A detailed comparison of Functional Threshold Power (FTP) versus Blood Lactate Thresholds, Ventilatory Threshold and Critical Power, proceeded by a trained model for FTP using GxT data.

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Thesis submitted for the award of Ph.D. to the Discipline of Anatomy, School of Medicine in Trinity College Dublin, 2022.

DECLARATION

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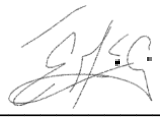
Signature:  _____ June 2022.

Summary: A detailed comparison of Functional Threshold Power versus Blood Lactate Thresholds, Ventilatory Threshold and Critical Power, proceeded by a trained model for FTP using GxT data.

The aim of the first investigation was to assess the reliability of the Functional Threshold Power test (FTP) and validity of the corresponding intensity, reportedly sustainable for 1-hour in a "quasi-steady state". Highly-trained athletes (n = 19) completed four non-randomised tests over successive weeks on a Wattbike; a 3-min incremental test (GxT) to exhaustion, two 20-min FTP tests and a 60-min test at computed FTP (c-FTP). Power at c-FTP was calculated by reducing 20-min FTP data by 5% and was compared with power at Dmax and lactate threshold (T_{Lac}). Ventilatory and blood lactate (BLa) responses to c-FTP were measured to determine whether c-FTP was quasi-steady state. Agreement between consecutive FTP tests was quantified using a Bland-Altman plot with 95% limits of agreement (95% LoA) set at ± 20 W. Satisfactory agreement between FTP tests was detected (95% LoA = +13 and -17 W, bias +2 W). The 60-min effort at c-FTP was successfully completed by 17 participants, and BLa and ventilatory data at c-FTP were classified as quasi-steady state. A 5% increase in power above c-FTP destabilised BLa data (P < 0.05) and prompted $\dot{V}O_2$ to increase to peak GxT rates. The FTP test was deemed representative of the uppermost power a highly-trained athlete can maintain in a quasi-steady state for 60- min. Agreement between repeated 20-min FTP tests was judged acceptable.

The purpose of the study presented in Chapter 4 was to determine whether Critical Power (CP) and c-FTP can be used interchangeably in a highly-trained group of cyclists and triathletes. CP was ascertained using multiple fixed load trials and c-FTP determined from a single cycling trial. Three different models for the determination of CP were initially addressed, one hyperbolic (H_{model}) and two linear (J_{model} and I_{model}). The J_{model} was identified as most appropriate for a comparison with c-FTP. The J_{model} and c-FTP were not found to be interchangeable as ANOVA detected significant differences (282 ± 53 vs. 266 ± 55 W, P < 0.001) between these indices and the associated Bland-Altman 95% limits of agreement exceeded those set *a priori*. As the J_{model} was found to be consistently higher than c-FTP, a correction

factor was posited to anticipate CP from c-FTP in this homogenous group of athletes using the mean bias (+16 W). An alternate method for assessing CP trial intensities using Dmax as a proxy for ventilatory threshold is also proposed.

The findings from Chapter 4 prompted the study reported in Chapter 5. The purpose of this phase of the research project was to derive an equation that could predict c-FTP from GxT data. Previous investigations to determine a comparable marker derived from a GxT have had limited success to date. Consequently, the investigation aimed to predict c-FTP from GxT data to provide an additional index of cycling performance. FTP has been reported to provide information not provided by a GxT. The study design facilitated a deliberate and transparent sequence of statistical decisions, resolved in part from the perspective of exercise physiology. Seventy triathletes (male n=50, female n=20) completed a cycling GxT and FTP test. Collected data (power output, blood lactate indices, VO_2peak, body mass) were analysed using stepwise regression to identify the key parameters for predicting c-FTP, and confirmed using Leave One Out (LOO) cross-validation. As a consequence of wittingly including some likely transiently highly correlated parameters on the basis of a physiological argument, the model's function is limited to predicting c-FTP. This investigation concluded the model "m-FTP" (FTP =-6.62 + 0.32 FBLC-4 + 0.42 BM + 0.46 Pmax) was the prediction model of choice.

The purpose of the final investigation (Chapter 6) was to appraise the efficacy m-FTP model in a more heterogeneously-conditioned group of rowers. Nineteen (8 female, 11 male) club-level rowers of wide-ranging abilities participated in the current study. The first rowing test was a 3-min graded incremental test (GxT) with a 1-min break between increments. The second test was the FTP test, adapted from the cycling protocol to rowing (r-FTP). Both tests were completed on the air-damped Concept2 ergometer. Computed variables m-FTP and r-FTP were highly correlated ($r = 0.99$, $P < 0.0001$), with no significant difference detected ($F = 1.13$, $P = 0.80$, repeated measures ANOVA). The Bland-Altman 95 % limits of agreement between the r-FTP and the m-FTP were -18 W to + 15 W, the $s_{y.x}$ was 7 W and the 95 % CI 0.97 to 0.99. The m-FTP derived equation was demonstrated to be resilient to both the alternate modality and heterogeneously-trained cohort. The incorporation of the m-FTP to rowing is recommended.

Acknowledgements

I would like to express my gratitude to Dr Nicholas Mahony and Dr Neil Fleming for affording me the opportunity to study in Trinity College Dublin and their continuing support and advice. I would also like to identify and thank Conor Raleigh for his expertise and participation in the investigation on Critical Power. Outside of the Anatomy Department, I also wish to thank Dr Alessio Benavoli for his statistical insight and direction. I would like to thank each athlete that gave up their time to facilitate these investigations. Additionally, I would like to acknowledge the supportive coaches and gatekeepers.

The dissertation and each step therein, is dedicated to Bernard Donne.

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List of Abbreviations

^{o}	Degree
μL	Microlitre
%	Percent
Ag	Silver
AgCl	Silver chloride
AIC	Akaike information criterion
AMP	Adenosine monophosphate
ANOVA	Analysis of variance
ANT+	Advanced and adaptive network technology (interoperable)
ATP	Adenosine triphosphate
beats.min^{-1}	Beats per minute
BLa	Blood lactate
BMI	Body mass index
BTPS	Body temperature and pressure saturated
C	Carbon
C2	Concept2 rowing ergometer
c-FTP	Cycling Functional Threshold Power
CI	Confidence interval
Cl-	Chloride
cm	Centimetre
CP	Critical Power
CPET	Cardiopulmonary exercise testing
DHAP	Dihydroxyacetone phosphate
Dmax	Load at maximal displacement
DOD	Department of Defence
e	Electron
ETC	Electron transfer chain
FAD	Flavin adenine dinucleotide
$FADH_2$	Reduced flavin adenine dinucleotide
FBLC-2	Workload associated with a fixed blood lactate of 2-mmol.L^{-1}
FBLC-4	Workload associated with a fixed blood lactate of 4-mmol.L^{-1}
FER	Force expiratory rate

FEV_1	Forced expiratory volume in 1 second
FRBL	Workload preceding a fixed rise of 1-mmol.L^{-1} in blood lactate concentration
FTP	Functional Threshold Power
FVC	Force vital capacity
g	Gram
G3P	Glyceraldehyde-3-phosphate
GLUT	Glucose transporter carrier protein
GTP	Guanosine triphosphate
GxT	Graded exercise test
h	Hour
H^+	Hydrogen ion
Ho	Null hypothesis
H_2O	Water
H_2O_2	Hydrogen peroxide
Hb	Haemoglobin
Hct	Haematocrit
H_{model}	Critical power measured from plotting power (W) against time (s) on a scatter plot, creating a hyperbolic curve (H_{model})
ICC	Inter-class correlation coefficient
I_{model}	Critical power measured from a linear transformation achieved by plotting power (W) against the inverse of time (s^{-1}).
J_{model}	Critical power measured from plotting the product of the fixed power output assessed and duration (W_{Lim} in kJ) against time (T_{Lim} in s)
IV	Independent variable
kCal	Kilocalorie
kg	Kilogram
$kg.m^{-2}$	Kilogram per meter squared
kJ	Kilojoule
L	Litre
LoA	Limits of agreement
LOO	Leave one out
LoT	Limits of tolerance

m	Metre
m-FTP	Modelled Functional Threshold Power
MCT	Monocarboxylate transporter
mg	Milligram
min	Minute
mL	Millilitre
MLSS	Maximum lactate steady state
mm	Millimetre
mmHg	Millimetre of mercury
mmol	Millimole
ms	Millisecond
N	Newton
n	Number of participants
NaCl	Sodium chloride
NAD+	Nicotinamide adenine dinucleotide
NADH	Reduced nicotinamide adenine dinucleotide
NEFA	Non-esterified fatty acid
Nm	Newton metre
NP	Normalised Power
O_2	Oxygen
OBLA	Onset of blood lactate accumulation
P	Probability (statistical)
PF	Peak expiratory flow
pH	Log_{10} Hydrogen ion concentration
pK	$Log_{10}(1/K_a)$, where K_a is the acid dissociation constant
PM5	Performance monitor 5
Pmax	Maximum power
r	Pearson product moment correlation coefficient
rad	Radian
r-FTP	Rowing Functional Threshold Power
r^2	Coefficient of determination
RBC	Red blood cell count
RER	Respiratory exchange ratio

rev.min^{-1}	Revolution per minute
s	Second
SD	Standard deviation
SEM	Standard error of the mean
STPD	Standard temperature and pressure and dry
stroke.min^{-1}	Stroke per minute
$s_{y.x}$	Root mean square of the error
TCA	Tricarboxylic acid
TEM	Technical error of the measurement
T_{Lac}	Lactate threshold
T_{Lim}	Time to exhaustion
T_{vent}	Ventilatory threshold
UKAS	United Kingdom Accreditation Service
USG	Urine specific gravity
VCO_2	Volume of Carbon Dioxide production
VE	Minute ventilation
VE/ VCO_2	Ventilatory equivalent for Carbon Dioxide
VE/ VO_2	Ventilatory equivalent for Oxygen
VIF	Variation inflation factor
VO_2	Volume of Oxygen consumption
VO_2max	Maximum volume of Oxygen consumption
VO_2peak	Peak volume of Oxygen consumption
vs.	Versus
W	Watt
WBC	White blood cell count
WKO+	Workout+
W_{Lim}	Work limit
yd	Yard
yr	Year

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List of Publications

Mc Grath E, Mahony N, Fleming N & Donne B (2019). Is the FTP test a reliable, reproducible and functional assessment tool in highly-trained athletes? *Int J Exerc Sci* **12**, 1334-1345.

Mc Grath E, Mahony N, Fleming N, Raleigh C & Donne B (2021). Do critical and functional threshold powers equate in highly-trained athletes? *Int J Exerc Sci* **14**, 45-59.

Mc Grath E, Mahony N, Fleming N, Benavoli A & Donne B (2022). Prediction of functional threshold power from graded exercise test data in highly-trained athletes. *Int J Exerc Sci* **15**, 747-759.

Mc Grath E, Fleming N, Mahony N & Donne B (2018). Validity and reproducibility of functional threshold power. *Proceedings of European College of Sports Science.* pp. 535-536 (Conference abstract).*

Mc Grath E, Mahony N, Fleming N & Donne B (2022). Prediction of rowing functional threshold power using body mass, blood lactate and GxT peak power data. *Int J Exerc Sci*, currently under peer review, submitted June 2022.

All testing and analyses were performed by the first author whilst the co-authors acted in an advisory capacity. Medical examinations were performed by Dr Nick Mahony.

