out. Athletes who did not start the race were not included in the analysis. Each athlete's age was calculated using date of birth, reflecting the age they turned in the respective year of competition. Age summaries included the age of each unique athlete for a given year.

The primary interest of this study was determining the probability of a podium result based on swim and bike segment position combinations. Podium finish (levels: false, true) was modelled using a generalised linear model with a binomial response distribution. Each parameter in the model was connected to a linear regression equation via a logit link function. The model included *sex* (levels: male, female), *swim position, bike position*, and all possible two- and three-way interactions between *sex, bike position* and *swim position* as fixed effects. We considered the effect of age on a podium finish by including *age* as a fixed effect in our modelling, along with an *age* by *sex* interaction term, to allow for any potential effect of age to be different for men and women. *Age* was included using a spline term with three degrees of freedom, as we expected age to have a non-linear relationship with the probability of a podium finish. No sample size calculation was completed as the study is retrospective. The model was implemented using the base R (R Core Team, 2022) function *glm*.

In interpreting the results, we focused on the average probability of a podium finish for all top 20 swim and bike position combinations. To highlight the relative importance of swim and bike positions, we visualised the probability of a podium finish for all top 20 swim or bike positions when the opposite segment was fixed at the first, fifth and 10th position.

Repeat observations for athletes competing multiple times per year were removed when reporting age values (median and first and third quartile). Age was reported in-text as an average for all years and visualised by each year and sex. The total combinations of observed swim and bike positions were tallied and displayed in a table format. The number of races for each year and for each sex were visualised.

Regression coefficients are reported on the logit scale. Statistical significance was set at an α level of 5%. Descriptive statistics of the races, athletes and characteristics were summarised using the median (1st and 3rd quartile). All figures were generated using the R package *ggplot2* (Wickham et al., 2019).

We further ran an internal cross-validation method of leave one out (race) to validate the logistic regression model. Model performance was determined by its discrimination and calibration. Discrimination is the sensitivity and specificity of the model, with calibration being the model's ability to predict outcomes accurately (Alba et al., 2017 & Steyerberg,. 2009). Each model was developed on *N*-1 races (where *N* is the total number of races). For each iteration (race), the mean response prediction of the model was retained, and the model was discarded and repeated for all *N* races. A receiver operating characteristics curve was generated to validate the model. The area under the operating receiver characteristic curve (AUC) was computed. The AUC value can change from 0 to 1, with values at 1 indicating the model can distinguish podium finishers from non-podium finishers perfectly (Steyerberg., 2009). AUC values in this study were not interpreted against any qualitative thresholds (de Hond et al., 2022).

A windowed calibration plot was also created. This compares the observed outcome to the predicted outcome in different percentiles. Percentiles for this study were chosen to be deciles (a step size of 0.1). For a perfectly calibrated model, the slope would have an intercept of 0, with values above the diagonal line indicating underestimation and values below the line indicating overestimating outcomes (Van Calster et al., 2019). The Brier Score was further used to summarise the calibration of a binary prediction model into a single numerical value to assess its predictive probabilities (Rufibach, 2010). Brier Scores are calculated via the following equation: $\Sigma(y_i - p_i)^2 / n$, where y is the observed race outcome and p is the prediction for race i in the data set of n athletes. A value of 0 indicates that the model was perfect in its predictive abilities, whereas a value of 1 indicates a complete error rate (Steyerberg et al., 2001).

4.4 Results

Figure 4.1 shows the total yearly races for men and women. Of the 425 unique races, 211 (49.6%) were for men. Elite level races included Continental Championships, Continental Cup, Major Games, Qualification Event, Recognised Event, Recognised Games, Regional Championships, World Championship Finals, World Championship Series, World Championships, and World Cup. The complete observations for men were 5,278 and 3,644 for women. The median number of males competing in each race was 20 (1st and 3rd quartile = 13 to 39), and the median number of females in each race was 14 (1st and 3rd quartile = 7 to 25). Men had a median age of 23 years (1st and 3rd quartile = 21 to 29) and the median age of females was 24 years (1st and 3rd quartile = 21 to 31). Of the 8,842 race records, only 98 had missing age values. No values were imputed for missing age data.

There were 2,940 unique athletes in the dataset, with 1,747 (59.4%) male. From the median, males competed in 1 race (1st and 3rd quartile = 1 to 3) and females competed in 1 race (1st and 3rd quartile = 1 to 3). The most races by a male triathlete were 27 races. The most races by a female triathlete were 25 races. 2020 had the least number of races, with 14 for men and 15 for women. The most were in 2019, with 68 for men and 66 for women.

Different swim and bike position combinations were tallied, and the ten most common combinations were ordered and displayed in Table 4.2. The most common position combination of swim and bike positions for men and women was to finish first out of the swim and first off the bike. This does not inform on whether athletes finished in a podium position. Females had a greater total of first-place swim and bike combinations, more than double the next most common combination (Table 4.2).

Parameter estimates are shown in Table 4.1. There was an effect of *swim position*, *bike position*, *swim position* by *bike position, swim position* by *sex, bike position* by *sex, sex* by *age* and *swim position* by *bike position* by *sex* (Table 4.1).

Figure 4.7 displays the receiver operating characteristic curve and calibration plot for model validation. The model could distinguish podium places from non-podium places 78% of the time (Figure 4.7A) with a very low average prediction error (Brier Score = 0.001; Figure 4.7B).

Table 4.1. Parameter estimates (on the logit scale) from the logistic regression model predicting podium finishers in elite-level triathlons between 2018 and 2022.

Parameter	*β* Estimate	Standard error	95% CI (Lower, Upper)	*z*-value	*p*-value
Intercept	–5.59	1.89	–9.16 to –1.14	–2.94	.003
Swim Position	–0.05	<0.01	–0.07 to –0.04	–7.75	<.001
Bike Position	–0.30	0.17	–0.34 to –0.27	–18.32	<.001
Sex (Female)	1.87	3.19	–4.47 to 8.03	0.59	.558
Age (df = 1)	13.51	4.23	4.05 to 21.38	3.19	.001
Age (df = 2)	0.41	1.21	–1.76 to 3.34	0.34	.733
Age (df = 3)	8.34	3.69	–1.02 to 14.77	2.56	.024
Swim Position by Bike Position	0.004	0.004	0.003 to 0.005	10.54	<.001
Swim Position by Sex (Female)	–0.06	0.01	–0.08 to –0.03	–3.96	<.001
Bike Position by Sex (Female)	–0.14	0.03	–0.19 to –0.08	–4.54	<.001
Sex by Age (df = 1)	–3.58	7.29	–17.70 to 10.97	–0.49	.624
Sex by Age (df = 2)	3.19	2.24	–1.24 to 7.64	1.43	.153
Sex by Age (df = 3)	–2.81	7.08	–16.66 to 11.38	–0.40	.692
Swim position by Bike Position by Sex (Female)	0.003	0.0009	0.001 to 0.005	3.58	<.001

Note. CI, confidence interval.

Table 4.2. The top ten most occurring combinations of positions at the end of the swim and end of the bike for men and women from the modelled data. The most common position was first at the end of the swim and first at the end of the bike for men and women. This does not include the overall finish position.

Men			**Women**		
Swim Position	**Bike Position**	**Occurrences**	**Swim Position**	**Bike Position**	**Occurrences**
1st	1st	60	1st	1st	96
1st	2nd	43	1st	2nd	46
2nd	1st	37	2nd	1st	42
2nd	3rd	36	2nd	2nd	42
3rd	2nd	35	3rd	3rd	40
3rd	3rd	35	4th	4th	38
2nd	2nd	33	2nd	3rd	32
1st	3rd	27	5th	5th	32
4th	4th	26	3rd	1st	29
4th	3rd	26	3rd	2nd	29
4th	5th	25	3rd	4th	27

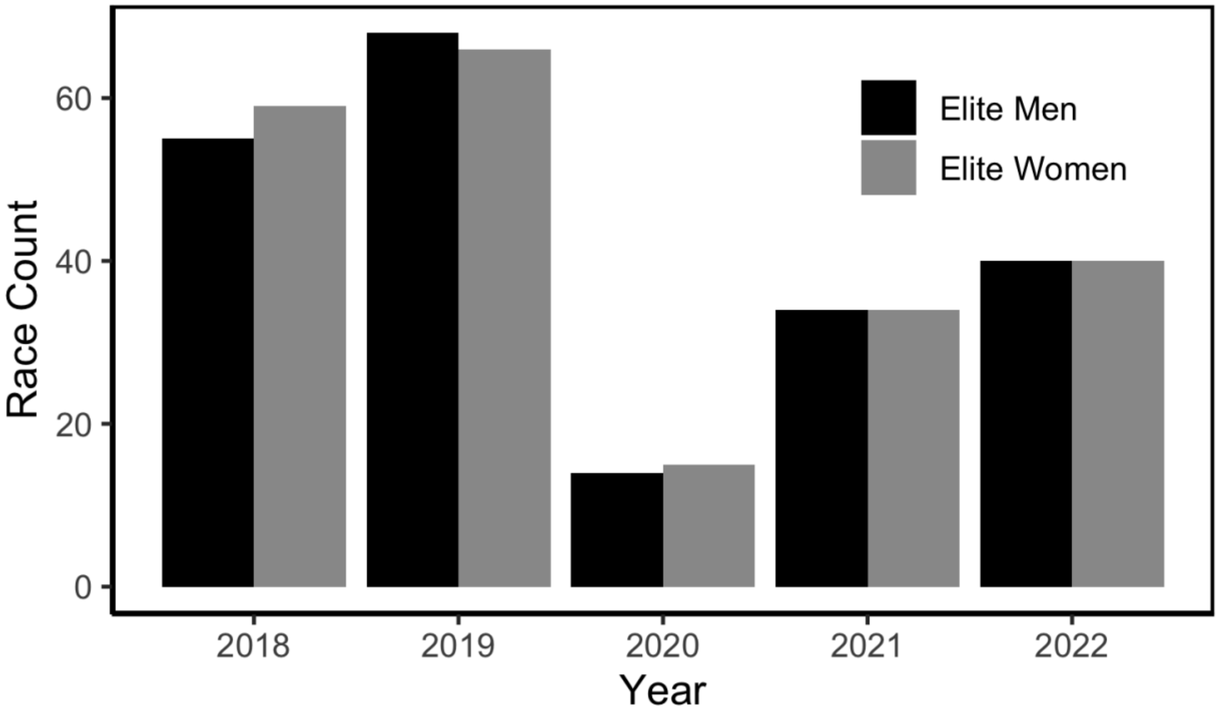

Figure 4.1. Total male and female races for each year in the data set. Males are represented by black, while women are represented with light grey. The total number of races is on the y-axis, and the year of competition is on the x-axis.

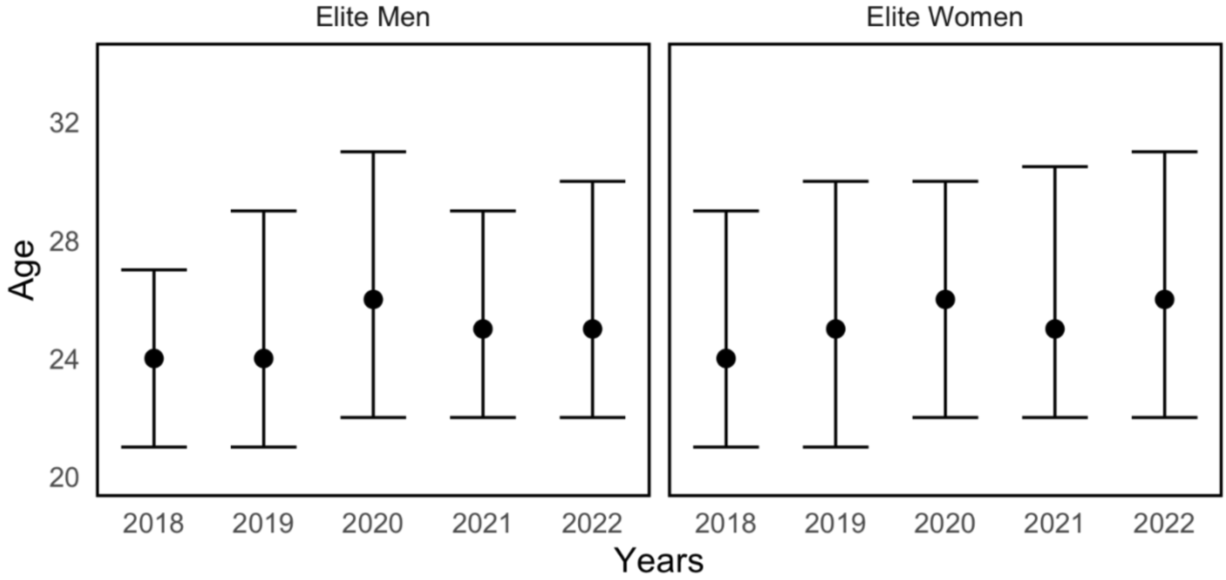

Figure 4.2. The ages of athletes competing across all years. The black points represent the median age of all athletes in the year of competition. The error bar indicates the interquartile range from the first to third quartiles.