Chapter 1: Introduction

1.1: General overview

In 1924, Hill *et al.* published one of the first laboratory exercise tests that sought to measure the physiological response to exercise, described as the measurement of "altering oxygen uptake and carbon dioxide output". The experiment used Douglas bags to collect expired air (Plate 1.1), "standing running" was regulated by a metronome, and heart rate (HR) data were assessed using a string galvanometer (Hill et *al.*, 1924). A staple cycling fitness test used in the current thesis was the graded exercise test (GxT), see Figure 1.1. The GxT may be performed to assess the effectiveness of the athlete's preceding training (Ghosh, 2004). Alternatively, but not mutually exclusively, the GxT may be performed with the view of informing the athlete's programme proceeding forwards. In the latter circumstances, the athlete requires a method of transferring the laboratory findings into their training routine. The cycling GxT requires the athlete to start pedalling at a low power output (W) and at specified regular time intervals increase the intensity of exercise until exhaustion. Often, heart rate (HR), oxygen consumption (VO_2) and blood lactate (BLa) data are monitored at each exercise intensity (Cheng *et al*., 1992), which in turn provides potential indicators of exercise intensity. With the arrival of the space age and the developments of miniaturisation in electronics, wireless telemetry systems were developed (Kozar, 1963). In 1977, Seppo Saynajakangas invented the first battery powered fingertip HR monitor, which was first made available commercially by his company Polar in 1978. In 1984, Polar brought the wireless Polar Sport Tester PE300 with a chest belt to market, permitting the HR response to each increment to be used to monitor training (Burke & Whelan, 1987; Mc Ardle *et al*., 1969). For example, in Figure 1.1, if an equivalent strain to 150, 180 and 210 W is targeted, the athlete should elect to ride at a HR of 138, 143 and 154 beats.min^{-1}, respectively.

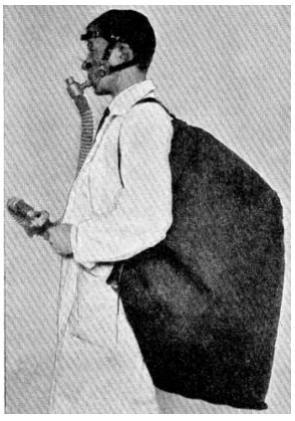

Plate 1.1: A portable Douglas bag system for exercise testing (Hill *et al*., 1924).

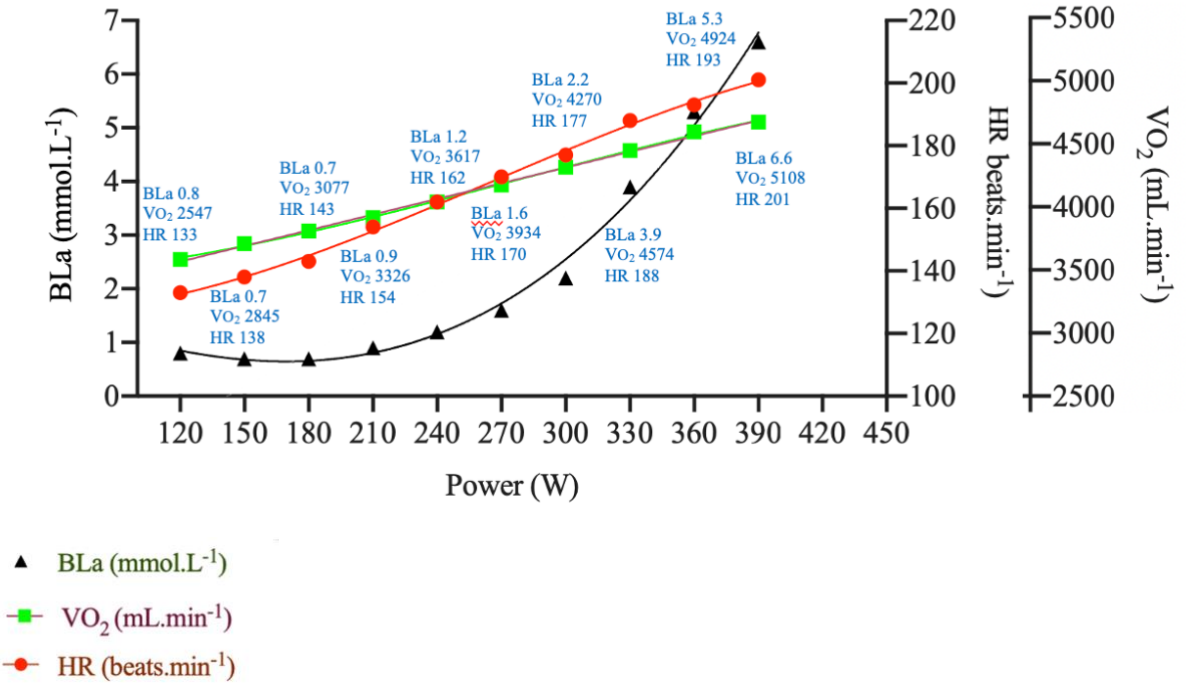

Figure 1.1: Illustrative GxT data using a 3-min step protocol. The data points for HR and VO_2 represent the average data recorded during the final minute of each step increase.

Although technological developments have been observed with the mobile measurement of oxygen consumption (Beaver *et al*., 1973), it is safe to suggest that this technology is not yet commonly available and that the index is frequently reported as being susceptible to random errors (Paton & Hopkins, 2001). Mobile blood lactate monitors have emerged as a more commonplace measure due to the ease of capillary blood sampling (Bonaventura *et al*., 2015) but should not be considered an unskilled procedure. Besides, unlike the linear response of HR and VO_2 to each increase in exercise intensity (Mazzeo *et al*., 1986), changes in BLa are often not observed during lower-aerobic exercise due to the reabsorption of lactate as a fuel (Ghosh, 2004). Therefore, in these circumstances, BLa cannot be used to monitor exercise intensity. For example, using the same power outputs as those used for HR above, it can be seen that the BLa cannot distinguish meaningfully with the individual workloads of 150, 180 and 210 W, which equates to 0.7, 0.7 and 0.9 $mmol.L^{-1}$, respectively, see Figure 1.1. On the other hand, the non-linear response of BLa to increasing power output permits the identification of a threshold intensity that defines the point when metabolic acidosis occurs (Ghosh, 2004). Although threshold is just one intensity on the exercise intensity spectrum, it is sensitive to changes in fitness and is a strong predictor of endurance performance (Conley

& Krahenbuhl, 1980). A high maximum aerobic capacity (VO_2max) is considered a prerequisite in high-performance endurance sport (Ghosh, 2004) and the threshold can be considered the trained state of the athlete (Heck *et al*., 1985; Ghosh, 2004).

More recently, bicycles have been equipped with a portable power meter, enabling the cyclist to monitor power output (W) whilst cycling (Meyer *et al*., 2005; Passfield *et al.*, 2017) and the option to complete power-based tests at home. This current thesis focuses on a power-orientated assessment called the Functional Threshold Power (FTP) test. The FTP test does not require a laboratory facility and can be performed on a stationary or an outdoors bicycle. The original bicycling FTP test commences with an atypically extensive and at times intense warm-up. The athlete then proceeds to complete a 20-min maximal effort time-trial. The 20-min average power, measured in Watt, is reduced by 5% to determine the individual's computed bicycling FTP (c-FTP), see Table 1.1; a downloaded illustrated FTP test file from a cyclist's power meter can be viewed in Figure 1.2. The c-FTP intensity is reported to the uppermost power output that can be sustained in a quasi-steady-state for 60-min (Allen & Coggan, 2010).

The authors of the FTP test were Hunter Allen and Dr Andrew Coggan. In their book / training manual, "Training and racing with a Power Meter", they described how their personal circumstances led to the development of the FTP test. Co-author Allen was reportedly an elite-level cycling coach and a former professional cyclist and co-author Coggan was working as an exercise physiologist. In their publication foreword, insight as to the genesis of Allen and Coggan's (2010) work is described; "With the introduction of a less expensive mobile power meter in the late 1990s, he (Coggan) began to collect even more data while racing and training outdoors. From what he had learned in the laboratory, he knew that this tool would benefit cyclists training in the real world by quantifying the demands of racing, by improving pacing, and even by tracking fitness changes. Soon, however, it became clear that this tool would provide many cyclists with more information than they could handle. Coggan set out to create a schema of training with a power meter". In 2003, Allen and Coggan, together with software developer Kevin Williams developed the platform "CyclingPeaks", later renamed TrainingPeaks WKO+ (CO, USA). The program on their platform claimed to "analyse workouts, compare race data, and track progress" (Allen &

Coggan, 2010). The variable c-FTP is used as the base number for the principle indices of their training platform and power-based training levels are derived from percentages of c-FTP, see Table 1.2. Within the training manual there is no apparent evidence to support these percentiles, making any further mention in the scientific literature inconsistent with publication standards. The training zones furnished by Allen and Coggan (2010) extend to in excess of 150% of c-FTP, therein it is evident that threshold is not an absolute maximum, rather the suggestion is that the intensity is the maximum "quasi-steady-state" intensity (Table 1.2). The basis of the term threshold had historically revolved around the metabolism of glucose and the consequential production of lactate (Meyer *et al.*, 2005), details of the bioenergetics of glucose and lactate metabolism are provided below. Prior to a threshold index being considered as a training guide, percentages of maximum oxygen capacity were used to identify exercise intensities (Coyle *et al.*, 1986). However, within highly-trained cohorts, VO_2max data have been reported to being insensitive to smaller differences in performance (Lucia *et al.*, 1998). Lucia *et al.* (1998) compared professional cyclists (n = 25) with elite cyclists (n = 25) and reported no significant differences in VO_2max data between the groups expressed as absolute intakes (4.9 ± 0.4 and 5.1± 0.6 $L.min^{-1}$ respectively, $P > 0.05$), or when subsequently scaled to body mass (72.9 ± 5.7 and 73.9 ± 7.4 $mL.kg^{-1}.min^{-1}$ respectively, $P > 0.05$). However, significant differences were apparent between group peak power data (429 ± 32 and 466 ± 31 W respectively, $P < 0.001$) and peak absolute BLa scores ($P < 0.05$).

Table 1.1: Test protocol for assessing an athlete's FTP (reproduced with permission from Allen & Coggan, 2010)

	Duration	Description	% c-FTP
Warm-up	20-min	Endurance pace	65
	3 by 1-min	Fast pedalling,	Not applicable
	with 1-min recoveries	100 $rev \cdot min^{-1}$	
	5-min	Easy riding	65
	5-min	Time-trial	Maximum effort
	10-min	Easy riding	65
FTP test	20-min	Time-trial	Maximum effort
Cool-down	10 to 15-min.	Easy riding	65

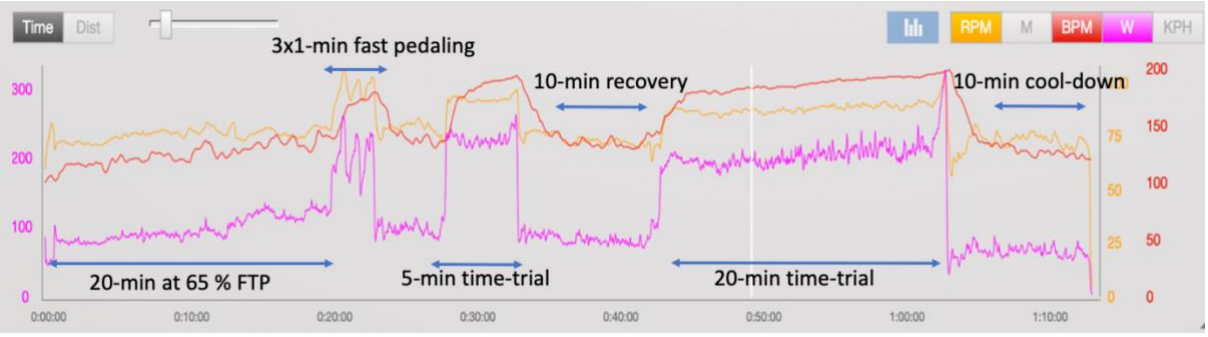

Figure 1.2: An illustrative FTP test data file recorded using Garmin Vector 3 pedals, paired with the Edge 1030 device, and connected using ANT+ wireless sensor technology.