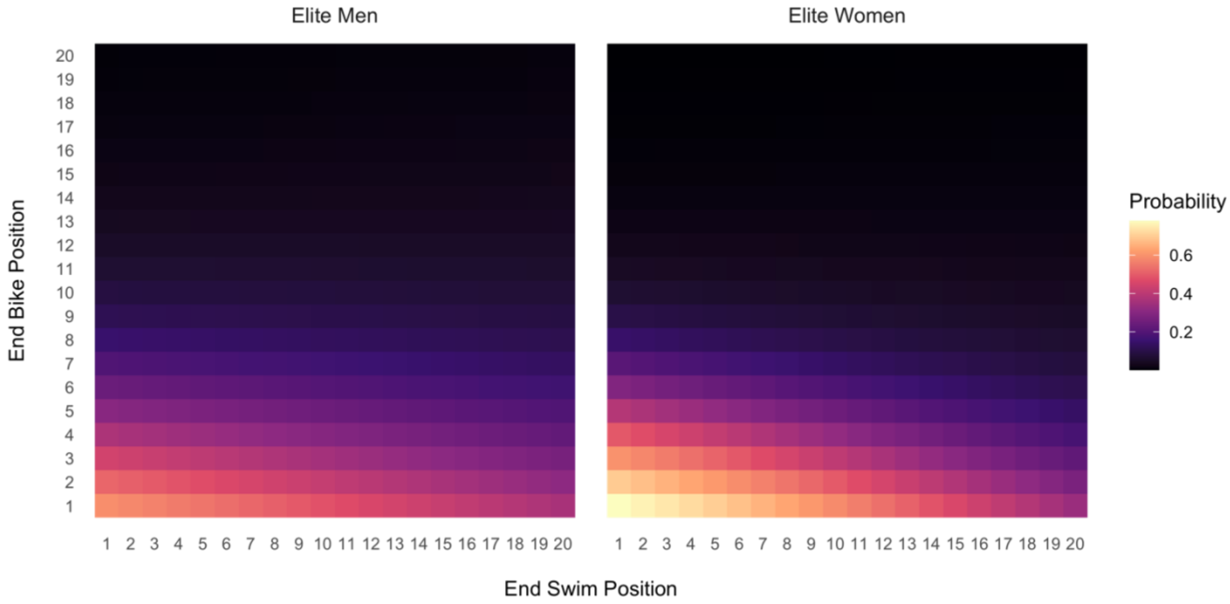

Figure 4.3. The estimated marginal mean probability of a podium finish for the top 20 swim and bike segment position combinations. Males (left panel) who placed first in the swim and first in the bike segment had a 59% chance of a podium finish. Females (right panel) who placed first in the swim and first in the bike segment had a 78% chance of a podium finish.

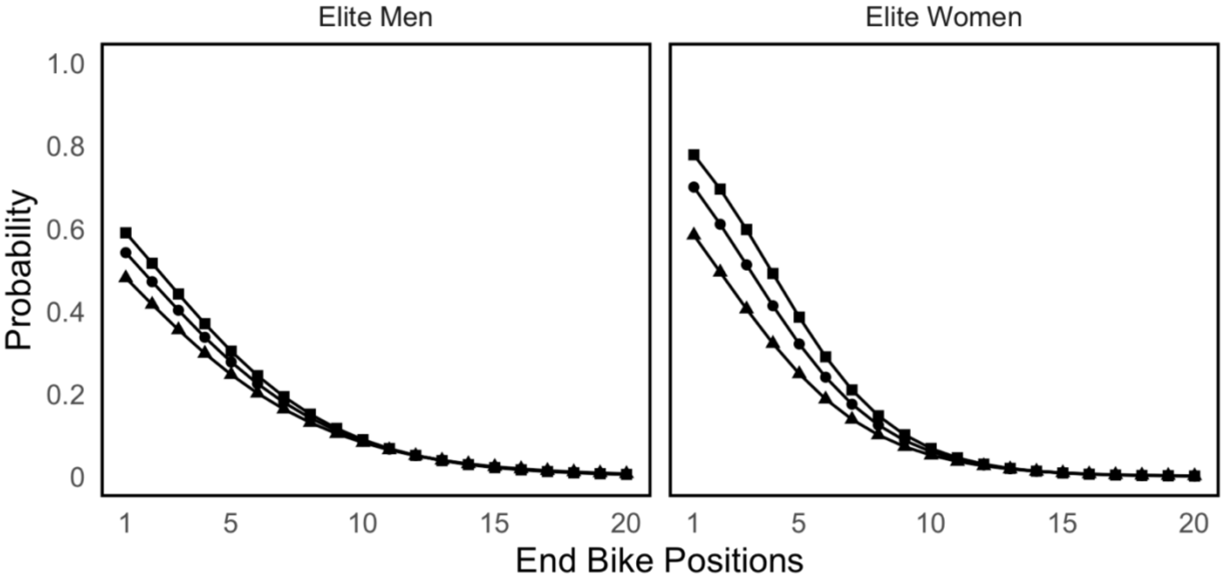

Figure 4.4. The estimated marginal mean probability of a podium finish for each bike segment position when placing first (square), fifth (circle) and tenth (triangle) in the swim for men (left panel) and women (right panel). Males who placed first in bike and first, fifth and tenth in the swim had a 59%, 54% and 48% chance of a podium finish. Females who placed first in bike and first, fifth and tenth in the swim had a 78%, 70% and 58% chance of a podium finish.

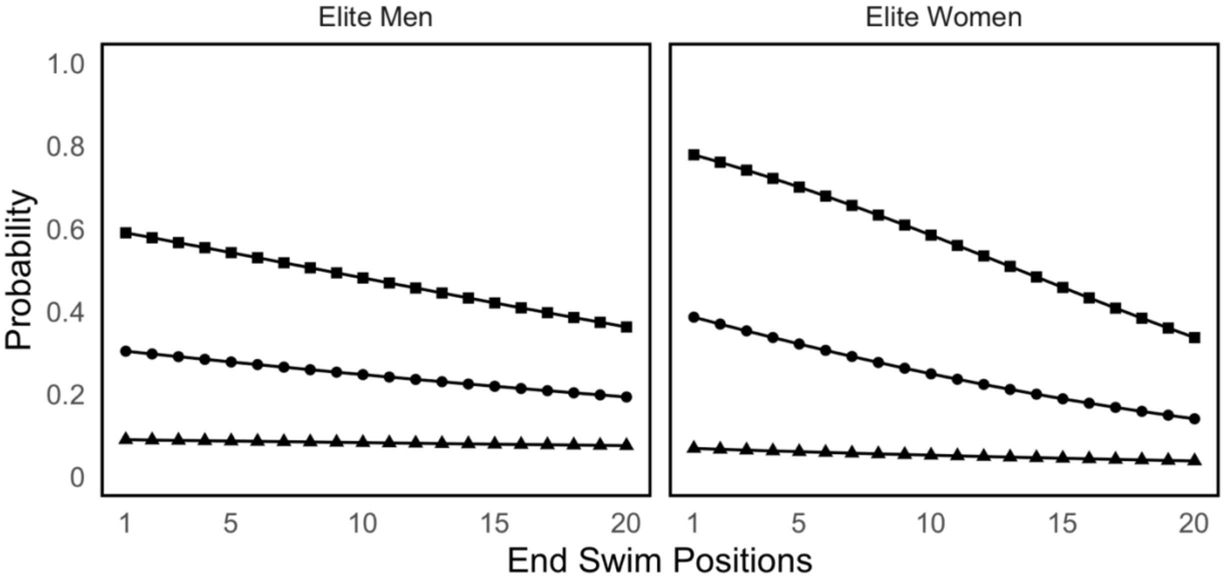

Figure 4.5. The estimated marginal mean probability of a podium finish for each swim segment position when placing first (square), fifth (circle) and tenth (triangle) in the bike segment for men (left panel) and women (right panel). Males who placed first in the swim and first, fifth and tenth in the bike had a 59%, 30% and 8% chance of a podium finish. Females who placed first in the swim and first, fifth and tenth in the bike had a 78%, 39% and 7% chance of a podium finish. The relatively large change in probability for each bike position highlights the importance of placing in the bike segment relative to the swim segment.

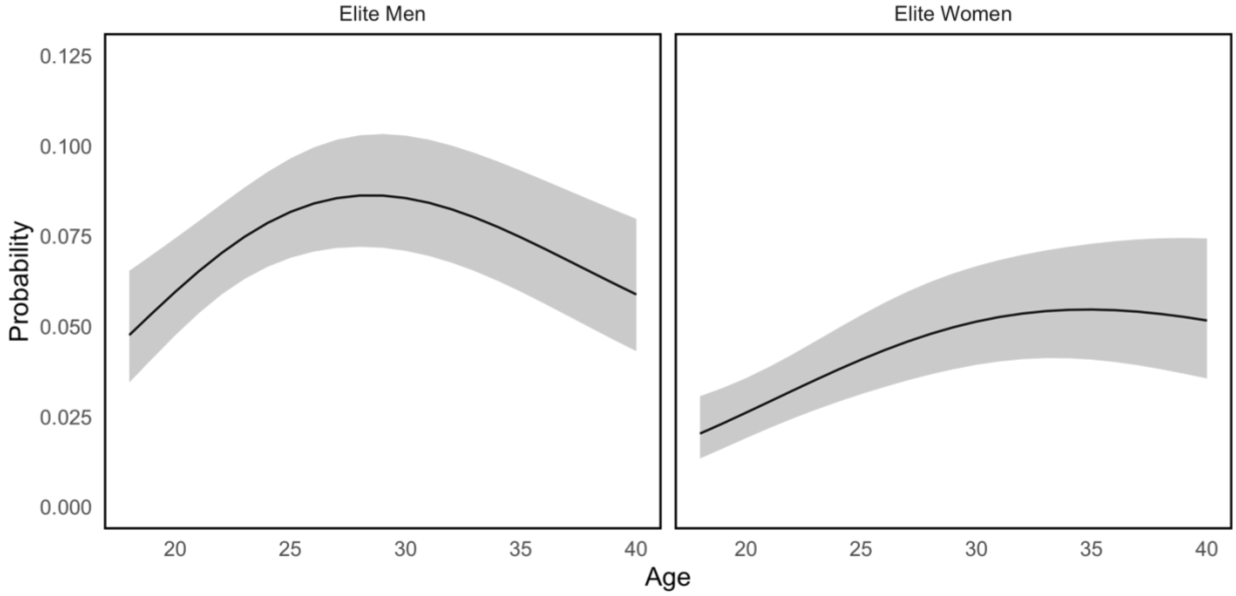

Figure 4.6. The estimated marginal mean effect of age on the probability of a podium finish for men (left panel) and women (right panel). The black line represents the mean probability. The grey shaded ribbon indicated the 95% confidence interval.

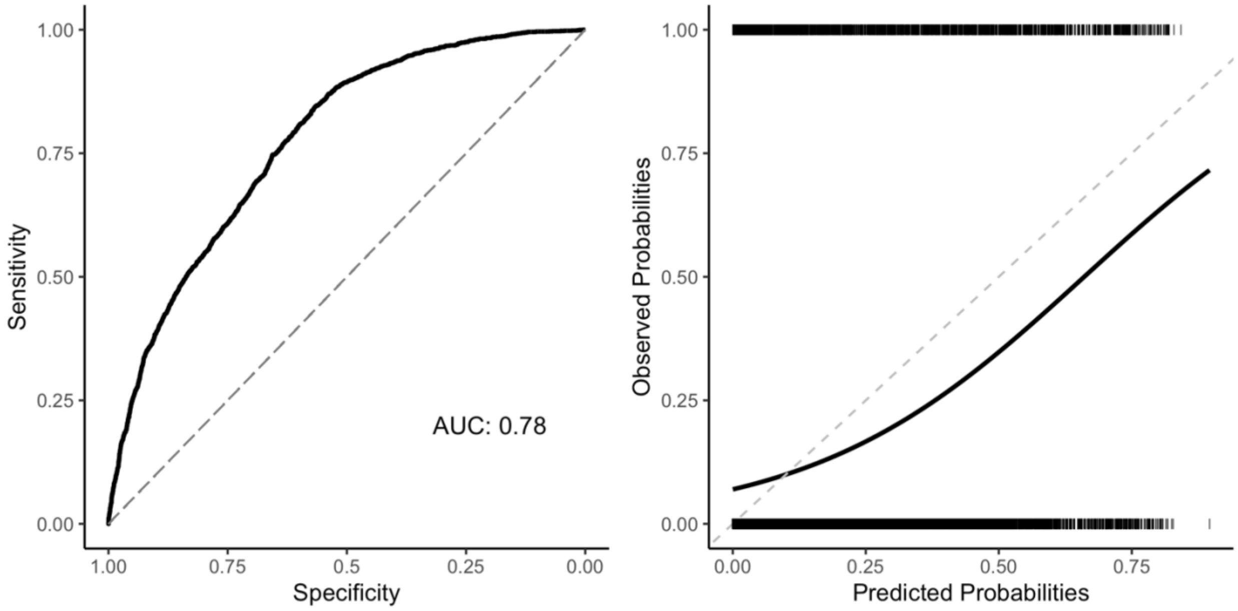

Figure 4.7. Receiver operating characteristic curve for the validation of predicting podium and non-podium finishers. The receiver operating characteristic curve shows the model performance at all classification thresholds. The dashed diagonal line represents a perfectly calibrated model, with values below the diagonal line indicating underprediction and over the line indicating overprediction. The area under the curve (AUC) is 0.78.

4.5 Discussion

We analysed triathlon performance by quantifying the probability of a podium finish, focusing on the influence of positioning at the end of the swim and bike segments. Previous studies have predominantly focussed on time-based performances (Barbosa et al., 2022; Figueiredo et al., 2016; Gadelha et al., 2020; Olaya-Cuartero et al., 2022; Sousa et al., 2021), though positioning is more informative as the final position determines the outcome, not time. We found that if a male triathlete were to complete both the swim and cycle segments in first place, they would have a 59% chance of a podium result. For women, the same positioning combination would result in a 78% chance of a podium result. The results supported our hypothesis that position out of the cycling segment is more important than position out of the swim segment for a podium finish. While these findings may be intuitive, our analyses provide empirical support for the change in probability across positions that can better inform race strategies.

Our primary finding was that bike position had a greater impact on the overall race outcome than the swim position. These results reflect prior studies indicating that cycling is the most influential on overall results (Barbosa et al., 2022; Olaya-Cuartero et al., 2022). However, identifying one segment as the most predictive oversimplifies triathlon race dynamics. Critically, pack dynamics may influence finish results (Landers et al., 2008). Grouping of athletes across the swim and bike can maintain an advantage of drafting between each other. Given these race complexities, results from Ofoghi et al. (2016) can be used in combination with our results to build a more complete understanding. Males must complete the swim, cycle, and run segments within 10 seconds, 40 – 50 seconds and 10 seconds of the race leader, respectively (Ofoghi et al., 2016). In comparison, females needed to complete the swim, cycle, and run within 20 – 30 seconds, 10 seconds, and 10 seconds, respectively, for the best chance of a podium finish (Ofoghi et al., 2016). Thus, to further discern between probabilities of outcome, our position analysis allows for further discrimination of performance targets (Figure 4.3). While multiple athletes can complete segments within the specified time differentials, athletes positioned ahead will have a better chance of achieving the desired outcome. As athletes want to maximise their chance of a podium finish, they would more effectively increase their overall results by improving cycling positions than swimming positions.

The effect of age on a podium position did not differ between the sexes. While its effect on outcome was relatively small (Figure 4.6), the peak age for women was seven years older, and its effect on outcome was smaller than that of men (Figure 4.6). Age-related success in triathlon has previously been determined to be ~27 years old, aligning with our results for males (R.Knechtle et al., 2014; Malcata et al., 2014; Villaroel et al., 2011). The peak performance age of females, being older than males, may be explained by the reduced total female sample size and female athletes per race. While age affects overall results, the low probability and large variance in winners' age, as discussed in Study 1, indicates that age is still less important than other measurements of success. Regardless, triathletes ~27 years old are likelier to win than other ages, potentially due to greater race experience, as previously suggested by Villaroel et al. (Villaroel et al., 2011). Female age for the probability of a podium being older than males may be due to an overall reduced participation rate, as seen in Chapter 3. However, it was also seen in Chapter 3 that the median age of men and women was similar across a larger amount of races, supporting a peak age of roughly 27 years old (Knechtle et al., 2014; Malcata et al., 2014; Villaroel et al., 2011). Further comparisons show females had a greater chance of a podium overall. A larger median field size of 20 men to 14 females sees more males trying to attain the same amount of podium places. This reduced field size is a possible contributor to the increased probability of females attaining a podium position.

Our model accurately distinguished 78% of podiums from non-podium finishers (Figure 4.7 Panel A). The calibration plot shows that the model did not overpredict, but generally underpredicted podium finishers by a small amount (Figure 4.7 Panel B). Only one previous study considered model validation using internal methods (Olaya-Cuartero et al., 2022). However, the authors did not include a ROC curve or calibration plot in the results, indicating how well the model performed (Olaya-Cuartero et al., 2022). Model validation should be featured in future studies that quantify the probability of finishing position (Sperrin et al., 2022; Steyerberg & Harrell, 2016). Specifically, external validation should be used to validate the model across different populations (Terrin et al., 2003). Future studies should also consider completing sample size calculations specific to prediction models (Riley et al., 2020) in the study's context (i.e., model development versus model validation) (Riley et al., 2021).

The current results suggest that completing an elite Olympic triathlon's swim and bike segments in first position is the optimal race strategy. However, the recording frequency of the sourced data does not allow for identifying in-segment positions and pacing strategies used to achieve final segment positions. Still, biomechanical adaptations such as the use of wetsuits, cleat positioning, cycling cadence and drafting across the swim and cycling segment are known to reduce energy output and improve cycling post-swimming and running post-cycling

(Ambrosini et al., 2022; Bentley et al., 2007; Delextrat, Tricot, et al., 2005; Hausswirth et al., 1999; Millet, 2000; Rico Bini et al., 2022; Vercruyssen et al., 2002). It has been observed that triathletes commonly opt for an unfavourable run pacing strategy − a positive split − and that triathletes should complete the first kilometre of running 5% slower than their ideal pace for improved running performance (Hausswirth et al., 2010). Therefore, a more optimal strategy for athletes may be to conserve energy through the swim and cycling segments, improving their position towards the end of each segment before starting the run segment with an optimal pacing strategy. Although triathletes typically complete the run segment in a positive split, evidence indicates a negative split is faster (Hausswirth et al., 2010). Regardless, triathletes must also maintain close contact with the front of the race (Ofoghi et al., 2016).

The main application of the results of this study was quantifying the change in probability for swim and bike positions for a podium result. This delivers athletes and coaches easily interpretable results to inform race strategies and decision-making. Several strengths of the study include the size of the data set, which includes 8,922 race records across five years, 6,295 more than a similar analysis period. This provides modelled results off recent race strategies to be current and relevant to today's elite racing. The validation of the model is an improvement on previous studies, but it could be further improved by including an external validation method examining the model's accuracy in different populations. That said, the strength of the data makes it challenging to find relevant external data sets (i.e., elite standard distance triathlon) that would appropriately validate the model. A limitation of this study was the variance in the levels of racing. Continental Championships and Continental Cup races may not have been available for all athletes to participate in and may have reduced the competitiveness of races. Further analysis with only higher level races such as the World Championships and Olympic Games may provide more specific results for those races.

4.6 Conclusion

This paper quantified the probability of a podium finish, focusing on the influence of swim and bike segment positioning. Our results showed that the cycle segment position was more important than the swim segment position in obtaining a podium result. This does not form a complete picture, and triathletes must maintain close contact with the front of the race at all segments to have the best chance of a podium result (Ofoghi et al., 2016). Completing each segment as close to the front of the race appears optimal for the best overall results. Finally, the cycling position, as opposed to the swimming position, appears to be more influential on race outcomes. The current data may be informative for elite triathletes when developing race strategies.

Chapter 5: The Effect of Water and Ambient Air Temperatures on Elite Standard Distance Triathlon Performance Outcomes

5.1 Abstract

Introduction and aims: Elite triathlon races occur across the globe, exposing athletes to various environmental conditions. However, no research has investigated how race performances of triathletes are affected by differing water and air temperatures. This study aimed to examine the effects of temperature on segment performance times and explore the effects on sex. **Methods**: World Triathlon elite standard distance race entries (n=377) were analysed from 2015 to 2022. Water temperatures were modelled against swim time, air temperatures against cycling time and air temperatures against run times. Fitted models included were polynomial (swim), linear (bike), and second-order polynomial (run) regression models fit in a Bayesian framework. Interaction terms were specified for age and sex, and random effects were specified for race and athlete identifiers to account for differences in geography and grouped-level competitiveness. **Results**: Water temperatures ranged from 14.7 °C to 30.9 °C and air temperatures ranged from 11.0 °C to 38.0 °C across six different continents. Water temperature was determined to affect swimming performances (-0.44, 95% CI -0.62, -0.27), while air temperature to affect running performances (1.11, 95% CI 0.69, 1.55) but not cycling outcomes (0.001 95% CI −0.001, 0.003). There were no differences between men and women on how they were affected by temperatures, swimming (0.166, 95% CI −0.01, 0.34), cycling (0.0005, 95% CI −0.002, 0.003) and running (0.07, 95% CI −0.56, 0.72) **Conclusion**: Male and females were affected similarly by water temperature for swimming and air temperatures while running. However, air temperature did not affect cycling performance times for either men or women. Swimming also showed no difference in the performance times of men and women.

5.2 Introduction

Environmental temperatures affect the physiological demands of athletic performance, particularly where prolonged exposure and high-intensity activity are required (Alexiou, 2014; Périard et al., 2021). For example, athletes must appropriately control physiological effort for temperature regulation (heat balance) in hot and humid environments. Otherwise, increasing core temperatures will subsequently reduce performance output, mitigating the risk of heat illness. Increased inhibition of the central nervous system drive to skeletal muscle, among other mechanisms (Cheung & Sleivert, 2004), reducing metabolic heat production and the rate of heat gain (González-Alonso et al., 1999; Maughan, 2010; Nielsen et al., 1997). Previous thermoregulatory research has lacked adequate female participation despite sex-specific physiological, behavioural, and hormonal differences that can influence the response to exercise in hot environments (Hutchins et al., 2021). Further, sex differences, specifically in the context of elite standard distance triathlons, have only been explored once (Le Meur et al., 2009). With known differences in response to heat, the added complexity of different exercise modes in triathlon may further influence sex differences.

Elite triathlon events occur across six of the seven world continents. Consequently, athletes are required to compete in various and sometimes extreme weather conditions. The World Triathlon Organization includes a range of temperatures to manage the health and safety of athletes competing in these environments. The use of wetsuits while swimming is governed by water temperature, with mandatory wetsuit use in water temperatures ≤ 15.9 °C, forbidden at temperatures ≥ 20 °C and optional between (*ITU Competition Rules*, 2015). Limits for water temperatures are set to a maximum of 30.9 °C and a minimum of 13.0 °C (*World Triathlon Competition Rules*, 2022). While a wet bulb globe temperature (WBGT) of 32.2 °C, which incorporates the influence of air temperature, humidity, and solar radiation, requires the rescheduling or cancellation of the event. No minimum temperature is outlined in the 2022 World Triathlon Organization competition rules (*World Triathlon Competition Rules*, 2022).