Table 1.2: Power based (% of c-FTP) training intensities suggested by Allen and Coggan (2010)

Level	Description	% c-FTP
1	Active recovery	<55
2	Endurance	56-75
3	Tempo	76-90
4	Lactate threshold	91-105
5	VO_2max	106-120
6	Anaerobic capacity	121-150
7	Neuromuscular power	N/A

The literature abounds with research comparing varying calculations of "threshold" (Faude *et al.*, 2009). Indices predating FTP with current citation counts according to a Google Scholar search engine for perspective include; 698 citations for lactate threshold (Beaver *et al.*, 1986), 499 citations for Dmax threshold (Cheng *et al.*, 1992), 1366 citations for 4 $mmol.L^{-1}$ threshold (Heck *et al.*, 1985), 1149 citations for maximal lactate steady state (Kindermann *et al.*, 1979), 1023 citations for the onset of plasma lactate accumulation (Farrell *et al.*, 1979) and 394 citations for Critical Power (Poole & Gaesser, 1985). The varying names for a threshold demarcation reflect the different data collection methods, the varying physiological markers of metabolic stress (oxygen consumption, heart rate and blood lactate) and the diverging data analysis formulae (Cheng *et al.*, 1992). Regardless of these numerous

extensively researched indices of threshold, Allen and Coggan (2010) wittingly coined the new term "Functional Threshold Power" (FTP). Poole *et al.* (2020) describe the various thresholds as "tipping points that establish boundaries between distinct domains of physiological control, such as moderate → heavy → very heavy/severe domains of exercise intensity". Understandably, many researchers argue the merit of one test versus alternate tests. Cheng *et al.* (1992) state that Dmax determinant of "threshold" is preferable as its calculation can reportedly be applied to both BLa and ventilatory indices. Poole *et al.* (2020) contrastingly argue that knowing an equivalent marker of the moderate / heavy domain is less relevant to athletic performance than the "tipping point" between the "heavy / severe boundary" associated with CP (Chapter 4). This thesis project reports the finding of our own original research relating to both FTP and a selection of already validated tests, to borrow an expression from the Royal Society, "verification by experimentation". Spontaneous questions relating to a "new', popular and unproven test provide the central questions of the current thesis. Is the FTP test scientifically valid? Is the FTP test a reliable test? Is c-FTP the same intensity as another pre-existing test? Can the FTP test protocol be applied to sports other than cycling?

There are a very limited number of publications on c-FTP according to a recent scoping review (Mackey & Horner, 2021). Consequently, there was no strict limitations on the search terms used within electronic databases to cull peer-reviewed papers on FTP (Arksey & O'Malley, 2007). Bibliographies of studies were also checked for articles that may have been missed by electronic databases. Grey literature was omitted on the basis of the content not being peer reviewed. The literature review was an iterative process that continued throughout this research project. Retrieved published articles appeared concomitantly with published material from the investigations in the current thesis. Borszcz *et al.* (2018) were the first to investigate the validity of c-FTP in a trained cohort of cyclists. Their investigation used the associated limits of tolerance (LoT) at c-FTP to determine the test's validity. Having completed an FTP test to predict c-FTP, a projector was used to generate an avatar pacer and the participants were requested to keep pace for as long as possible. The participants (n = 23) completed 50.9 ± 15.7 min of the projected 60-min. The investigators identify the completion of 45 to 60-min at c-FTP as a validation of c-FTP, rather than a specific 60-min epoch. The study also required the cyclists to complete an un-paced 60-min time-trial. The

average power of the 60-min time-trial was compared with that of the predicted 60-min power derived from the 20-min FTP time-trial test. The advantages and disadvantages of an uncontrolled pacing study-design may be worth consideration given the power output at c-FTP is reportedly at the precipice of anaerobic metabolism, and exceeding this steady-state boundary may be irrevocable (Fukuba & Whipp, 1999). The importance of appropriate statistical assessment is illustrated as the authors discard the finding that there were no significant differences ($P > 0.05$) between c-FTP and actual 60-min trials (236 ± 38 and 231 ± 33 W, respectively). Instead, Borszcz *et al*. (2018) advised caution when predicting 60-min power from FTP tests, as a consequence of the large limits of agreement detected between variables (-42 to 32 W). Despite the reported utility of completing a 60-min time-trial, the relatively long duration of this test limits its application, as the effort requires a high-degree of concentration (MacInnis *et al*., 2018). This inaugural FTP investigation by Borszcz *et al*. (2018) reported that they endeavoured to recruit both male female participants but were unsuccessful recruiting any female participants.

Two separate investigations assessed the repeatability of the 20-min portion of the FTP test. MacInnis *et al*. (2018) reported no significant differences between repeated tests ($P = 0.4$) using paired Student's T-tests; Lillo-Bevia *et al*. (2022) "showed a very high consistency and low bias" reporting ICC = 0.983; CV = 1.2% and 95% limits of agreement (LoA) = -11 W and 6 W with a mean bias of -2 W. MacInnis *et al*. (2018) reported a limited number of study participants (n = 8 male trained cyclists), whilst Lillo-Bevia *et al*. (2022) reported on male cyclists and triathletes (n = 11) aged between 22 to 49 yr. Neither investigation included the extensive, and, in parts, intense recommended warm-up outlined in Table 1.1. Lillo-Bevia *et al*. (2022) warmed-up their participants for 5-min at 80 to 90% of (ventilatory) threshold; MacInnis *et al*. (2018) instructed the participants to complete a self-paced warm-up with the stipulation that a 1-min interval at their self-anticipated trial power be included. The omission of the prescriptive and atypical FTP warm-up (MacInnis *et al*., 2018) limits comprehensive conclusions regarding the FTP tests reliability.

Lillo-Bevia *et al*. (2022) also assessed the relationship between c-FTP and the power output associated with maximal lactate steady state (MLSS) and ventilatory threshold. MLSS was identified on the basis of the highest power output (W) at which blood lactate concentration

increased by < 1 mmol.L^{-1} between the 10th and 30th minute of exercise. Repeated measures ANOVA detected significant differences between c-FTP and MLSS ($P < 0.001$). Lillo-Bevia *et al*. (2022) concluded that MLSS could best be predicted from a 20-min cycling trial-trial using the equation; MLSS = 0.7488 x 20-min power (W) + 43.24, albeit derived without the recommended FTP warm-up, see Table 1.1, and without the 5 % reduction in the 20-min average power required to predict c-FTP. The basis of a predictive equation likely requires further scrutiny due to the limited participants that were used to train the predictive equation (n = 11) and the absence of an assessment of the trained equation. The issue of limited study participants is not restricted to investigations comparing load at c-FTP with load at MLSS. The same issue arises with the gold standard format of calculating CP, a protocol requiring multiple fatiguing exercise bouts. Jones *et al*. (2010) concluded that the interruption to training and considerable fatigue associated with these multiple test protocols were likely influences on participants volunteering for testing. The awareness of researchers of this issue was illustrated by Borszcz *et al*. (2018) in a study that sought to compare c-FTP with MLSS. To reduce the burden of additional testing on enlisted athletes, an alternate single surrogate measure of MLSS was used: namely, the load (W) associated with a 1.5 mmol.L^{-1} increase above the point of minimum ratio between lactate and work rate in a GxT. CP is a threshold that represents the uppermost exercise intensity that a cyclist can maintain without the necessity for maximum oxygen uptake with an associated LoT of 30-min (Poole & Gaesser, 1985). With relatable time frames and similar described intensities to FTP, Morgan *et al*. (2018) compared c-FTP and CP in a group of twelve male cyclists. Paired Student's T-tests detected no significant differences between c-FTP and CP ($P = 0.57$), however, the investigators highlighted that the percentage limits of agreement (+11 to -13 %) were too large to consider these variables as equivalent.

Jeffries *et al*. (2021) investigated the relationship between c-FTP and the laboratory based indices: lactate threshold (T_{Lac}) as the point of intersection between two linear splines; Dmax threshold as the point on the BLa-exercise intensity curve at maximal distance from a line connecting starting and finishing intensities; modified Dmax threshold as the point on the BLa-exercise intensity curve at maximal distance from a line connecting T_{Lac} and finishing intensities; the load associated with a fixed blood lactate of 4-mmol.L^{-1} (FBLC-4) and the individual anaerobic threshold defined as the load associated with a BLa concentration 1.5

mmol.L^{-1} above the minimum ratio between BLa and work rate. The structured warm-up of the FTP test, see Table 1.1, was omitted and a 10-min warm-up at 100 W followed by 2 by 20-s maximum efforts were instead completed. The GxT trial was completed using the electronically braked CompuTrainer (RacerMate One; RacerMate, WA, USA) which has been reported to be reliable (SEM range was 0.5 to 0.7 %; CV ranged 0.2 and 0.9 % across a cadence range of 80 to 100 rev.min^{-1}), however, measurement errors have been documented within the range of 2.9 to 4.4% and 3.3 to 3.9% for the first 6-km and 10-km, respectively, of longer time-trial assessments (Jeker *et al.*, 2021). Jeffries *et al.* (2021) reported that c-FTP (266 ± 42 W) was significantly different to loads at Dmax (221± 25 W, P = 0.001) and modified Dmax (238 ± 32 W, P = 0.008). However, the results are difficult to interpret as a consequence of the incongruent GxT construct versus the data analysis methodology. The GxT commenced at 120 W and increase at a rate of 30 W every 4-min until the end of a stage that produced a BLa greater than 4 mmol.L^{-1}. The cyclist then proceeded to rest for 10-min prior to a ramp test commencing at 150 W and increasing at a rate of 30 W.min^{-1}. Jeffries *et al.* (2021) parsed their GxT and ramp data, using the GxT data to estimate their laboratory based BLa indices. The threshold marker Dmax is dependent on the initial and final lactate and associated power data (Newell *et al.*, 2007; Cheng *et al.*, 1992), the latter of which was not the maximum power as the researchers stopped their GxT at a BLa of 4 mmol.L^{-1}. The same disparity exists with respect to the threshold "modified Dmax", which is also calculated from the maximum distance from a line connecting the finishing intensity, the distinction between Dmax and modified Dmax being the straight line in the modified Dmax commences from the BLa datum point that precedes a 0.4 mmol.L^{-1} increase in lactate above baseline data (Bourdan, 2013). c-FTP was also reportedly significantly different compared to T_{Lac} (236 ± 32 W, P = 0.02), citing Lundberg *et al.* (1986) which used a log-log transformation of data to yield two linear segments, however, neither their reported data nor the graphed data were transformed. There was no significant difference detected between c-FTP and FBLC-4 (268 ± 30 W, P = 1.000), but the tabulated 95% limits of agreement for FBLC-4 and c-FTP were 73 to -24 W, with a potentially incorrectly reported mean bias of 2.9 W. The context of a clinician establishing *a priori* limits of agreement that are pertinent to the context of the role of the data is discussed in Chapter 3 of the current thesis. The laboratory indices selected by Jeffries *et al.* (2021) were all calculated using the software package Lactate E (Newell *et al.*, 2007). The accessibility of software and concurrently available threshold indices is

undoubtedly a positive, however, computerisation of calculations and subsequent usage for scientific comparison still requires data to be prepared in concordance with the fundamental calculations in order for results to be scientifically meaningful.

1.2: Bioenergetic models

In 1952, Turing developed a model for chemical substances reacting together and diffusing through tissues (morphogenesis). The system is described as "originally quite homogeneous, may later develop a pattern or structure due to an instability of the homogeneous equilibrium, which is triggered off by random disturbances". Turing (1952) proceeded to describe the derived mathematical model as,

"a simplification and an idealisation, and consequently a falsification".

The Department of Defence (DOD) describe a model as "a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process" (Department of Defence, 1998). More specifically, the DOD (1998) described an analytical model as the "abstraction of a system based on probability theory, using a formal system consisting of equations used to estimate the performance of the system". The mathematical models used herein have clearly defined structures, have been validated by a standard (with the exception of FTP at the time of writing), and represent human energetics. The description by Turing (1952) of models representing a "falsification" is addressed in the current thesis by combining statistical analyses with understood physiological responses. For example, in Chapter 5, stepwise regression was used to analyse data, as results are furnished in a detailed and parsed format, allowing the mathematical results at each juncture to be appraised from the purview of science. Another example, as there is no perfect gold standard for threshold, the true value is unknown. The Bland and Altman method was adapted in Chapters 3, 4, 5 and 6 to determine LoA and bias (Bland & Altman, 1986). The degree of agreement between c-FTP and the alternate threshold indices listed above and interpreted from the perspective of, "We want to know by how much the new method (c-FTP) is likely to differ from the old; if this is not enough to cause problems in the clinical interpretation we can replace the old method by the new or use the two interchangeably" (Bland & Altman, 1986).