Previous triathlon performance research has highlighted the importance of physiological (Ambrosini et al., 2022; Delextrat et al., 2003; Hausswirth & Lehenaff, 2001; Millet et al., 2003; O'Toole & Douglas, 1995; Rico Bini et al., 2022), biomechanical (Ambrosini et al., 2022; Delextrat, Tricot, et al., 2005; Millet, 2000; Millour et al., 2020; Quagliarotti et al., 2023; Rico Bini et al., 2022), and time-performance correlates (Figueiredo et al., 2016; Landers et al., 2008; Ofoghi et al., 2016; Piacentini et al., 2019; Sousa et al., 2021). Although unclear, swimming has been indicated to affect triathlete cycling performances negatively (Ambrosini et al., 2022; Delextrat, Brisswalter, et al., 2005; Kreider et al., 1988). Cycling in warmer temperatures further hinders running performance by up to 15.7% compared to cool-temperature cycling (Chan et al., 2008). An increased energy cost in running at the end of a triathlon is associated with reduced plasma volume and body mass resulting from excessive sweat loss (Guezennec et al., 1996; Hausswirth et al., 1996). Accumulative fatigue related to the subsequent segment modalities of triathlon races likely exacerbates the adverse effects of heat on running performance. However, the performance response to temperature between sexes in triathlon is yet to be elucidated and may differ across the course of a triathlon race.

The objectives of this study were to 1) examine the effect of water temperatures on swimming performance times and air temperatures on cycling and running performance times; and 2) explore sex differences in the effect of environmental temperatures on performance times. We hypothesised that women would be slower across each segment than men and that men would be affected more by the heat while running.

5.3 Methods

Data for this analysis was extracted from the World Triathlon Organization for elite-level races from 2015 to 2022. Data contained two categories, elite men and elite women, with water and air temperature measured in degrees Celsius, segment times in seconds, the age the athlete was turning in the year of competition, and race and athlete identifiers. Swim times were modelled with a splines model, while cycling was modelled with linear regression and running times were modelled with a 2nd-order polynomial. Ethical approval was not required for this study as all data was publicly available to be downloaded and examined. These data and R code are available at https://github.com/alexdgibson/mphil_triathlon (alexdgibson, 2024).

The data variables contained sex, race notes, birth year, race identifier, athlete identifier, segment and overall race times, finish position, longitude, latitude, and a status variable. The status variable included information if the athlete did not start, did not finish, was disqualified, or lapped on the bike segment during the race. Age was calculated as the age at which the athlete turned in the competition year. Repeat observations for athletes competing multiple times per year were removed when reporting age summaries. Previous segments were included as fixed effects in the models to account for the effect of a previous segment (e.g., swimming) on a subsequent segment (e.g., cycling). Thus, the previous segments were centred and scaled for the cycling model (just swimming) and the run model (swimming and cycling). Centring and scaling swim and bike times for these models maintained variability while reducing the mean to zero and standard deviation to one (Geladi & Kowalski, 1986). No sample size calculation was completed as the study is retrospective.

Segment distances were retrieved from race notes and races were included in the analysis if they contained the full 1,500 m swim – duathlons were not included. All races were of an elite level and the standard distance triathlon. A wetsuit categorisation variable was created, indicating whether wetsuits were illegal, optional, or mandatory for the race. The categorisation was done as illegal ≥ 20 °C, mandatory ≤ 15.9 °C and optional between the two temperatures. Water and air temperature were also retrieved from the race notes.

Our primary interest was determining the effect of water temperature on swim performance times, air temperature on cycling performance times, and air temperature on run performance times. The secondary aim of this study was to examine the sex differences of water temperature and air temperature of segment times. Races were included in the analysis if swim, bike and run times were present, water and air temperatures were recorded, and the event contained the full 1,500 m swim. All races were elite standard distance triathlon events. The analysis did not include athlete race results if they did not start. Athletes who dropped out of the race (i.e., did not finish) were retained until the last completed segment.

Swim, cycle, and run segment times were modelled separately. Swim time was modelled against *water temperature*; cycle time modelled against *air temperature;* and run time modelled against *air temperature*. A mixed effects approach was undertaken in a Bayesian framework. Each model had the same negative binomial response distribution, examined through exploratory plots of the modelling data being over-dispersed. A polynomial splines model was fit for swim times as the effect was not linear. A linear model was implemented to determine the air temperature effect on cycling times, while a second-order polynomial model the effect of air temperature on running times.

Segment time was modelled together for men and women to determine the effect of temperature on segment time performance and sex differences. The swimming model included *water temperature, age* and *wet suit classification* as fixed effects, a *water temperature* by *sex* interaction, *age* and *sex* interaction and random effects for *race* and *athlete* identifiers with splines terms specified at 18 °C, 19 °C and 20 °C. The cycling model included *air temperature*, *age* and *swim time* as fixed effects with *air temperature* by *sex*, *swim time* by *sex*, *age* by *sex* interaction and *race* and *athlete* identifiers as random effects. The running model included *air* *temperature*, *age*, *swim time*, *bike time* as fixed effects with *air temperature* by *sex*, *air swim time* by *sex, bike time* by *sex*, *age* by *sex* interactions with *race* and *athlete* identifiers as random effects. For each model, *age* was included as a fixed effect to account for age-related improvements in segment times. A random intercept term was specified for each *race* and *athlete*, to account for differences in course geography, topology and grouped-level competitiveness. The year was not included for models as it did not influence segment times in the data examined through exploratory plots. To account for the effects of the previous segment on athletes' time performance in later segments (i.e., cycling and running), *swim time* was added as a fixed effect in the bike model, while both *swim time* and *bike time* were added as a fixed effect for the run model. Transition times were not included in the analysis, as the primary outcome was on the effect of swimming, cycling and running times.

All analyses were underktane in R (R Core Team, 2022), using RStudio (version 4.03) (RStudio Team, 2022) with the *brms* interface (Bürkner, 2017) and *lme4* (Bates et al., 2015). Data wrangling was completed using the *tidyverse* package (Wickham et al., 2019). Further, each model was specified with a negative binomial distribution and log-link predictor. Weakly informative prior distributions were specified for regression coefficients (*t*-distributions (mean = 3, df = 0, SD = 2.5 and variance (Gamma (shape = 0.01, scale = 0.01)) components. Monte Carlo Markov Chain (MCMC) methods generated posterior estimates (15,000 iterations, 8 chains, 50% iteration burn-in, no thinning), resulting in 60,000 posterior estimations. The convergence of MCMC to the posterior distribution was visually assessed using trace plots. We calculated posterior probabilities that the regression coefficient (β) was greater or less than zero to substantiate if there was evidence of effects, denoted Pr β >0 or Pr β <0. Posterior estimates were summarised as the mean, and 95% confidence interval (CI). All descriptive statistics were reported as mean, standard deviation.

Water temperature and air temperature summary statistics were also expressed as the mean, standard deviation, minimum and maximum. Repeat observations of water and air temperature variables for each race were removed, so temperature data had only one value for each race. The air temperature was modelled with *water temperature* as a fixed effect. Summary statistics of this model were expressed as the model coefficients and 95% confidence interval, as well as the location of water temperatures and air temperatures across the world. These values were plotted on a world map with colour scales denoting the different temperature changes. All visualisations were plotted using *ggplot2* (Wickham et al., 2019).

5.4 Results

The original data set had 545 male races and 537 female races. Only races that contained recorded water and air temperatures were included in the final analysis. A total of 377 races (men = 188 and women = 189) were included in the analysis, and observations from swimming, cycling, and running for males and females are seen in Table 5.1.

Water temperature had a mean (SD) temperature of 22.3°C (3.6°C) with a minimum temperature of 14.7°C and a maximum temperature of 30.9°C. The air temperature had a mean temperature of 23.9°C (4.81°C) with a minimum temperature of 11.0°C and a maximum temperature of 38.0°C. There were 185 male and 186 female races with water and air temperature results. Water temperature results were missing for three male and three female races. No races had missing air temperature values.

The median age of male athletes across all years was 24 (IQR 21 to 27). Women had a median age across all years of 24 years old (IQR 21 to 28). Of all the athletes, only 62 were missing age values, representing 33 unique athletes from 26 races.

The Pr $\beta < 0$ for water temperature on swimming was 1.0, and the evidence of effect was -0.44 (CI = -0.62 to -0.27). The Pr $\beta < 0$ for air temperature on cycling was 0.13, and evidence of effect 0.001 (CI = -0.001 to 0.003). The Pr $\beta < 0$ for air temperature on running was 0, and the evidence of effect was 1.11 (CI = 0.69 to 1.55).

Table 5.1. Total data records for the races, swim, cycle and run times of men and women were used in the analysis.

	Men	**Women**	**Total**
Races	188	189	377
Swim Records	7,501	4,770	12,271
Bike Records	6,543	4,123	10,666
Run Records	6,219	3,858	10,177

Table 5.2 Parameter estimates (on the logit scale) from the swim, bike and run segment models of performance time in elite-level triathlons between 2015 and 2022.

Model	Parameter	*β* Estimate	95% CI (Lower, Upper)
Swim	Intercept	7.48	7.31 to 7.62
	Sex (Female)	−0.06	−0.23 to 0.10
	Wetsuit—mandatory	−0.11	−0.22 to −0.01
	Wetsuit—optional	−0.02	−0.07 to 0.03
	Age	0.001	0.0004 to 0.0016
	Temperature 18°C (Cubic)	−0.47	−0.72 to −0.22
	Temperature 18°C (Linear)	−0.46	−0.66 to −0.26
	Temperature 19°C (Cubic)	−0.44	−0.61 to −0.27
	Temperature 19°C (Linear)	−0.40	−0.61 to −0.19
	Temperature 20°C (Cubic)	−0.47	−0.67 to −0.26
	Temperature 20°C (Linear)	−0.42	−0.62 to −0.23
	Temperature 18°C (Cubic) by Sex (Female)	0.18	−0.14 to 0.50
	Temperature 18°C (Linear) by Sex (Female)	0.21	0.00 to 0.42
	Temperature 19°C (Cubic) by Sex (Female)	0.15	−0.03 to 0.32
	Temperature 19°C (Linear) by Sex (Female)	0.16	−0.04 to 0.36
	Temperature 20°C (Cubic) by Sex (Female)	0.14	−0.11 to 0.38
	Temperature 20°C (Linear) by Sex (Female)	0.16	−0.04 to 0.37
Bike	Intercept	8.20	8.15 to 8.26
	Air Temperature	0.001	−0.001 to 0.004
	Sex (Female)	0.10	0.02 to 0.18
	Scaled Swim	0.02	0.02 to 0.02
	Age	−0.0012	−0.0016 to −0.0009
	Temperature	0.001	−0.001 to 0.003
	Temperature by Sex (Female)	0.0005	−0.002 to 0.003
Run	Intercept	7.76	7.74 to 7.78
	Sex (Female)	0.14	0.12 to 0.15
	Scaled Swim	0.025	0.021 to 0.029
	Scaled Bike	−0.001	−0.004 to 0.002
	Scaled Swim by Sex (Female)	−0.028	−0.034 to −0.022
	Scaled Bike by Sex (Female)	−0.012	−0.17 to −0.007
	Age	−0.0036	−0.0043 to −0.0029
	Temperature (df = 2, Cubic)	1.45	0.76 to 2.13
	Temperature (df = 2, Linear)	0.78	0.11 to 1.46
	Temperature (df = 2, Cubic) by Sex (Female)	0.35	−0.63 to 1.32
	Temperature (df = 2, Linear) by Sex (Female)	−0.19	−1.13 to 0.74

Note. CI, confidence interval.