A model for bioenergetics may provide information that is already measurable in a laboratory domain but access may not be possible. The concept that the simple FTP test could replace the necessity of a laboratory resource was a catalyst for the current thesis. Chapter 3, 4 and 6 explore this possibility from the vantage point of replacing a validated laboratory threshold measure with c-FTP. A model may also be the approach of choice where a prediction of competitive performance is required, a role that a single laboratory index may not fulfil. The prediction of performance in the field is a major focus of Chapter 4, which compares c-FTP with Critical Power (CP). The relationship between intensity of effort and the effort duration (LoT) has been highlighted as early as 1925 by Hill, therein the publication presented a graphical illustration of the hyperbolic relationship of world records versus time (Figure 1.3), which has formed the basis of many ensuing models. Regardless of the rigours of model design, any models predictive capacity is inevitably flawed. Preceding any comparisons between c-FTP and CP, three methods of determining CP itself were applied to the same data set, see Chapter 4. The determination of the "best model" to be compared with FTP was on the basis of the least error (root mean square of the error) rather than zero-error. Moreover, prior to applying the three potential models to the CP data, an awareness of the source of potential error between the models requires attention. For example, CP was derived from both linear models and a hyperbolic line. The linear models are not necessitated to go directly through a specific datum point, whereas the hyperbolic line is required to dissect the final datum point (Bishop *et al.*, 1998; Gaesser *et al.*, 1995). Commonly known physiological principles may be knowingly ignored, for example that exercise can continue *ad infinitum* (Figure 1.4), or where variates are held constant with the view of enhancing the fit of a particular model (Morton, 2006). Morton (2006) provides an illustration of a theoretically (and untrue) limitless supply of energy from aerobic sources and a fixed energy supply from anaerobic source in the form of two vessels (Figure 1.4). The imperfections of such models should be recognised and the magnitude of the error interpreted to determine the models inclusion or possible role in a particular circumstance. This illustrative "hydraulic model" forms the basis of CP and permits the determination of the ancillary markers termed W prime (W′ is an index of anaerobic capacity, see Chapter 4) the function of identifying upper-limits of pacing strategies. The determination of the functionality of a model herein is viewed principally from the perspective of the magnitude of the errors and the context of the models use.

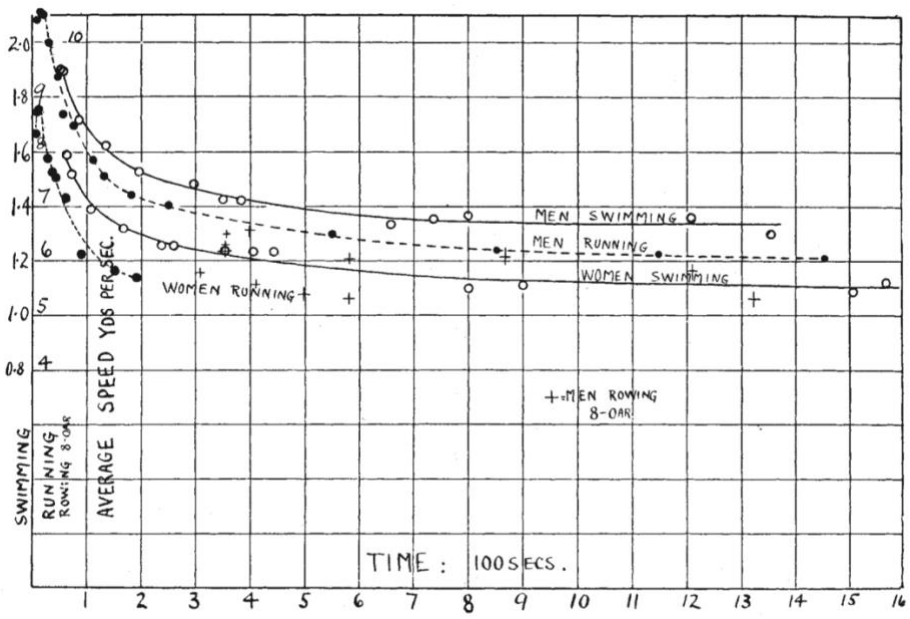

Figure 1.3: World records for men and women swimming and running: Average velocity (yards.s^{-1}) versus time (s) from Hill (1925).

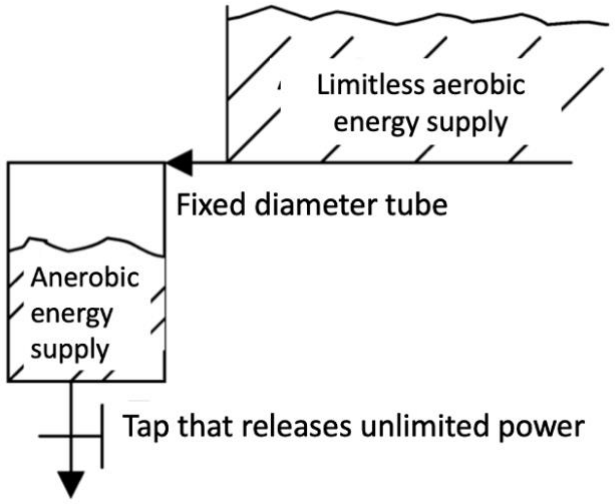

Figure 1.4: The CP concept as a hydraulic model modified from Morton (2006).

Of course, errors are not limited to predictive models. A human performance laboratory will likely measure indices including VO_2, blood lactate concentration and HR data during continuous or graded incremental exercise assessment; the target typical error of these respective measures is < 0.15 L.min^{-1}, < 0.2 mmol.L^{-1} and < 5 beats.min^{-1}, respectively (Tanner & Gore, 2013). These errors are further compounded with the impact of

environmental conditions and biological variations including heat (Sawka *et al.*, 2015), hydration (England *et al.*, 1984) and nutritional status (Jeacocke & Burke, 2010). High standards of testing can mitigate these errors but cannot remove the sum of errors. Repeat tests can mitigate reliability issues by a factor of $1/\sqrt{(n)}$ (Pyne, 2013), however, this resource is likely atypical. Often, once a laboratory test is completed, a model is employed to derive specific findings, for example a threshold index or a specific datum point that was not measured and requires interpolation or extrapolation, guided by a model's projection of a relationship between a dependent and independent variable. In the proceeding chapters, the role and limitations of models applied to assessed physiological data are reviewed. To recapitulate, even a forensic physiological approach to human bioenergetics contains errors and "micro" laboratory data is habitually modelled to discern end-test results. Herein, the efficacy and subsequent projected effectiveness of testing is appraised statistically. The statistical measures include calculations that are discerning to the smallest worthwhile change. The statistical design of each investigation is explained within each discrete study discussion.

1.3: Overview of energy pathways

1.3.1: Adenosine triphosphate

The macronutrients carbohydrate, protein and fat are used to provide energy with varying usefulness. The energy from these macronutrients cannot be transferred directly into cells for energy; rather it is converted to the energy rich compound adenosine triphosphate (ATP). This ATP nucleotide molecule is a five-carbon sugar bound to three inorganic phosphates. Energy can be stored as potential energy or transferred to exercise. One ATP molecule can be broken down for energy into one phosphate (usual) or two phosphates (infrequent), leaving the residual molecule as adenosine diphosphate (ADP) and adenosine monophosphate (AMP), respectively. The processes by which an atom or a molecule loses or gains a high-energy electron is termed oxidation (donate electrons) and reduction (accept electrons), respectively. These coupled reactions form the basis of energy transfer from food to ATP. In relation to sports competition, there is a limited store (2.43 mmol per 100g dry muscle) of ATP available in skeletal muscle (Hultman *et al.*, 1967) that can provide energy immediately without oxygen. Moreover, approximately 40% of these stores cannot be accessed as they are retained as an ATP reserve (Hultman *et al.*, 1967; Marcinek *et al.*, 2010). The molecule

ATP can however be resynthesised by combining with creatine phosphate (CP). This resynthesised source of ATP will only sustain exercise for approximately 15 to 30-s, insufficient for extensive high-intensity endurance exercise.

1.3.2: Glycogenolysis and glycolysis

Carbohydrate that is being transferred in the blood is called glucose, whereas that which is stored in tissues is termed glycogen. Both glucose and glycogen can be broken down in the cytoplasm of a cell in processes called glycolysis and glycogenolysis. Normally, if glycogen provides the initial substrate, then "anaerobic glycolysis" or "rapid glycolysis" will ensue. On the other hand, where glucose is the initial substrate, typically "aerobic glycolysis" or "slow glycolysis" occurs (Mc Ardle *et al*., 2015). Glycolysis principally occurs in the watery medium of the cell outside of the mitochondrion. Glucose is transferred into the muscle using a glucose transporter carrier protein (GLUT), of which there are thirteen (Richter & Hargreaves, 2013). If an athlete is at rest and glucose levels are normal (approximately 90 $mg.dL^{-1}$), glucose will be transported by GLUT-1 complex that resides in the cell membrane (Mc Ardle *et al.*, 2015). Alternatively, when exercising (muscles contracting) or having consumed a high carbohydrate meal, the majority of glucose will be transported using the GLUT-4 complex (Richter & Hargreaves, 2013). The GLUT-4 act as portals in the cytoplasm through which glucose enters the cell. The GLUT-4 action is mediated through a second messenger, which permits migration of the intracellular GLUT-4 protein to the surface to promote glucose uptake, allowing active muscles to absorb glucose without insulin (Mc Ardle *et al*., 2015).

The process of garnering energy from glycolysis commences with an "energy investment" of either one or two ATP molecules, the former if the molecule is derived from glycogen and the latter if the starting point is glucose. The phosphate furnished by ATP provides an associated charge that traps the glucose in the muscle cell (Plowman & Smith, 2014). Also, the ATP molecule enables the separation of the single six carbon glucose molecule into two identical three-carbon component atoms; dihydroxyacetone phosphate (DHAP) and glyceraldehyde-3-phosphate (G3P). The DHAP is subsequently rearranged to G3P. At the end of glycolysis, each G3P has a net gain of just two ATP molecules when originating from glucose and three ATP molecules when derived from a glycogen (Plowman & Smith, 2014).

The reaction to produce these ATP molecules is described as "substrate level phosphorylation". In substrate-level phosphorylation, ADP receives a P_i directly from a substrate without any oxidation occurring. Oxidation reactions transfer oxygen atoms, hydrogen atoms, or electrons. A loss of electrons always occurs in oxidation reactions, with a corresponding net gain in valence (Mc Ardle *et al.*, 2015). A schematic representation of glycolysis can be viewed in Figure 1.5.

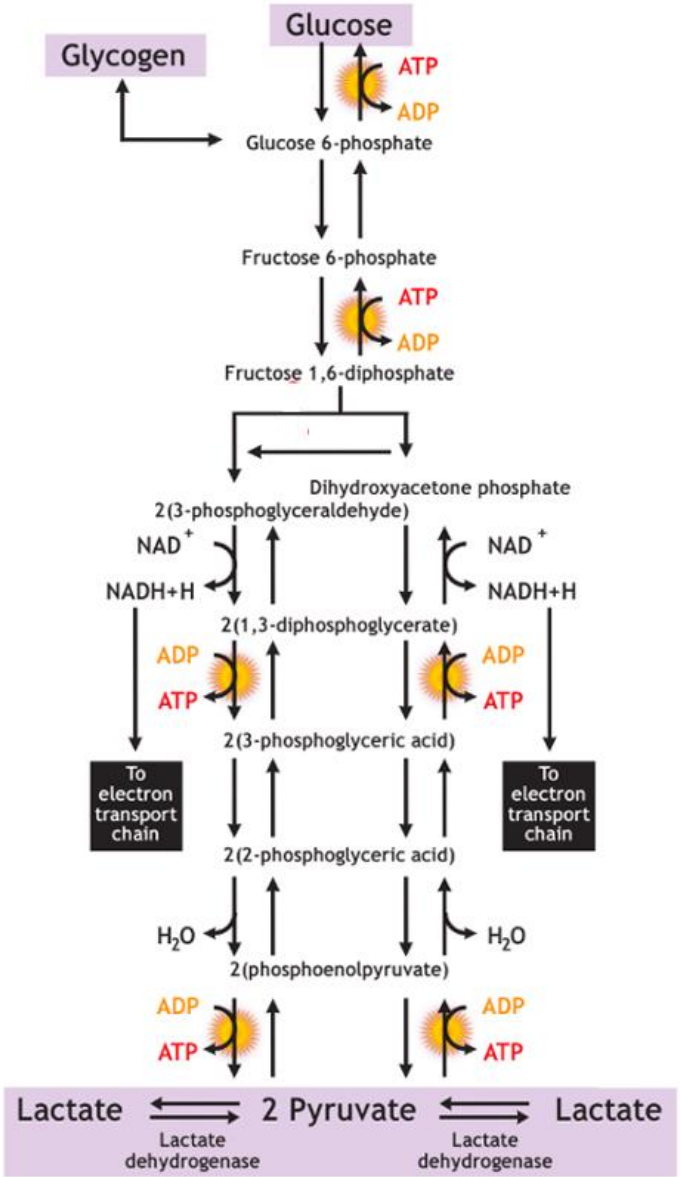

Figure 1.5: Schematic of the process of glycolysis, sourced with permission from Mc Ardle *et al.* (2015).

Specific dehydrogenase enzymes catalyse the release of hydrogen from a substrate, utilising the co-enzymes nicotinamide adenine dinucleotide (NAD^+) and flavin adenine dinucleotide (FAD) to transfer the associated high-energy electrons. The NAD^+ gains one of the two hydrogen ions (becoming NADH) and the second hydrogen appears in the cell fluid. The FAD accepts both hydrogen ions becoming $FADH_2$. During "aerobic glycolysis", it is the NAD molecules (two) that are reduced to NADH + H^+, which have the capacity to produce more ATP in the process described later called the "electron transfer chain" (ETC). The FAD serves as an electron acceptor later in the process described below as the tricarboxylic acid (TCA) cycle. If the hydrogen cannot enter the ETC, the hydrogen from this NADH + H^+ will instead combine with pyruvate to temporarily form lactate, see Figure 1.6. From a measurement perspective, it is noteworthy, there is no waste product CO_2 from glycolysis. When totalling the net gains from glycolysis, the estimate should include: ATP; potential ATP derived from NADH + H^+ and $FADH_2$ transferred to the ETC; and either two pyruvate or lactate molecules.

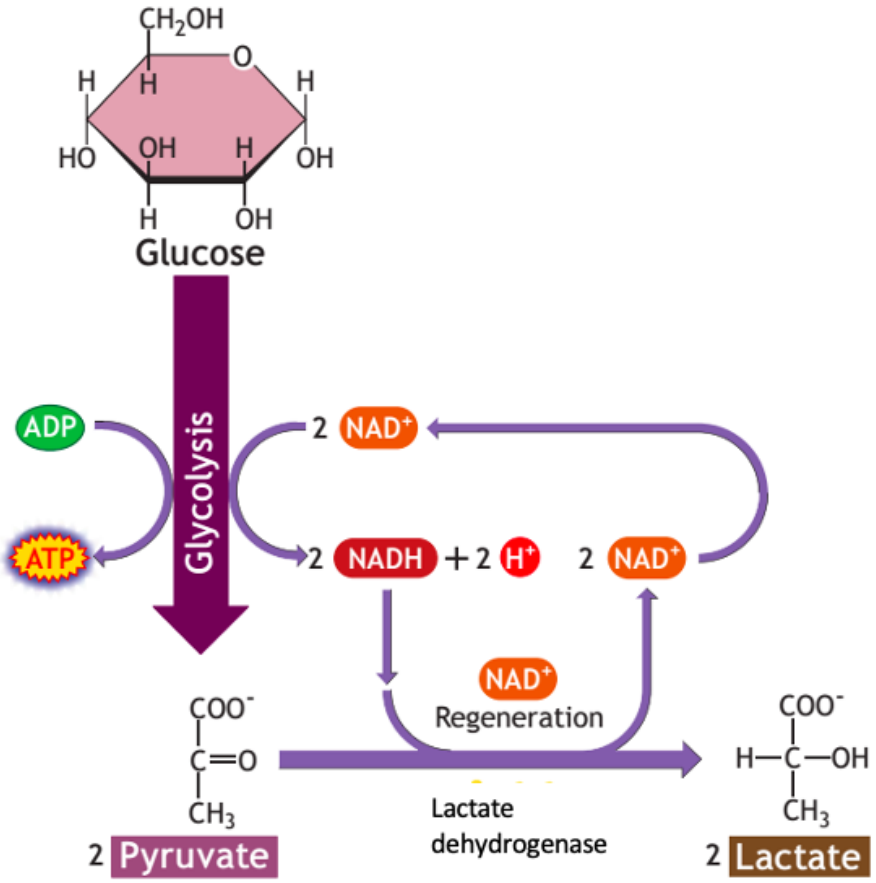

Figure 1.6: Illustrated formation of lactate when hydrogen from NADH combines temporarily with pyruvate. This frees up NAD^+ to accept additional hydrogen ions generated in glycolysis, sourced with permission from Mc Ardle *et al*. (2015).

1.3.3: Formation of Acetyl Coenzyme-A

The conversion of pyruvate to Acetyl Coenzyme-A (Acetyl CoA) occurs in the mitochondria. Mitochondria are sub-cellular bean-shaped organelles that have both an inner and outer membrane. The inner membrane can be observed to have folds called crista which markedly increases the available surface area. Protruding through these cristae is ball and stalk complexes. Both the ball and stalk, and cristae portions support the production of ATP. The inter-membrane space, between the inner and outer membranes, contains deoxyribose nucleic acid (DNA) that allows mitochondria to replicate in response to exercise stress (Voltarelli *et al*., 2020). Waste CO_2 is first released when pyruvate is converted to acetic acid. The majority of this CO_2 combines with water and is expelled through expiration, the remaining CO_2 (approximately 20%) combines with blood proteins such as haemoglobin (Osnes & Hermansen, 1972). The acetic acid combines with Coenzyme A, producing two further NADH + H^+ and the formation of acetyl CoA. The next step of energy production process sees acetyl CoA combining with Oxaloacetate marking the commencement of the TCA cycle.

1.3.4: The Tricarboxylic Acid (TCA) cycle

The primary function of the TCA cycle is to generate H+ for the final stage of ATP production, namely the ETC. During this cycle, six NADH + H+ and two $FADH_2$ are transferred to the ETC. The TCA cycle produces just two ATP (or more precisely guanosine triphosphate, similar to ATP) molecules by substrate-level phosphorylation. The TCA cycle is termed a bioenergetic cycle because oxaloacetate from the first TCA reaction is retained and can combine with a new acetyl fragment to restart the process. The integrated processes of glycolysis and the TCA cycle can be viewed in Figure 1.7.

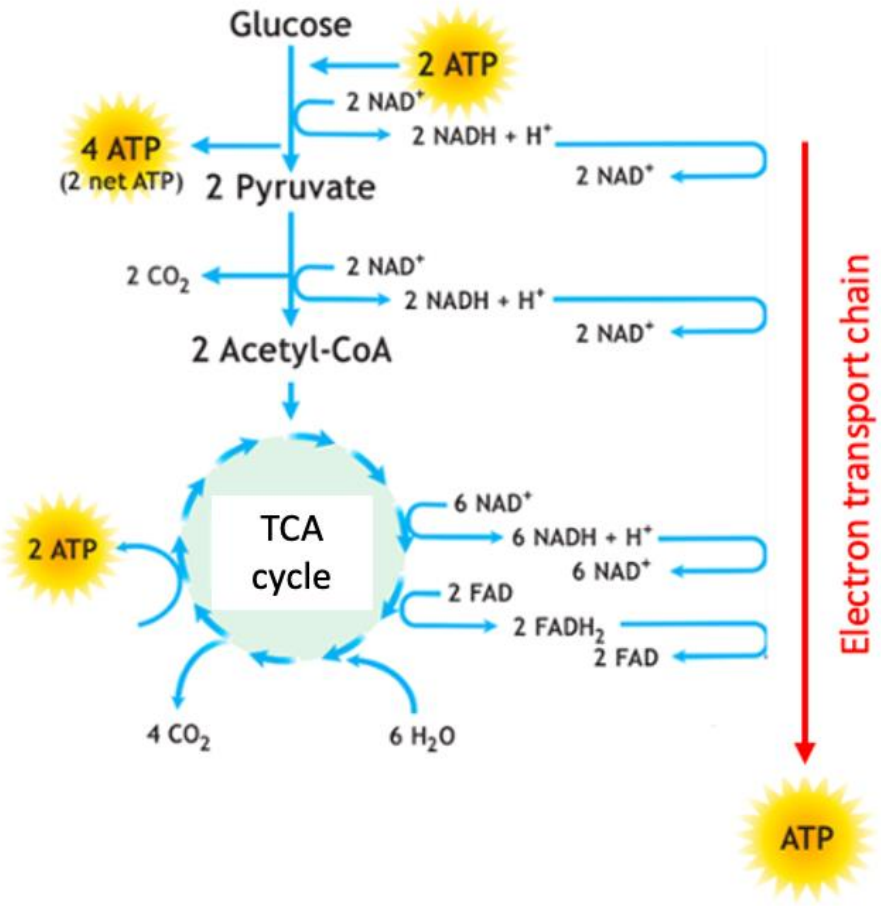

Figure 1.7: The integrated processes of glycolysis and the TCA cycle, sourced with permission from Mc Ardle *et al*. (2015).

1.3.5: The electron transfer chain

The electron transport chain synthesises ATP using the potential energy derived from an electrochemical gradient. This electrochemical gradient is created by pumping the H+ from NADH and $FADH_2$ from the inner mitochondrial membrane into the intermembrane space (mitochondrion are bound by two membranes), see Figure1.8. The proceeding chemiosmotic coupling of ADP and Pi is achieved using the energy from the reverse flow of these protons back across the inner membrane at three sites. Note, three ATP molecules are produced from NADH + H^+, whereas two ATP molecules are derived from the carrier $FADH_2$, which as stated above, enters the ETC at a later stage. The average number of ATP produced per NADH and $FADH_2$ is 2.5 and 1.5 ATP molecules, respectively. The ETC produces a theoretical net gain of 32 ATP molecules per glucose molecule. The final stage of this aerobic respiration sees the electrons that were transported with the H+ ions to the outer

compartment of the mitochondria combining with oxygen and hydrogen to become water. The acetyl-CoA is degraded to CO_2 and H^+. The CO_2 is readily taken up by the deoxygenated blood and carried back to the lungs. The relinquishment of CO_2 by the lungs is to a large extent a consequent of the taking up of oxygen (Christiansen *et al*., 1914).

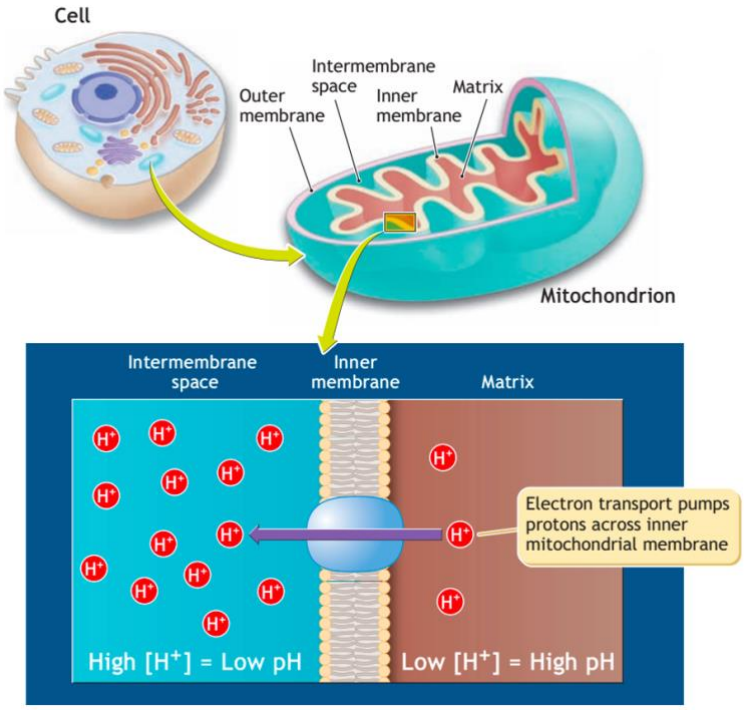

Figure 1.8: The mitochondrion: The site for aerobic energy metabolism. Electron transport creates a proton (H^+) gradient across the inner mitochondrial membrane, sourced with permission from Mc Ardle *et al*. (2015).