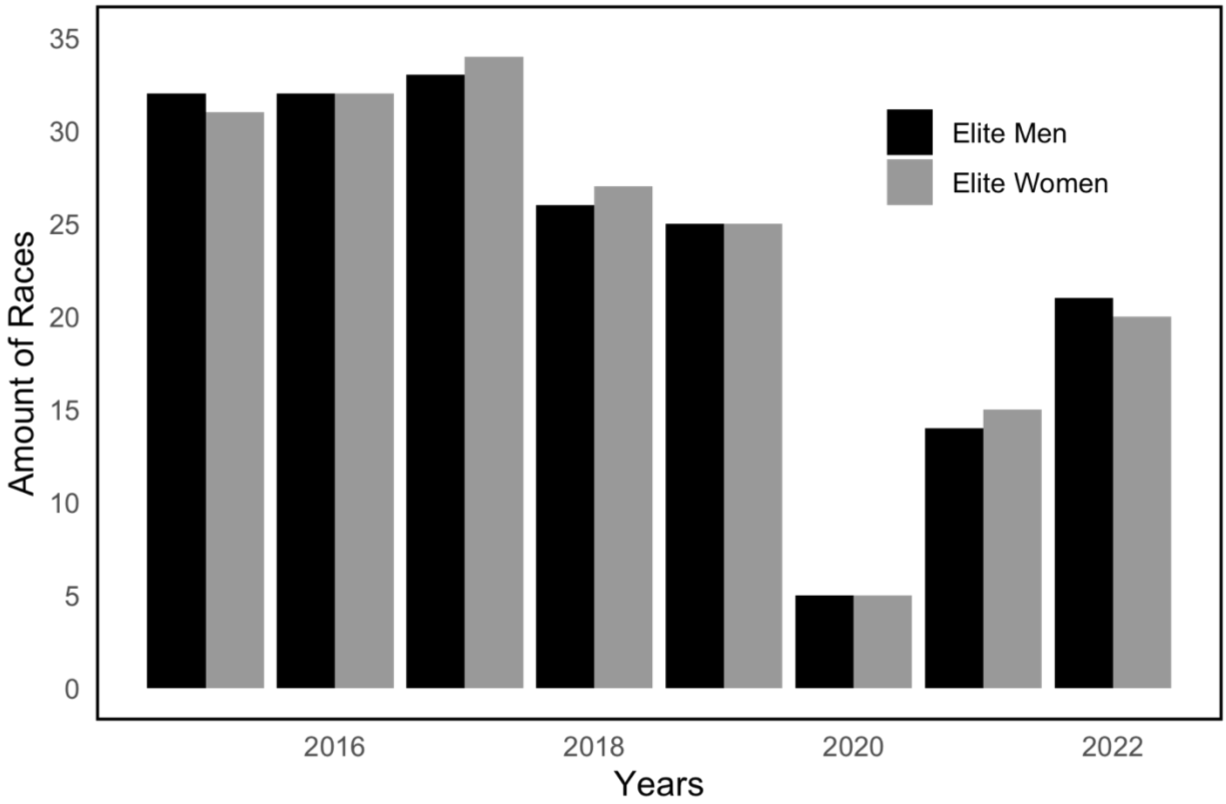

Figure 5.1. The total male and female races for each year in the analysis. Males are represented by black, while women are represented by light grey. The most recorded races were in 2017, with a total of 67, and the least were in 2020, with ten races.

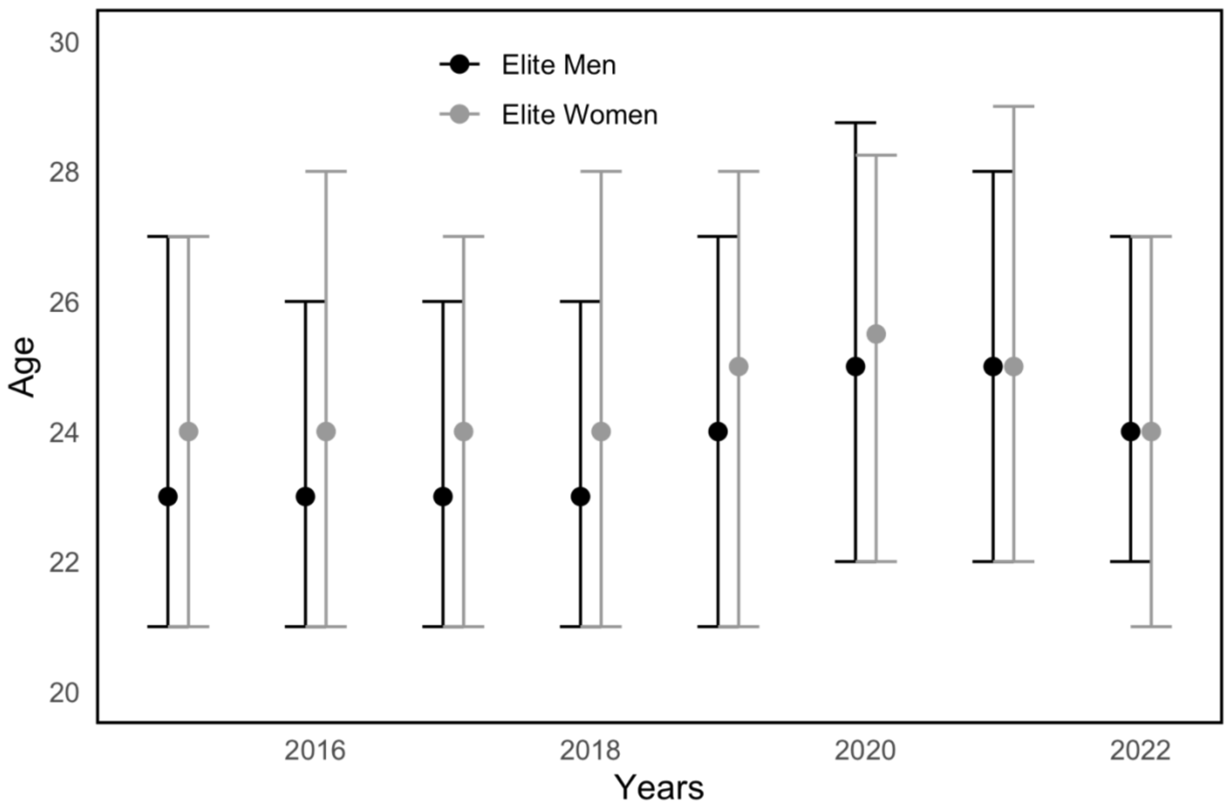

Figure 5.2. The age of male and female athletes used in the analysis from each year. The black point represents the median age, while the error bars indicate the first and third quartile ranges.

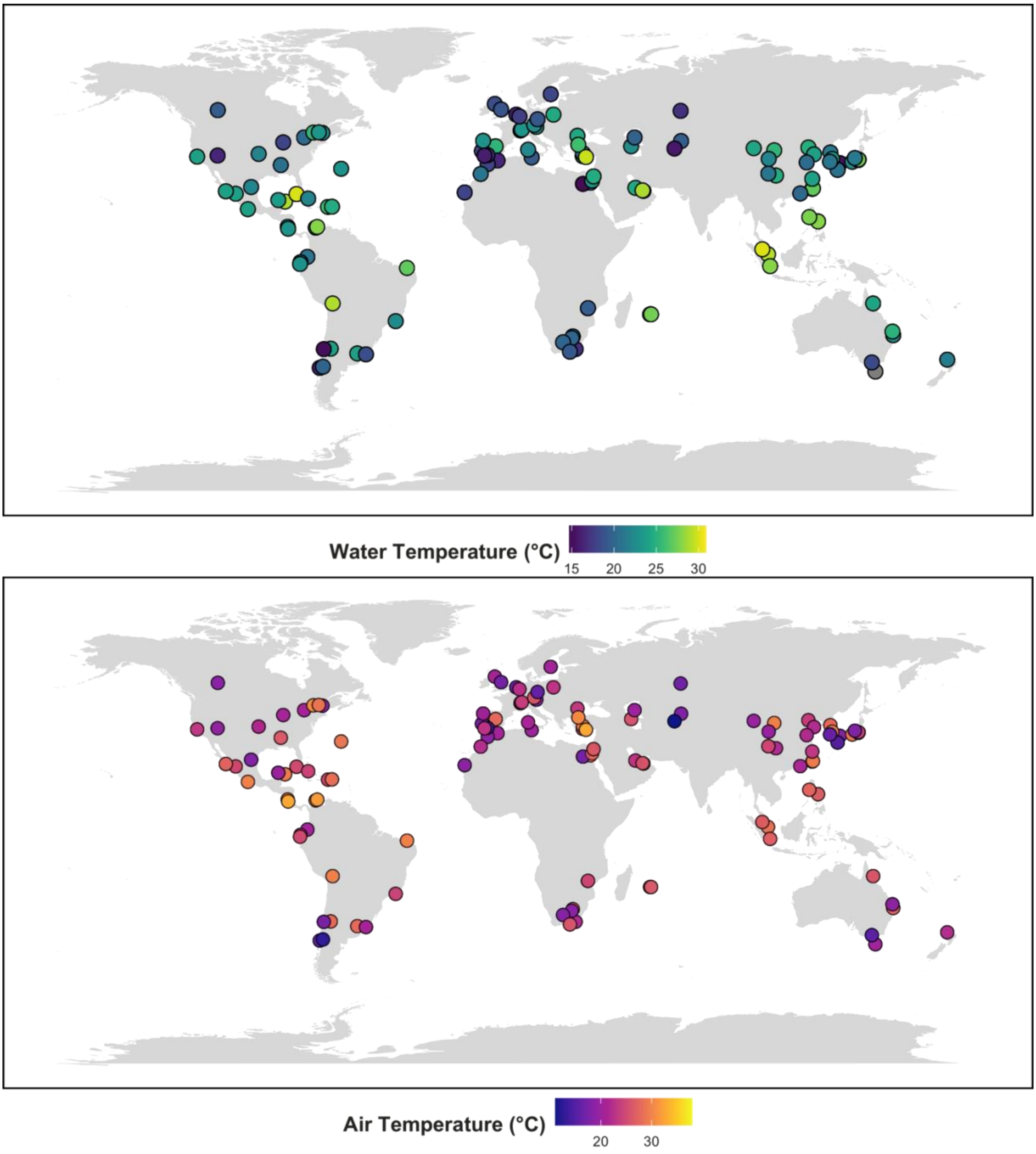

Figure 5.3. Top panel: the spread of water temperatures across latitude and longitude locations of the world. Water temperatures ranged from a minimum of 14.7 °C and a maximum of 30.9 °C. The lighter colour represents warmer water temperatures. There were 371 races with water temperatures recorded. Bottom panel: the spread of air temperatures across latitude and longitude locations of the world. Air temperatures ranged from a minimum of 11.0 °C and a maximum of 38.0 °C. The lighter colour represents warmer air temperatures. There were 377 elite standard distance triathlon races with air temperatures recorded.

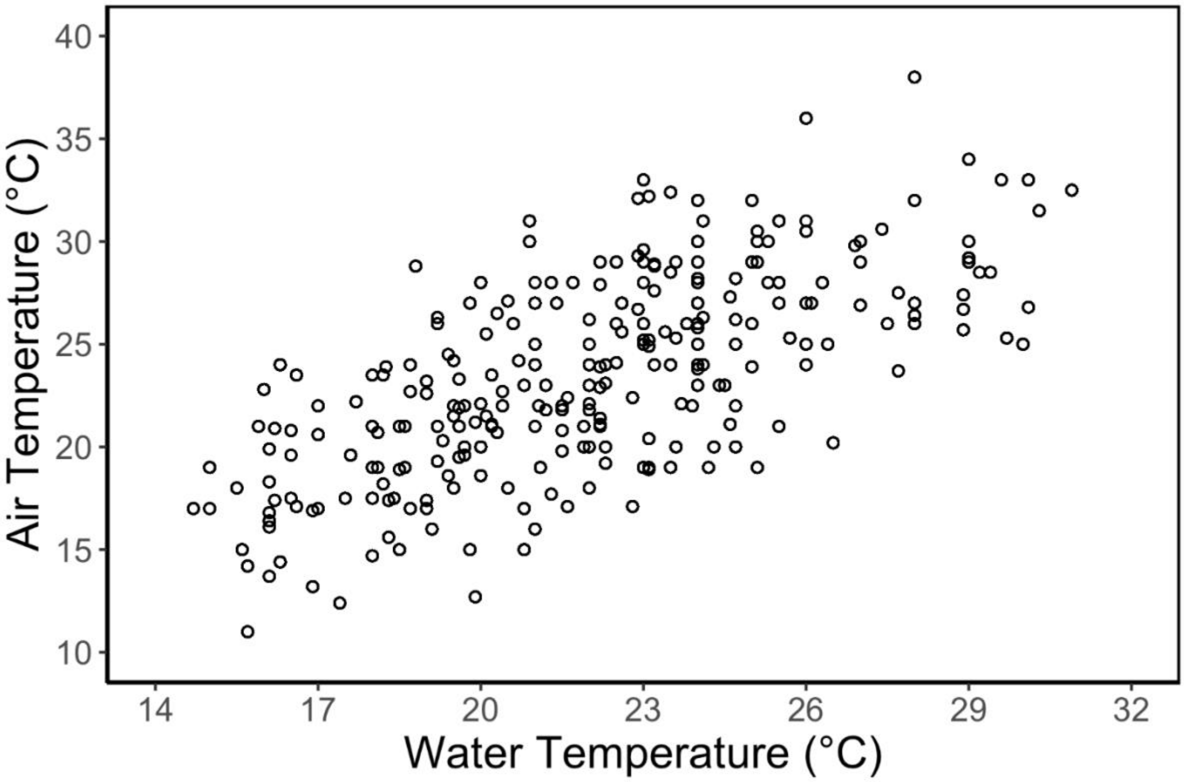

Figure 5.4. The relationship of water and air temperature for elite standard distance triathlon races (n = 371) from 2015 to 2022.