1.3.6: Fat metabolism

Stored fat represents the most plentiful body stored source of energy, however, fat oxidation is rate-limited, thereby hampering fat metabolism's effectiveness during very high-intensity exercise (Osnes & Hermansen, 1972). The inadequate rate of fat metabolism is mitigated by the rapid availability of glucose (Edwards *et al*., 1934). Acutely, increased blood flow through adipose tissue with exercise increases the release of non-esterified fatty acids (NEFA) for delivery to working muscle (Mc Ardle *et al*., 2015). In a more chronic sense, endurance training has been demonstrated to increase total fat turnover (Martin *et al*., 1993). Although all cells contain some fat, adipose tissue is the principal source of fatty acid

molecules. The main location of adipocyte is below the skin, followed by muscle tissue (Plowman & Smith, 2014). In the context of hydrogen atoms providing electrons and protons to the ETC to support ATP production, the advantages of fat as a fuel source are apparent from its chemical composition. The chemical composition of the NEFA palmitate is $C_{16}H_{32}O_2$. The 16 carbon and 32 hydrogen atoms of this NEFA heavily outnumber the 6 carbon and 12 hydrogen atoms found in the metabolised form of glucose ($C_6H_{12}O_6$). This plentiful storage fuel (9.13 $kCal.g^{-1}$) is broken down (lipolysis) in the cytosol into glycerol and NEFA, collectively termed a triglyceride. These NEFA are transported to the mitochondrial matrix to undergo beta-oxidation in the mitochondria.

Beta-oxidation, depicted in Figure 1.9, removes successive pairs of carbon atoms from the NEFA forming acetyl CoA, the universal intermediate of all food stuffs. Now in the form acetyl CoA, ATP is produced in a similar manor to glycolysis except that no ATP is derived from substrate-level phosphorylation. The name "beta-oxidation" is derived from the location of the two carbon atoms derived from the NEFA, that is the alpha (α) and beta (β) carbon bonds. The process of manufacturing ATP from NEFA can be prohibited by a lack of oxaloacetate as a consequence of exhaustive exercise or diet (Askew *et al.*, 1975). In these circumstances, oxaloacetate is instead converted to ketone bodies for energy. A schematic of the breakdown of the glycerol and NEFA components of a triacylglycerol molecule can be viewed in Figure 1.9.

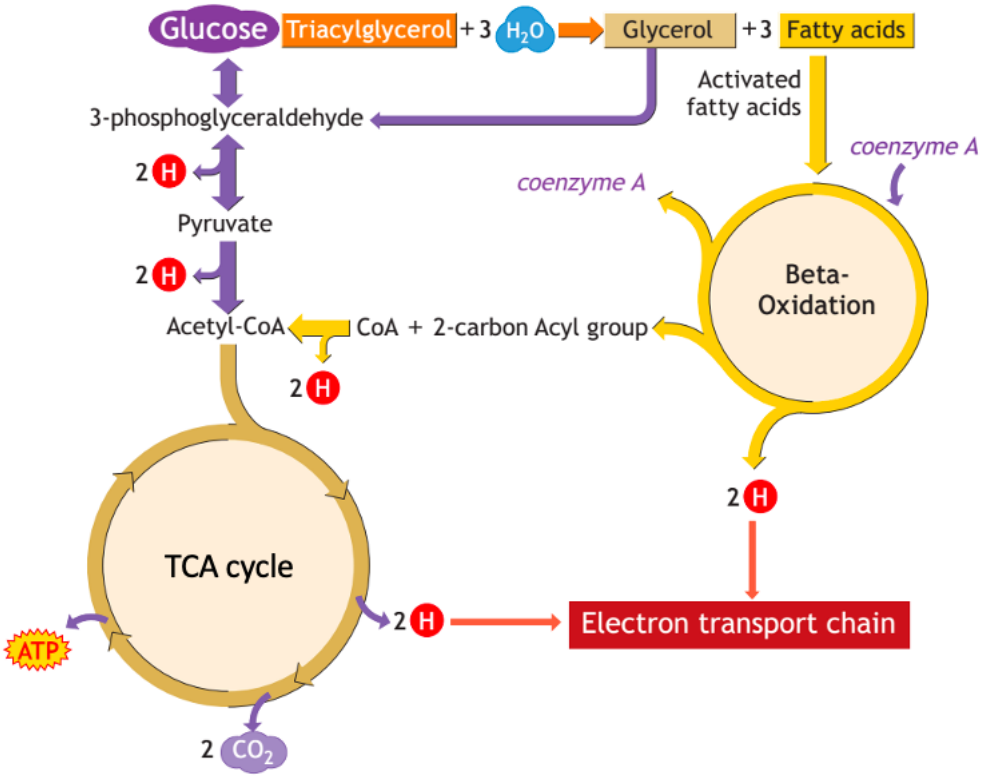

Figure 1.9: Schema for the breakdown of the glycerol and fatty acid components of a triacylglycerol molecule, sourced with permission from Mc Ardle *et al.* (2015).

1.3.7: Protein metabolism

During exercise, carbohydrate and free fatty acids are regarded as the major energy sources (Lemon & Nagle, 1981). Protein supplies a small quantity of energy, typically from the branched chain amino acids; leucine, isoleucine and valine. Amino acids can enter cellular respiration at a number of locations once the common amino group (NH_2) has been removed via transamination or oxidation deamination. In transamination, the NH_2 is transferred to a keto acid, including; pyruvic acid, acetyl CoA, and the TCA intermediaries. Alternatively, a new keto acid and amino acid is formed, typically followed by gluconeogenesis or oxidative deamination (Plowman & Smith, 2014). The physiological roles of protein as an enzyme, a contractile or providing structure, takes precedence over the provision of energy (Lemon & Nagle, 1981). Combined urine and sweat analyses have shown a rate of protein breakdown of 5.8 $g.h^{-1}$ for a carbohydrate replete group and interestingly 13.7 $g.h^{-1}$ in athletes that have been carbohydrate restricted (Lemon & Mullin, 1980). Although relatively small quantities,

it is noteworthy that the exercise and dietary intervention were not extreme. The duration and intensity of the intervention was 60-min at 70 to 75 % of VO_2max. The depletion protocol was replicating the exercise trial the evening prior to testing followed by a zero-carbohydrates meal.

1.3.8: Lactate metabolism

Lactate is metabolised continuously in the human body, at rest lactate concentration is reportedly 123.4 $mg.kg^{-1}.h^{-1}$ (Mazzeo *et al.*, 1986). Lactate production has been described as a "compensatory strain response" (Brooks, 2020), as lactate generation increases with exercise intensity (Stainsby & Welch, 1966). The increased exercise intensity evokes a cellular shift from aerobic to anaerobic ATP generation (Park *et al.*, 2015). During intense exercise, immediate energy requirements can supersede the rate of ATP supply from the ETC. In these circumstances, the protons and high-energy electrons from $NADH + H^+$ and $FADH_2$ cannot enter the ETC. Consequently, the proton may combine with pyruvate ($C_3H_3O_3$) forming pyruvic acid ($C_3H_4O_3$), lactate ($C_3H_5O_3$) and debatably lactic acid ($C_3H_6O_3$) (Rogatzki *et al.*, 2015). Insightfully, the hydrogen count is the sole change in the respective aforementioned chemical formulae. The pKa is a value associated with the negative base-10 logarithm of the dissociation constant of a solution. As a consequence of the pKa of lactic acid being 3.6, its presence in humans is contested (Robergs *et al.*, 2018; Wasserman *et al.*, 1973). From a competitive sporting vantage point, the option to bind H^+ with pyruvate to form lactate can be considered an advantage, temporarily at least, as this alkalising reaction mitigates the drop in blood pH (Osnes & Hermansen, 1972).

The "lactate shuttle theory" is that lactate shuttles among producer (driver) and consumer (recipient) tissues, cells, and cellular compartments (Brooks, 2020). This hypothesis asserts to explain the presence of higher concentrations of lactate in working oxidative red skeletal muscle than in the glycolytic white portions of the same muscle, an "intracellular shuttling" (Park *et al.*, 2015). Alternately, the "extracellular shuttle" describes the instance where cell-cell or tissue-tissue lactate shuffling occurs. In this instance lactate is shuttled from the active exercising muscle to an alternate tissue or cell for oxidation, such as the heart. The shuttle of lactate from a production site to an alternate location for consumption has been expanded to

include recipient extracellular locations including the heart, liver, kidney and brain (Garcia *et al*., 1994; Jacobs *et al*., 2013).

The major pathway for the removal of increased lactate during exercise is though oxidation. During exercise, the rate of oxidation increases linearly with VO_2 and represents a significant fuel source (Mazzeo *et al*., 1986). The primary sites for removing lactate from the circulation is the active slow twitch skeletal muscle fibres and the heart (Mazzeo *et al*., 1986). Beyond the functionality as a substrate for exercise and everyday functioning, lactate containing solutions are now frequently used in the treatment of traumatic brain injury where glucose uptake is limited or impaired (Brooks, 2020).

More recently, researchers have assessed the possibility of lactate being processed in the mitochondrial "framework" or reticulum. The identification of mitochondrial lactate oxidation complex supports the presence of a lactate shuttle between the cytosol and the mitochondria (Park *et al*., 2015; Brooks *et al*., 2022). Although findings have not been unanimous, advocates (Park *et al*., 2015; Brooks *et al*., 2022) of this energy-generating process suggest unsupportive research (Jacobs *et al*., 2013; Bakeeva *et al*., 1978) is as a consequence of limitations associated with *in vitro* design and the usage of isolated mitochondrion rather than the full reticular tubular network existing in skeletal muscle. Advocates of the concept propose that lactate passively diffuse through the outer membrane of the mitochondrion into the inter-membrane space, where lactate is converted back to pyruvate by an isoform of lactate dehydrogenase. A monocarboxylate transporter then relocates the pyruvate across the inner membrane of the mitochondrion into the matrix, where oxidation occurs (Juel *et al*., 2003).

With exercise training, an athlete's ability to clear lactate is enhanced because of increased oxidation and gluconeogenesis (Brooks, 2020; Donovan & Brooks, 1983; Stanley *et al*., 1988; Baldwin *et al*., 1972). Stanley *et al*. (1988) stated that caution is advised when interpreting net lactate as a proxy for total lactate. With the prevalence of mobile lactate analysers this cautionary message is likely increasingly pertinent. As a consequence of exercise training, the difference between total lactate production and net lactate appearance is greater. In the context of a highly-trained endurance athlete, the sustainable (endurance)

upper-end intensity is likely to be a high percentage of their maximum work capacity (Olbrecht, 2007). Historically, blood lactate threshold leap-frogged oxygen carrying capacity as a marker of trained state, as VO_2max becomes insensitive to training in highly-trained athletes (Daniels *et al.*, 1978). However, in the circumstance where lactate is cleared very effectively, the "fractional utilisation" (Costill, 1970) or "performance VO_2" (Joyner & Coyle, 2008) may provide insight as to the actual cost of the high-intensity exercise. Fractional utilisation is then expressed as a percentage of VO_2max and is the by-product of competitive demands.