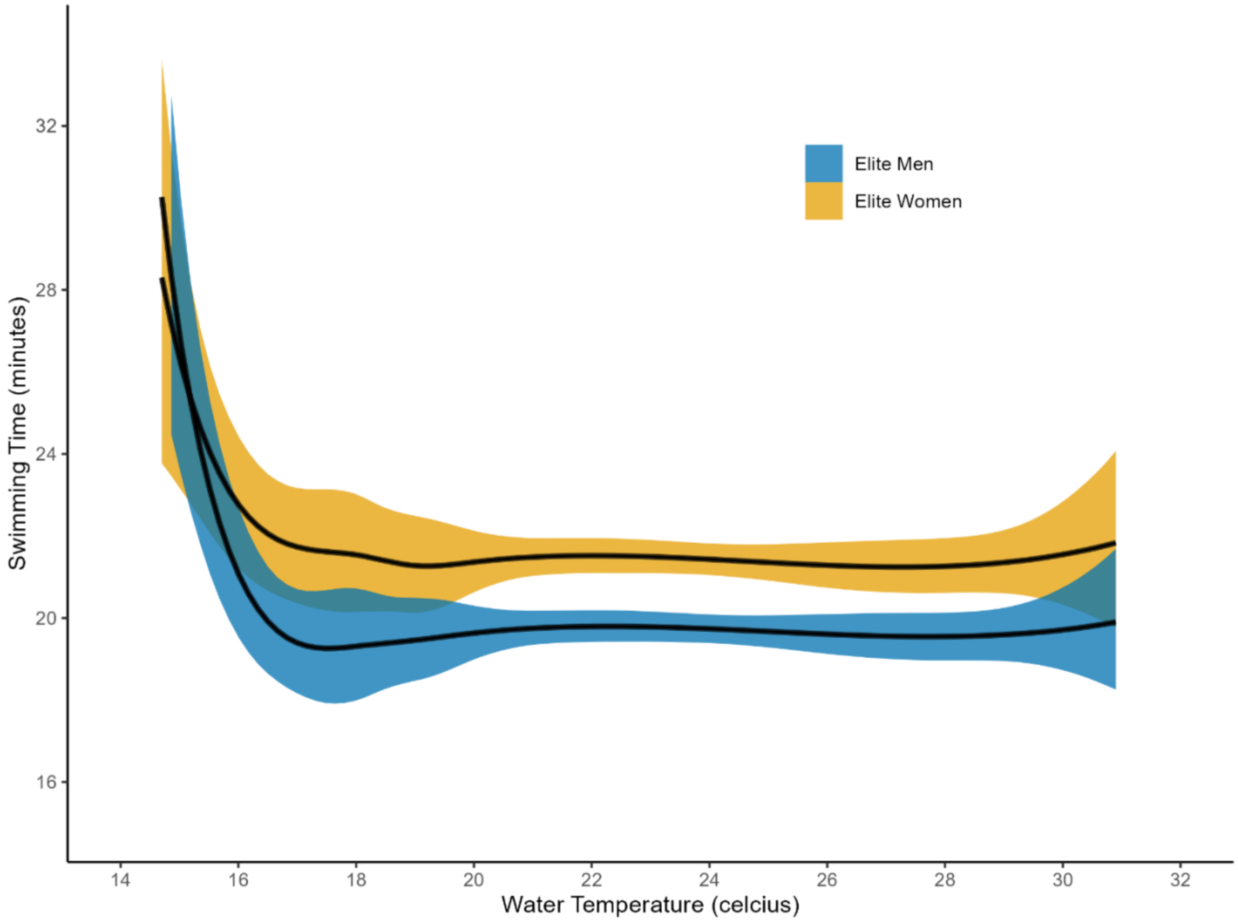

Figure 5.5. Visualisation of swim times and water temperatures for elite men (blue) and women (yellow). The fastest times are associated with the wetsuit optional category ~17 °C to 20 °C, while the slowest time with cold wetsuit mandatory. The black line represents the fitted posterior mean swim time estimate, while the shaded areas are 95% credible intervals.

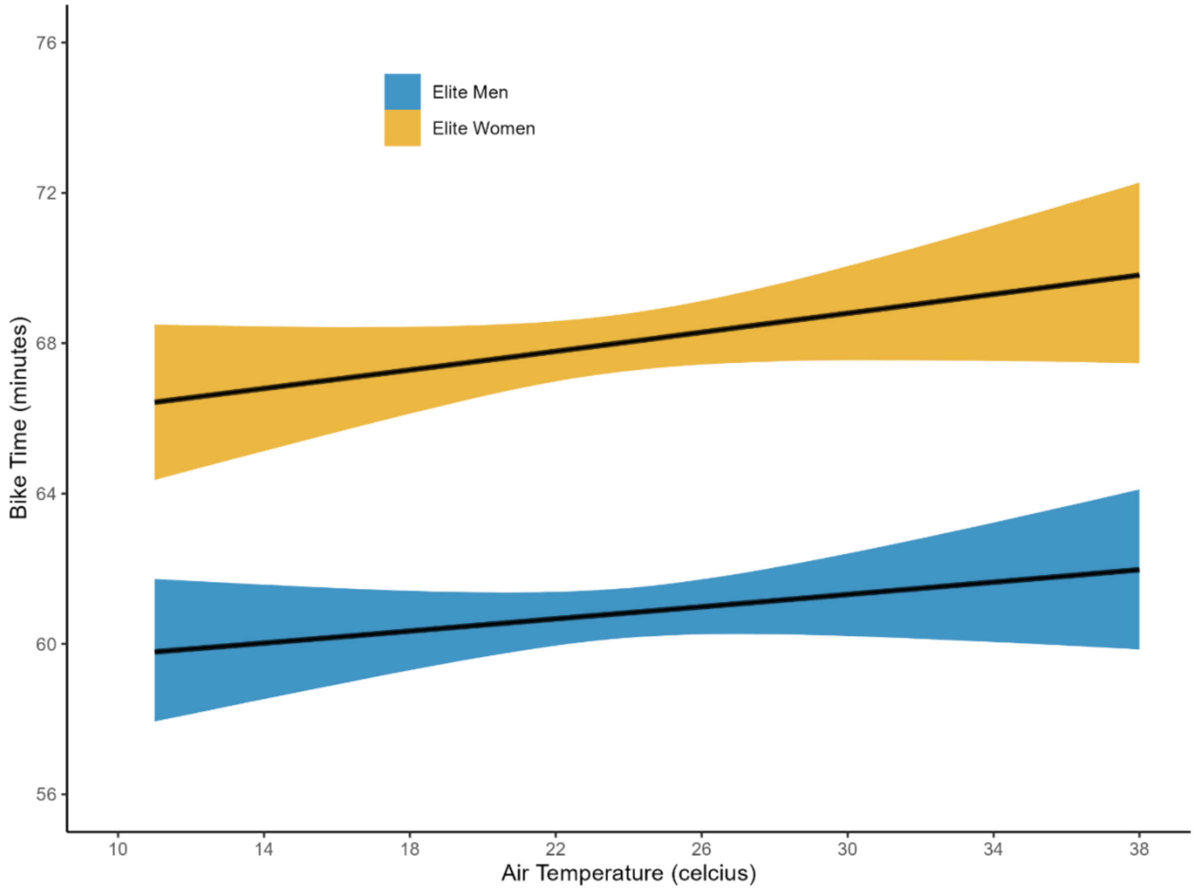

Figure 5.6. Bike time and air temperature were modelled with a linear regression model. Fast time for men and women was the coolest at ~12 °C. Performance declines are associated with an increase in temperature for men and women. The black line represents the fitted posterior mean swim time estimate, while the shaded areas are 95% credible intervals.

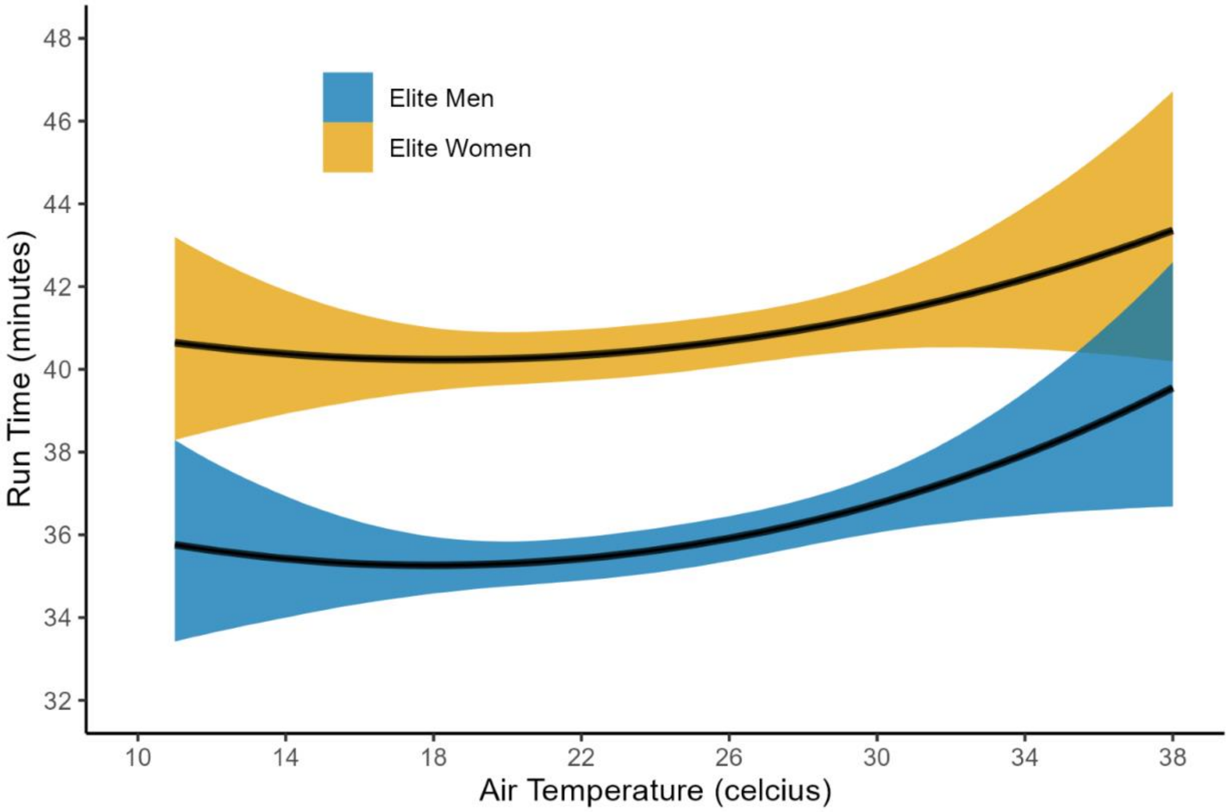

Figure 5.7. Run time and air temperature modelled with a 2nd-order polynomial regression model. Fast times were associated with cool temperatures at ~18 ℃. Performance declined greater for men than women when temperatures increased and decreased beyond ~18℃. The black line represents the fitted posterior mean swim time estimate, while the shaded areas are 95% credible intervals.

5.5 Discussion

This study investigated the effects of environmental temperatures on standard distance triathlon performances. Specifically, water temperature was explored in the context of swimming performances and ambient air temperatures in cycling and running performances. The effects of environmental temperatures on the sexes were also examined. Notably, the results showed an association between swimming times and water temperature. Interestingly, however, air temperature affected running times but not cycling times (Figure 5.6). It was also found that men and women were not affected similarly by air temperatures during the run (Table 5.2), but both were affected similarly by temperature while swimming or cycling (Figure 5.7, Figure 5.8).

Environmental temperatures appear to affect each segment of the standard distance triathlon differently. For example, water temperature was negatively associated with swimming performance times – with cold temperatures decreasing swimming performance times. Optimal water temperatures to maximize swimming performances were ~ 17 °C to 20 °C for men and women (Figure 5.7). This coincides with optional wetsuit swimming – the upper wetsuit legal temperatures (3) offer improved buoyancy and propelling efficiency, contributing to faster swimming times (J.-C. Chatard & Millet, 1996; Gay et al., 2021; Quagliarotti et al., 2023; Tomikawa et al., 2008). Performances above 20 °C remained unchanged, evidenced by 25.6 °C swimming having shown no detrimental performance effects in triathlon (Kerr et al., 1998). Further, with a relatively short time spent swimming (~20 mins), 32 °C swimming for 20 mins has only modest increases in core temperatures to 38.1 °C (Carl D, 2013). No association existed between air temperatures and cycling performance times (Figure 5.6). This ability to complete cycling without a decrease in performance is most likely due to enhanced evaporative and convective heat loss from high movement speeds (Nybo, 2010), maintaining lower thermal strain. Ambient air temperatures, however, had the greatest effect on running performance times (Figure 5.10). Regardless of temperature, running at the end of triathlon races is associated with decreased plasma volume and increased energy expenditure, potentiating further decreased performances (Guezennec et al., 1996). Hot environments further exacerbate these adverse effects through heat stress and sweat loss, affecting the thermal balance of triathletes (Bergeron, 2014), with the slowest running performance in hotter temperatures for men and women (Figure 5.9).

Disparities between male and female responses to exercise in the heat have been shown through thermoregulatory literature (Hutchins et al., 2021). Morphology, the size and density of sweat glands, and sweat output differ between men and women, as well as surface area to body mass ratio and hormonal differences, contributing to changes in metabolic heat production (Bar-Or, 1998; Gagnon & Kenny, 2012). The results indicate that women were slower across the cycling and running segments of the triathlon (Table 5.2, Figure 5.8 and Figure 5.9). Men and women were also similarly affected by temperature across each triathlon segment (Table 5.2). This does not support the hypothesis that men would be affected more by temperature in the running segment than women. Females typically have a larger surface area to body mass ratio, facilitating a more efficient heat transfer to the environment (Yanovich et al., 2020). Further, as heat is generated through the contraction of skeletal muscle, males, with generally a greater muscle mass than females, will subsequently have a higher heat production (Yanovich et al., 2020). Increased heat production may reduce overall performance, though there was no evidence of differences between men and women.

The results of this study have indicated that warm wetsuit swimming is optimal for performance times for both men and women. While there was no data to suggest whether athletes opted to use wetsuits in these optional wetsuit conditions, the benefits of reduced oxygen consumption, heart rate, and improved efficiency provide strong evidence that triathletes should opt for wetsuits when available (J.-C. Chatard & Millet, 1996; Gay et al., 2021; Quagliarotti et al., 2023; Tomikawa et al., 2008). Where we did not find evidence of an effect of temperature on cycling times for either men or women (Figure 5.9), cycling strategies have been studied to improve overall triathlon performances. Previous research to improve running in hot environments saw Stevens et al. (2013) compare cycling in hot environments with room temperature water or ice slurry ingestion on subsequent 10 km running performances. Ice slurry ingestion improved running performances by 2.5% compared to room-temperature water and could be a cost-effective strategy for athletes; however, it may be challenging to implement in races (Stevens et al., 2013).

This is the first study to examine the effect of temperature from in-race segment time. The data set includes elite-level races from The World Triathlon Organisation across eight years of competition with male and female representation across six continents (Figure 5.5). A limitation of the study was that there was no detailed information on temperature data (e.g., time of recording, humidity). This has the potential to influence the results as daily temperatures can fluctuate across the course of a triathlon race (~ 2 hours). The drastic effect of cold water (<16 °C) could warrant future investigations, further examining a minimum water temperature. Previously, water temperatures have been investigated, and the minimum water temperature was set at 13 °C by the World Triathlon Organization for a 1,500m swim. However, in the study, one elite triathlete failed to complete wetsuit swimming at 12 °C (Saycell et al., 2018). With non-elite swimmers spending more time in water, they have an increased chance of hypothermia. The dataset's minimum water temperature of 14.7 °C was associated with the slowest times (Figure 5.7). With temperatures closer to the minimum 13 °C, it would be unsurprising if athletes were placed at risk of hypothermia.

5.6 Conclusion

Overall, this chapter has shown that males are faster than females at completing the cycling and running segments, but there is no evidence that men swim faster. Decreasing changes in water temperatures were shown to slow swimming performance times for men and women. Air temperatures were observed to have no effect on cycling performance times for either sex. Increasing air temperature negatively affected running performance times for both men and women. Lastly, there was no evidence that the environmental temperatures affected men and women differently when competing in elite standard distance triathlons.

Chapter 6: General Discussion

This thesis examined the changes in the demographics, success, and characteristics of triathlon participation over 36 years and predicted the performance of elite triathletes and the effect of environmental temperature on performance times. Individually, for elite standard distance triathlons, this thesis examined 1) the participation rates, athlete demographics and country success of elite standard distance triathletes between 1986 and 2022 (Chapter 3); 2) Quantifying the probability of obtaining a podium position based on swim and cycle segment position combinations (Chapter 4) and; 3) The effect of water temperatures on swimming performance times and air temperature on cycling and running performance times (Chapter 5).

Success in Elite Standard Distance Triathlon

Chapter 3 examined the success of triathlon in reference to national federations, the outcome of race results, performance in environmental conditions and the growth of triathlon generally as a sport. Australia has experienced the most triathlon success with regard to a longitudinal view on triathlon across nearly four decades, with the most cumulative male and female wins, the highest female wins-to-start ratio, and the third-highest male ratio. Australia is a country that has had many successes through individual endurance sports (De Bosscher et al., 2006), which makes it unsurprising that it would attain such a result. However, what appears to differentiate Australia's triathlon success is the administration and delivery of the sport. Compared to the United States of America (USA), which had the second-highest total wins, three meso-level elements supported the success: development processes, development settings and delivery (Newland & Kellett, 2012). The first two levels are interesting and set Australia apart from the USA. The sport's development process in the USA 'poaches' athletes from the sub-disciplines of triathlon to transfer them to triathletes, while Australia implements direct, triathlon-specific pathways (Newland & Kellett, 2012). This leads to triathlon having a unique identity and pathways within grassroots sporting community clubs. With specificity in mind, it might be that processes like these underpin Australia's dominance in elite triathlon. Further examination of the leading countries across the same period highlights a pattern of Western, English-speaking countries. This could be indicative of more opportunities to access sport funding.

Overall, the growth of triathlon has risen to become a competitive Olympic sport and participation at the elite level. A discrepancy between male and female participation has concerned the ITU. During the 2002 ITU congress meeting (International Triathlon Union (ITU) Minutes of Congress, 2002), the decline in female participation was highlighted as an area of focus. Since the following year, female participation rates have steadily increased (Figure 2.1). A further WTO Women's Committee was formed to develop and implement policies promoting equal opportunity for women in triathlon and para-triathlon (*Women's Committee*, n.d.). It is assumed that the policies are working to make progress, as women now represent 41.9% of all elite triathletes. However, there appears to be no information on the policies implemented. Regardless, these rates are higher than elite road cycling at 22% (Current UCIuci world champions - road, 2022), similar to 10 km running athletes at 39%, although less than marathon athletes at 47% (World Rankings, 2022). Although sex parity in triathlon has not yet been achieved, the women's committee's continued progress and ongoing support have resulted in commendable advancements for the sport.

Relevant to Chapter 3 and Chapter 4, the age of triathletes was analysed in the context of performance. The age of maximum performance in elite standard distance triathlons was previously suggested to be around 27 years old for men and women (Cuba-Dorado et al., 2022). The results of our analysis support this proposal with a median podium (1st to 3rd place) age of 26 years old for men and women. However, a large interquartile range was revealed. Half of the male podium finishers were aged between 23 and 29, and the females were 22 to 30 years old. The larger variance has been documented before, suggesting that race experience is a critical component of performance (Villaroel et al., 2011). Age trajectories for the 2012 London Olympics as well as the top 10 elite men and women from 2003 to 2013 were 26 to 28 years old, 27.1 ± 4.9 (mean ± SD) years old, while females 26.6 ± 4.4 (mean ± SD) years old respectively (R. Knechtle et al., 2014; Malcata et al., 2014). This common theme of similar age of performance finishes (~ 8 to 9 years after being allowed to race) suggests that race experience is an essential factor for success for both men and women. However, the large age variability may indicate that the impact of age on performance outcomes is relatively low. This was examined in Chapter 4, where age was included as a predictor of race outcomes. Age was determined to have a relatively low effect on the probability of achieving a podium result in elite races between 2018 and 2022. The effect of age was greater in men than in women. However, the greatest probability of age on a podium result was still less than 0.1, indicating that age is a relatively incomplete metric in determining success in triathlon races. It could be further examined that the country would be used in the model for predicting success. This would then quantify the probability of success between countries with practices and strategies that aid their athletes' success. However, this was beyond the scope of the thesis.

Another interesting outcome from this thesis is the effect of water temperatures on swimming performance times and air temperatures on cycling and running performance times. Unsurprisingly, there was no effect of air temperature on cycling times, likely due to the increased cooling effects of travelling at high speeds outlined in the discussion of Chapter 5. Interestingly, however, there is a relatively large reduction in the performance times of elite triathletes who swim in cold water temperatures. The minimum temperature point for a 1,500 m swim is 13.0 ℃; however, the lowest temperature in the data set was 14.7 ℃. As per Figure 5.7, a further 1.7 ℃ reduction in water temperature would greatly decrease the overall performance times, increasing immersion time, which is associated with reducing core temperatures and increasing the risk of hypothermia. Given that the analysed population consisted of elite athletes with high levels of performance and ability, it is likely that the same water temperature points need to be examined for age group athletes.

Limitations

Several limitations arise throughout the thesis, which need to be addressed. The largest limitation of the study is the use of secondary data from the World Triathlon Organization, as it was not involved in data collection (Church, 2002). Given the use of secondary data, the accuracy and validity of the results are unclear. However, the data accessed for this thesis was publicly available from the World Triathlon Organization, which opened the data for researchers to use. The thesis focused on the elite population of standard distance triathlons and would likely not apply to other race distances of triathlons. The elite population analysed in the thesis has different rules and regulations than age-group or amateur races.

A major limitation of Chapter 4 is the inference made to the running segment, as it was not directly examined. As a positional-based approach was used, the position at the end of the running segment is also the final position and, thus, the outcome. Therefore, there were no results on the running segment, and information about the strategy and performance of triathlon running can be taken from the literature, as discussed in Chapter 4. While validation of the model improved over previous studies and included all the appropriate available data from the World Triathlon Organization, it may be challenging to validate the model externally. External validation of the model would involve separate data, which may not be available for elite standard distance races if the World Triathlon Organization provided all.

In the context of Chapter 5, there are a few limitations on the data used, which is a further limitation on the use of secondary data. Firstly, the recording time was not captured, which could influence the modelled performance – specifically regarding the running segment. As discussed in Chapter 5, the time of recording of water temperatures is known relative to the start of the race, not air temperatures or the race start time. This means cycling and running times were modelled across the same air temperatures. Given that the cycling segment can be ~ 20 minutes after the start of the race and the running segment ~ 60 minutes beyond the start of the cycling segment, air temperatures would have likely changed. Further, WBGT was not included, which could further discriminate between the temperature and humidity of environments that influence endurance performance (Vihma, 2010).

Practical Applications

Several different applications can be gained from the work of this thesis. Chapter 3 shows that triathlon has constantly increased female participation since 2003 (Figure 3.1). Based on this data, other sporting organisations may potentially use strategies and policies implemented by the World Triathlon Organization to further improve equity between males and females in sport. The largest application from Chapter 3 would be the development of triathlon as a sport in Australia. The information provided comparing Australia and the United States of America (leading countries in triathlon) shows that Australia's specific pathways may indicate their overall success in triathlons.

The performance outcomes outlined in Chapter 4 are perhaps the thesis’s most interesting and applicable information. The quantified chance of a podium finish from in-race performances provides unique evidence that the bike segment is the most important for the overall success of an individual athlete. The change in the probability of outcomes across the swim was less affected by position than the bike segment for a podium position. Therefore, this can influence strategy for athletes, indicating more benefit can be obtained by focusing on improving the bike position over the swim position.