During exercise performance testing, the measured concentrations of BLa associated with a specific cycling intensity can be effected by diet (Maassen & Busse, 1989). Ideally, the test design controls for diet and therefore diet can be considered extraneous (Jeacocke & Burke, 2010). In the circumstance where either diet or exercise preceding a test is not controlled, an understanding of the impact on lactate data is elucidating. In a carbohydrate loaded state, athletes may produce higher lactate concentrations and higher associated powers (Maassen & Busse, 1989). Perhaps lesser known and particularly misleading in the appraisal of sub-threshold metabolism, low glycogen stores preceding a test can present with lower levels of lactate (Maassen & Busse, 1989).

1.4: Maximal oxygen uptake

In 1925, exercise scientist Archibald Vivian Hill identified that oxygen consumption could only increase up to a point, and, thereafter, regardless of any increase in workload, consumption could not rise any further. This phenomenon known now as "VO_2max" provides an upper-limit demarcation for aerobic exercise. VO_2peak describes the same ventilatory upper-limit but is the appropriate alternate term when the exercise test is not designed with a primary focus of provoking VO_2max, in other words a VO_2max test gives a VO_2max, whereas, for example, a GxT stimulates a VO_2peak relative to the study protocol. The GxT is designed to allow a transient steady-state to be reached within each exercise load. Conversely, the expedient nature of a ramp VO_2max test prevents a steady-state being attained and increases the likelihood of VO_2max being attained (Buchfuhrer *et al.*, 1983). The test format does not guarantee maximum oxygen uptake being prompted (Midgley *et al.*, 2007) and consequently secondary criteria such as a plateau in oxygen uptake , high blood

lactate levels and elevated respiratory exchange ratio (Howley *et al*., 1995). In addition, verification tests employed soon after the completion of the VO_2max test are commonly used (Poole & Jones, 2017). VO_2max may be defined more comprehensively as the maximum integrated capacity of the pulmonary, cardiovascular and muscular systems to uptake, transport and utilise O_2 (Poole *et al.* 2008). VO_2max is commonly indirectly measured using open-circuit calorimetry (Poole *et al.* 2008) and can be stated in absolute terms relative to time, for example 4000 $mL.min^{-1}$. Alternatively, VO_2max is scaled to body mass, for example 72.7 $mL.kg^{-1}.min^{-1}$ (4000 $mL.min^{-1}$ consumed by an individual with a body mass a 55 kg). Scaling VO_2max to body mass aids inter-individual comparisons in circumstances were the sports performance is affected by body mass. For example, racing cyclists "A" and "B" both have identical absolute data of 4000 $mL.min^{-1}$ but individual body masses of 55 and 70 kg, respectively. Were cyclist "A" and "B" to race up a hill climb, the absolute VO_2max available would equate to 72.7 and 57.1 $mL.kg^{-1}.min^{-1}$, respectively. This is appropriate when climbing, due to gravitational effect on body mass. Alternatively, during high-intensity cycling, for example on flat terrain in still conditions, VO_2max can be scaled to the surface area of the cyclist (Swain *et al*., 1987). Using body mass as the reference variable, area scales to the power of 0.666 (Swain *et al*., 1987). Again using illustrative cyclists A and B, their surface area scaled to body mass can be anticipated as 14.5 $m^2.55\ kg^{-1}$ and 17.0 $m^2.70\ kg^{-1}$, respectively. Therein, it becomes apparent that the impact of surface area is proportionately greater for cyclist A with the smaller body mass, presenting 0.26 units of surface area, versus 0.24 units for cyclist B. However, it should be acknowledged that with the advent of aerodynamic bikes and consequentially reduced surface area being presented to oncoming air, a lower surface area exponent could be expected. Commonly, a mass exponent of 0.32 is used for level cycling (Mujika & Padilla, 2001) but intra and inter-individual variability is anticipated (Swain *et al*., 1987). The need to perform at VO_2max assessments in cycling is event-specific and complex.

1.5: Aims and objectives

The FTP test is a commercially successful test, *vis-à-vis* TrainingPeaks.com, WKO+ desktop software and client lists including Tour de France teams, Ironman World Champions, Olympians, and age group athletes. The first undertaking of the current project was to determine whether the c-FTP represented the physiological occurrences that it was ascribed

to measure. Sequentially, the next aim was to determine the test-retest repeatability. Given the mountain of research already reported on similarly described exercise intensities and epochs, the goal was to identify an alternate well-researched test that measured the same exercise intensity. Conceptually, this scenario would permit the two perspective tests to be used interchangeably and that the deficits in knowledge regarding the FTP test might be made up by the more established test. A variety of physiological tests have been validated to anticipate an athlete's "threshold". The possibility of having a very accessible and simple test available as a proxy for highly resourced and specialist test seemed valuable.

Credibly, one might argue that the gold standard exercise test is the GxT as a consequence of being the most widely used examination of the dynamic relationship between exercise and integrated physiological systems (Beltz *et al*., 2016). Consequently, the next objective of the current investigation was to create a model to predict c-FTP from the GxT data. Intuitively then, given the expansive and apparently successful use of the c-FTP test in the cycling field, we sought to determine whether a similar relationship existed between GxT data versus rowing and cycling performance data.

The current thesis is ordered around the proceeding questions and hypotheses.

1. H_o: There is no significant differences between repeated c-FTP trials ($P > 0.05$) and any differences are less than the LoA determined *a priori* at + 20 W to – 20 W.
2. H_o: There are no significant differences between c-FTP versus Dmax, T_{Lac} or T_{vent} ($P > 0.05$) and any differences are less than the LoA determined *a priori* at + 20 W to – 20 W.
3. Does the elicited metabolic and BLa response to cycling at c-FTP demonstrate an upper-limit quasi-steady-state intensity?
4. H_o: There are no significant differences between Critical and Functional Threshold Power in highly-trained athletes ($P > 0.05$) and any differences are less than the LoA determined *a priori* at + 20 W to – 20 W.
5. Can cycling GxT data be used as a proxy for VO_2max test-data in the determination of the fixed loads (W) required to determine CP?

6. Can cycling GxT data be used to model FTP using a multi-parameter model containing transiently highly correlated prediction variables on the basis of physiological foundations?
7. Can rowing FTP (r-FTP) be predicted using body mass, blood lactate and GxT peak power data in a heterogeneously trained group of rowers?

Chapter 2: General methodology

2.1: Medical examination

A full medical examination was performed by a registered medical practitioner, including spirometry, blood pressure, full blood count and any other tests deemed necessary. If any medical abnormalities were identified on examination the potential participant was excluded from the trial and pertinent details relating to the diagnosed abnormalities forwarded to their GP with the participant's consent. All enlisted participants were requested to complete a detailed medical questionnaire (Appendix 9.1) prior to the medical examination; which was reviewed by the medical practitioner to assess suitability for study inclusion.

2.2: Height and body mass assessment

Participant's height (cm) and body mass (kg) were measured using a stadiometer (Holtain, Dyfed, UK; see Plate 2.1 a.) and counterbalance scales (Seca, Hamburg, Germany; see Plate 2.1 b.), which have reported precisions of 0.1 cm and 0.1 kg, respectively. Participant's body mass and height were assessed with minimal clothing and without footwear. Subsequently, body mass index (BMI in $kg.m^{-2}$) was calculated using Equation 2.1 (Mc Ardle *et al*., 2015).

Equation 2.1: BMI ($kg.m^{-2}$) = body mass (kg) / stature (m^2)

a. 

b. 

Plate 2.1: a. Holtain stadiometer used to measure stature in cm. **b.** Seca counterbalance scale used to measure body mass in kg.

2.3: Body fat assessment

Skinfold thickness data in millimetre (mm) were assessed with the participant wearing comfortable clothing, euhydrated and the bladder evacuated. No showering or exercise was permitted prior to recording of skinfold thickness data to avoid erroneously elevated scores as a consequence of hyperaemia. A Harpenden skinfold caliper (Baty International, West Sussex, UK; see Plate 2.2) was used to record skinfold thickness data at four discrete anatomical sites; namely, biceps, triceps, subscapular and supraspinale on the right side of the body. The caliper was placed at 90° to the surface of the skinfold, 1-cm from the thumb and index finger of the investigator. The measurement was recorded 2-s after the caliper was applied to the assessed site. The recorded skinfold sites were assessed in succession to minimise any compression or measurer bias. Two measurements were recorded, unless the difference between the first two measurements exceeded 5%, whereby a third measurement was recorded. The double-fold of skin and adipose tissue was held between the thumb and index finger of the investigator's left hand. The size of the fold was the minimum to allow ensure the two skinfolds were parallel.

The biceps and triceps skinfold sites were located from the midway point between the acromiale and the radiale. The biceps and triceps skinfold thickness data were recorded from the anterior and posterior surfaces of the arm, perpendicular to its long axis. The subscapular skinfold site was 2-cm from the subscapulare in a line 45° laterally downwards, following the natural fold lines of the skin. The supraspinale skinfold was recorded from the point of intersection between a horizontal line from the iliocristale dissecting an oblique line from the iliospinale to the anterior axillary border and following the natural fold lines of the skin. The sum of the four skinfold thicknesses was computed and percentage body fat was estimated from age, gender and skinfold thickness tables reported by Durnin and Womersley (1974).

Plate 2.2: Harpenden skinfold caliper used to assess skinfold thickness.

2.4: Pulmonary function test

Pulmonary function data were assessed before and after each GxT using a Microlab Microspirometer (Micro Medical, Blessingstoke, UK; see Plate 2.3). The procedure was explained clearly by the operator to each athlete prior to testing and subsequently the operator demonstrated good technique. Subsequently each participant' age, height, body mass and gender were recorded and inputted into the participant's data file. The spirometer used a single-use disposable unidirectional cardboard mouthpiece and a nose clip to restrict nasal airflow. Pulmonary function tests were performed in the standing position and participants were informed to maintain an upright posture during inspiration and maximal expiration. Two or more expirations were performed, with a variation of < 0.15 L in recorded volumes required (Graham *et al*., 2019). The participant was instructed to inspire rapidly, then within < 2-s insert the mouthpiece, seal the lips around the mouthpiece, and initiate maximal expiration (Graham *et al*., 2019). Verbal encouragement was provided "inspire as deeply as possible" prior to commencement and "more, more, more" during the effort. Indicators of maximal inspiration were observed by the operator; namely, raising eyebrows, eyes widening and possible head quivering (Graham *et al*., 2019). Forced vital capacity in litre (FVC), forced expiratory volume in one second measured in litre (FEV_1), peak expiratory flow in litre per second ($L.s^{-1}$) and forced expiratory rate (%) (FER) were recorded. Subsequently, recorded data were compared with normative data for age, gender, height and ethnicity to screen for asthmatic contraindications pre-exercise and evidence of exercise induced broncho-constriction post-exercise.

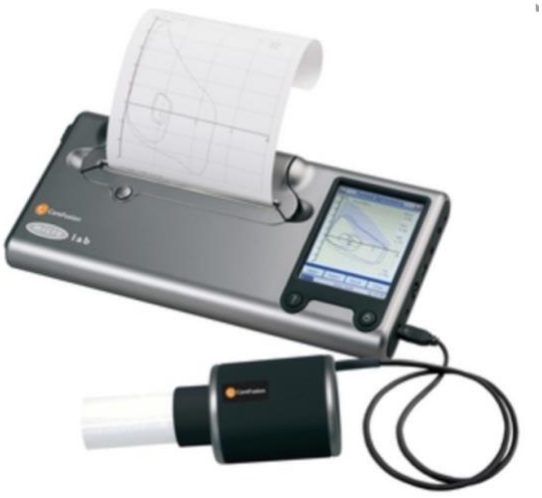

Plate 2.3: Microlab Microspirometer (Micro Medical, Blessingstoke, UK) used for pulmonary function tests.