Lastly, Chapter 5 shows optimal temperatures for performance in elite-level standard distance triathlons. This information can help schedule races through locations and times of day to promote performance. Moreover, it exhibits the change in performance across temperature ranges, which can be used to identify further areas of possible concern, including the large decrease in cold-water swimming and running performances in hot air temperatures.

Recommendations for future research

Future research should consider examining and determining the health and safety of cold-water swimming. Chapter 4 provides evidence of a drastic decrease in performance during cold water swimming in elite populations. This, however, could be exacerbated in age-group populations who are less equipped to swim in cold water, increasing immersion time and subsequent risk of hypothermia. There was again a further 1.3 ℃ before the minimum temperature for 1,500m swimming, suggesting the adverse effects of cold-water swimming can be exacerbated.

Findings from Chapter 5 show the change in probability for a podium finish from swim and bike segment positions. However, it did not consider the run in the model and inference had to be made for the run segment. Further research into quantifying the influence of the run on the outcome of elite triathlons could benefit. Given that the run position is also the final position, this may be relatively difficult, and other performance measures, such as athlete position throughout the run, may be important. However, there does not appear to be high-fidelity data to examine this at the current time. The model in our analysis included only those variables that were relevant and available. Attainment of other variables such as athlete training background (training, load, taper, resources or funding) may be able to explore new avenues of performance. Given the results of Chapter 3 and relevant research on Australian and USA triathlon pathways, including the country’s triathlon funding or coaching experience/team may again influence results.

Conclusion

This thesis examined athlete, country demographics, characteristics and success, the performance of triathletes given in race performances and the effect of temperature on segment performance times. Results suggest that Australia has had the most success in triathlon, given overall race wins and the highest relative success rate for men and 3rd highest for women. The reasons for Australia's success are outlined in the discussion of Chapter 3. Elite triathlon as a sport has progressed in its equity, with 41.9% of athletes being female.

The position of an athlete at the end of the cycling segment had more influence on the outcome of a podium position than the athlete’s position at the end of the swim segment. This thesis appears to be the first to provide a quantifying change in the probability of outcome given combinations of the top 20 swim and bike segment combinations. At the same time, the effect of water and air temperatures on swimming, cycling and running performance was examined. Evidence shows that air temperatures did not affect the performance times of male or female triathletes cycling times, while cold water temperatures negatively affected men’s and women’s swimming times. Hot air temperatures then negatively affected both male and female running times; however, men were affected more than women.

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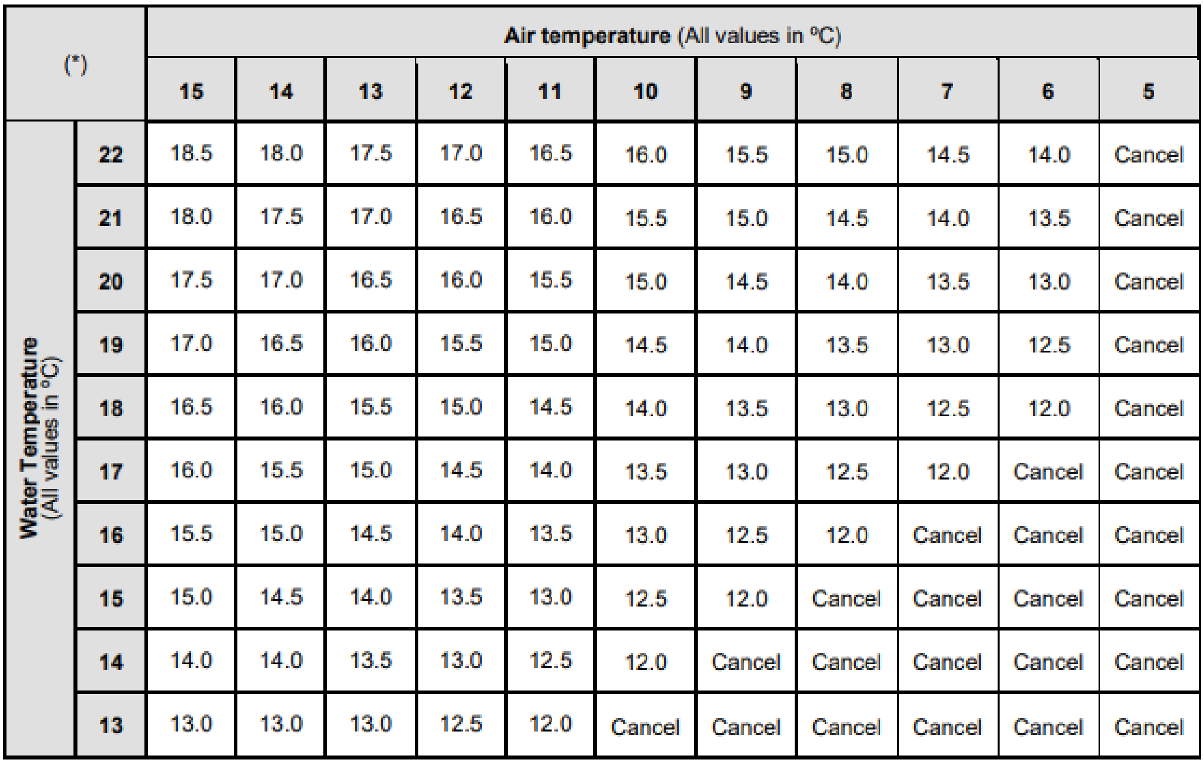
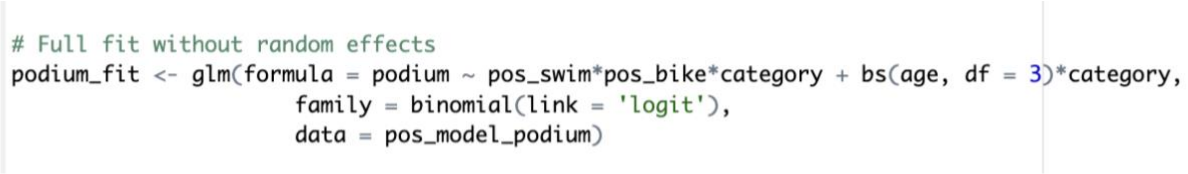
Appendix A



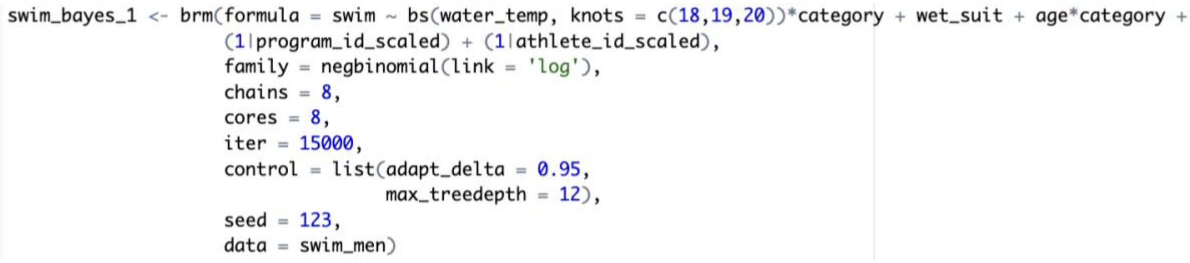
(*)		**Air temperature** (All values in °C)										
		15	**14**	**13**	**12**	**11**	**10**	**9**	**8**	**7**	**6**	**5**
Water Temperature (All values in °C)	**22**	18.5	18.0	17.5	17.0	16.5	16.0	15.5	15.0	14.5	14.0	Cancel
	21	18.0	17.5	17.0	16.5	16.0	15.5	15.0	14.5	14.0	13.5	Cancel
	20	17.5	17.0	16.5	16.0	15.5	15.0	14.5	14.0	13.5	13.0	Cancel
	19	17.0	16.5	16.0	15.5	15.0	14.5	14.0	13.5	13.0	12.5	Cancel
	18	16.5	16.0	15.5	15.0	14.5	14.0	13.5	13.0	12.5	12.0	Cancel
	17	16.0	15.5	15.0	14.5	14.0	13.5	13.0	12.5	12.0	Cancel	Cancel
	16	15.5	15.0	14.5	14.0	13.5	13.0	12.5	12.0	Cancel	Cancel	Cancel
	15	15.0	14.5	14.0	13.5	13.0	12.5	12.0	Cancel	Cancel	Cancel	Cancel
	14	14.0	14.0	13.5	13.0	12.5	12.0	Cancel	Cancel	Cancel	Cancel	Cancel
	13	13.0	13.0	13.0	12.5	12.0	Cancel	Cancel	Cancel	Cancel	Cancel	Cancel

Table 7. 1. Table adapted from the WTO competition rules (World Triathlon Competition Rules, 2023). The table represents the adjusted water temperature when air temperatures are below 15.0 and water temperatures below 15.0.



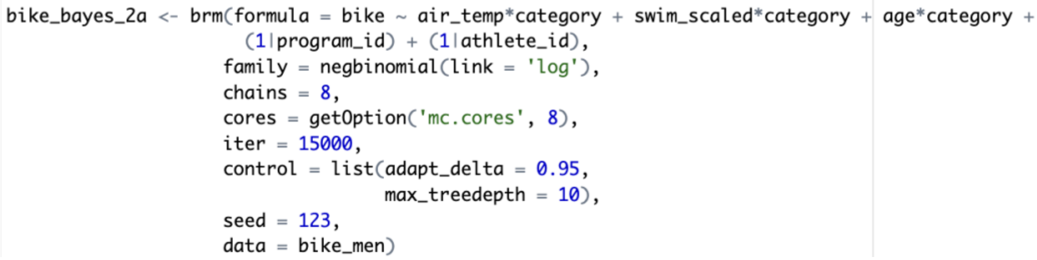
```
# Full fit without random effects
podium_fit <- glm(formula = podium ~ pos_swim*pos_bike*category + bs(age, df = 3)*category,
                  family = binomial(link = 'logit'),
                  data = pos_model_podium)
```

Supplementary 1. R code for the model of performance outcomes in Chapter 4



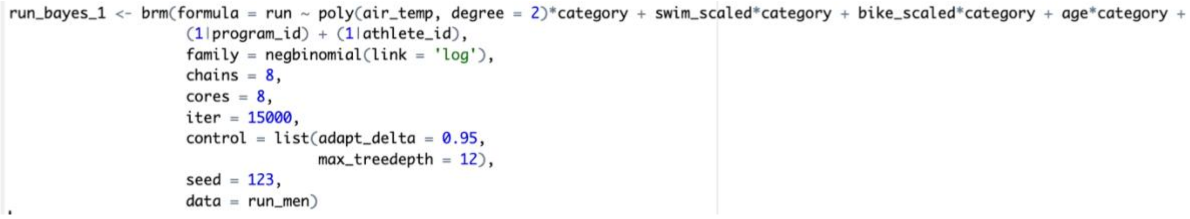
```r
swim_bayes_1 <- brm(formula = swim ~ bs(water_temp, knots = c(18,19,20))*category + wet_suit + age*category +
                    (1|program_id_scaled) + (1|athlete_id_scaled),
                    family = negbinomial(link = 'log'),
                    chains = 8,
                    cores = 8,
                    iter = 15000,
                    control = list(adapt_delta = 0.95,
                                   max_treedepth = 12),
                    seed = 123,
                    data = swim_men)
```

Supplementary 2. R code for the model of swim performance times from Chapter 5



```r
bike_bayes_2a <- brm(formula = bike ~ air_temp*category + swim_scaled*category + age*category +
                      (1|program_id) + (1|athlete_id),
                    family = negbinomial(link = 'log'),
                    chains = 8,
                    cores = getOption('mc.cores', 8),
                    iter = 15000,
                    control = list(adapt_delta = 0.95,
                                   max_treedepth = 10),
                    seed = 123,
                    data = bike_men)
```

Supplementary 3. R code for the model of cycle performance times from Chapter 5



```r
run_bayes_1 <- brm(formula = run ~ poly(air_temp, degree = 2)*category + swim_scaled*category + bike_scaled*category + age*category +
                   (1|program_id) + (1|athlete_id),
                   family = negbinomial(link = 'log'),
                   chains = 8,
                   cores = 8,
                   iter = 15000,
                   control = list(adapt_delta = 0.95,
                                  max_treedepth = 12),
                   seed = 123,
                   data = run_men)
```

Supplementary 4. R code for the model of run performance times from Chapter 5