2.5: Heart rate data

The HR data were recorded by radio-telemetry using a Cardiosport GT1 HR monitor (Cardiosport, Hampshire, UK; see Plate 2.4) consisting of a coded transmitter belt and monitor. The HR data were also integrated with a calibrated cardio-metabolic cart (CPET; Cosmed, Rome, Italy). A small amount of electroconductive ultrasound transmission gel (Aquasonic 100, Parker, NJ, USA) was placed on the transmitter electrodes to allow for more accurate and consistent readings. Data for HR were transmitted from the belt to the monitor at a 1-s sampling rate. The HR data was monitored and recorded every 30-s during testing. During field-based testing, HR data were recorded by radio telemetry using a Garmin Forerunner 310 (Garmin, KA, USA). Field-based HR data were subsequently downloaded to a laptop post-exercise via Bluetooth.

Plate 2.4: Cardiosport GT1 heart rate monitor (Cardiosport, Hampshire, UK) coded transmitter belt (Bluetooth and ANT^{+}) used to record heart rate data.

2.6: Respiratory data

Gas exchange variables were recorded using a Cardio Pulmonary Exercise Testing (CPET) metabolic cart and associated software (Cosmed, Rome, Italy; see Plate 2.5). The CPET metabolic cart assessed oxygen consumption (VO_2), carbon dioxide production (VCO_2), minute ventilation (VE), pulmonary gas exchange ratio (RER) and HR data via an ANT+ receiver on a breath by breath basis. The system's oxygen analyser was a rapid response paramagnetic cell with a measurement range of 0 to 100%, a 120 ms response time and an accuracy of ± 0.1%. The dual cell carbon dioxide (CO_2) analyser used non-dispersive infra-red gas analysers with a range of 0 to 10%, a response time of 100 ms, and an accuracy of ± 0.02%, The associated bidirectional digital turbine has a flow range of 0.08 to 20 L.s^{-1} and a flow accuracy of ± 2%, a measured ventilation range of 0 to 300 L.min^{-1} and a calibrated pre-test ventilation accuracy of < ± 0.5%. The flowmeter used a bi-directional digital turbine

with air passing through helical conveyors, causing the rotation of the turbine rotor. The rotating blade interrupted an infra-red light beam emitted by the three photodiodes of the optoelectronic reader. Every interruption represented 16.6% turn of the rotor; this allowed for accurate quantification of the number of rotations in a fixed time ($rev.s^{-1}$). There was a constant ratio between the air passing through the turbine and the number of turbine rotations thus allowing for accurate measurement of volume and flow rate. The sequence of photodiode interruption distinguished between inspiratory and expiratory flow and volume. The CPET analyser also contained solid-state in-line detectors to measure analyser cell temperature, analyser cell pressure and barometric pressure and humidity, to convert measured metabolic data to BTPS and STPD where relevant. The CPET analyser can accommodate ambient temperatures ranging from 0 to 50°C, barometric pressures ranging from 400 to 800 mmHg and humidity ranging from 0 to 100%.

During metabolic data collection participants wore a uniport suitable sized (small, medium and large) facemask (Hans Rudolf, KA, USA) connected by a nafion tube (Permapure, NJ, USA) to equilibrate the water content of the gases entering the CPET analyser to the relative humidity of the environment. It was necessary to attach the mask as tightly as possible with the adjustable straps in order to maintain a tight seal and avoid any volume losses during data collection.

Plate 2.5: Cardiopulmonary Exercise Testing (CPET) metabolic cart used for on-line breath by breath collection of metabolic and heart rate data.

2.7: Blood lactate data

Two lactate analysers were used in the current set of studies, a standard non-lysed laboratory bench analyser (YSI 1500 Sport lactate analyser; Yellow Springs Instruments, OH, USA; see Plate 2.6) and a mobile whole blood lactate measurement device (Lactate Pro 2, Arkray, Shiga, Japan; see Plate 2.9). The YSI 1500 Sport lactate analyser was calibrated using a certified 5 mmol.L^{-1} lactate standard and has a measurement range of 0 to 30 mmol.L^{-1}. The operating ranges were 5 to 45 °C and 10 to 90% relative humidity. Samples were injected using a 25 μL blunt needle YSI syringepet (see Plate 2.7). Blood samples were obtained from the fingertip of the middle finger of the non-dominant hand using a sterile lancet (Solofix, Braun, Bratislava, Slovakia). Prior to each consecutive sample collected, the finger was wiped clean of sweat and dried blood. A fresh sample of blood was then gently squeezed and drawn via capillary action into a heparinised capillary tube (Marienfeld Laboratory Glassware, Laud-Konigshofen, Germany). A 25 μL sample of whole blood was then collected from the capillary tube and transferred into the analyser well (containing 600 μL of buffer solution) using the syringepet. The syringepet was rinsed three times with buffer between samples and with the whole blood sample twice prior to injection. The glass barrel of the syringepet was inspected to ensure minimal bubbles were present. The YSI 1500 Sport analyser's probe was fitted with a three-layer lactate membrane (Yellow Springs Instruments, OH, USA) containing lactate oxidase to assess lactate concentration in the reaction chamber.

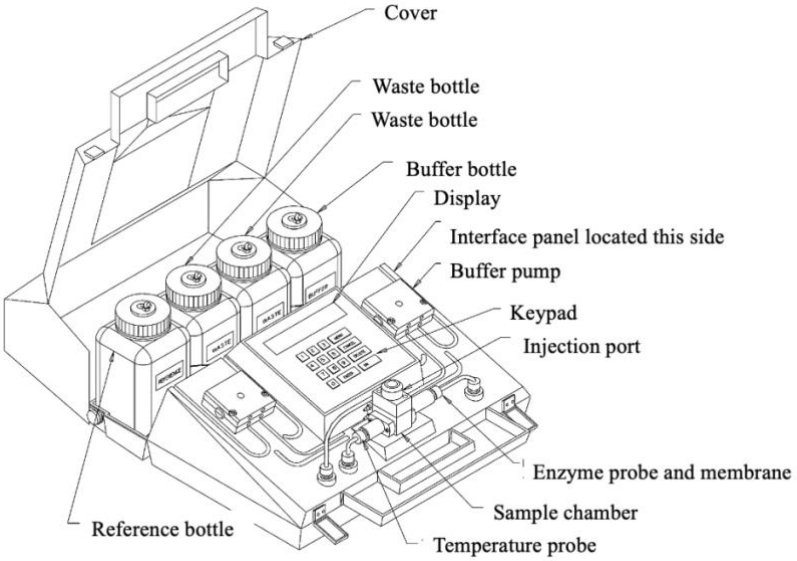

Plate 2.6: The YSI 1500 Sport lactate analyser (Yellow Springs Instruments, OH, USA) bench analyser used to measure plasma (non-lysed) blood lactate.

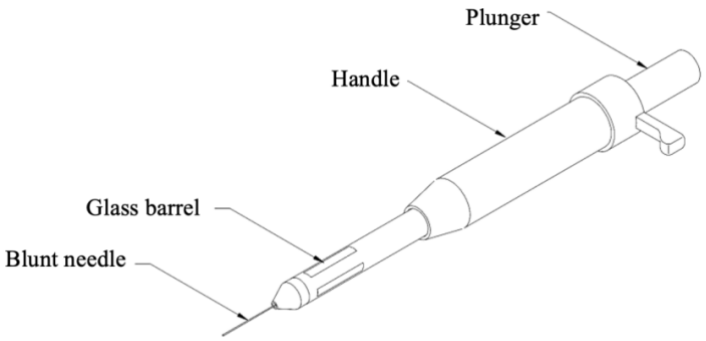

Plate 2.7: The YSI 1501 Syringepet used to inject 25 μL whole blood samples.

The assessment of non-lysed blood lactate concentration [BLa] involved a series of chemical reactions within the sensor probe of the YSI lactate analyser. The probe consisted of a silver cathode and platinum anode. A three layered membrane consisting of a polycarbonate, immobilized L-lactate oxidase and cellulose acetate covered the probe. When a blood sample was injected in the reaction chamber some of the diluted sample diffused through the membrane. The outer membrane was porous and resisted diffusion of enzymes but was large enough to allow the passage of O_2, H_2O, H_2O_2, NaCl and lactate. The inside membrane of cellulose acetate was permeable to H_2O_2, but impermeable to ascorbic acid and other substances with a molecular weight greater than 200. When the lactate in the blood sample diffused through the outer polycarbonate membrane and came into contact with the L-lactate oxidase membrane, the lactate was rapidly oxidised producing H_2O_2 and pyruvate in the reaction below:

Reaction 1: $\text{L-Lactate} + O_2 \xrightarrow[\text{L-Lactate Oxidase}]{} H_2O_2 + \text{Pyruvate}$

The H_2O_2 produced passed through the inner membrane of cellulose acetate and was oxidised at the platinum anode producing electrons:

Reaction 2: $H_2O_2 \xrightarrow[\text{At the platinum electrode}]{} 2H^+ + O_2 + 2e^-$

The circuit was completed at the silver reference cathode where the following reaction occurred

Reaction 3: $2\,AgCl + 2e^- \longrightarrow 2Ag + 2Cl^-$

The current produced was linearly proportional to the lactate concentration in the sample chamber. The analyser calculated the lactate concentration of the sample by comparing the current produced by the sample with a reference sample of known lactate concentration. Prior to each test, the analyser was calibrated using a 25μL sample of 5mmol.L^{-1} lactate standard solution was passed into the reaction chamber using the YSI syringepet. The analyser was calibrated to a precision of a 0.1 mmol.L^{-1}. The sensor probe and enzyme membrane can be seen in Plate 2.8.

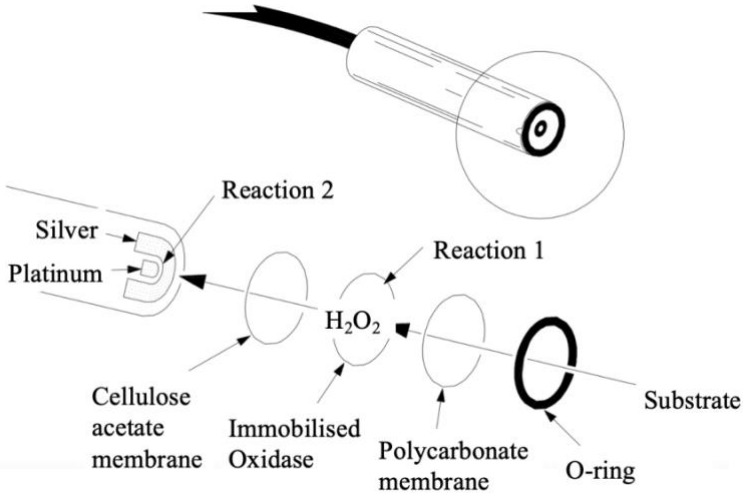

Plate 2.8: The sensor probe and enzymatic membrane contained within the YSI 1500 Sport lactate analyser (Yellow Springs Instruments, OH, USA).

The portable lactate monitor used in the reported studies was the Lactate Pro 2 (Arkray, Shiga, Japan; Plate 2.9). The measurement range was 0.5 to 25.0 mmol.L^{-1}, the sample volume required was 0.3 μL and the processing time was 15-s. The analyser's temperature range is 5 to 40 °C and an operating range of 20 to 80% relative humidity.

Plate 2.9: Lactate Pro 2 (Arkray, Shiga, Japan) portable lactate monitor.

Test strips were removed from their aluminium packaging without any contact with the strip window and the strip was inserted into the meter. An audible beep indicates the meter was ready to receive a sample. The ear lobe puncture procedure was identical to that used with the bench analyser (*vide supra*) albeit from the earlobe. The test strip was placed at a 90° angle to the drop of blood. The test strip withdrew the blood by capillary action until the reaction window was filled; the upper and lower surfaces of the test strip in the area of the reaction window were wiped to ensure that no ancillary blood impacted on the assessment of lactate concentration. Lactate in the sample reacts with potassium ferricyanide and lactate oxidase to form potassium ferrocyanide and pyruvate. Upon the application of a given voltage, ferrocyanide is oxidised, releasing electrons and creating a current. The current is measured amperometrically and is directly proportional to the concentration of the lactate in the sample (Pyne *et al*., 2000).

2.8: Haematological analysis

Each study participant had a venous blood sample collected aseptically from the medial cubital vein in the antecubital fossa of the left arm using a 21G 1.5 inch needle (Precision Glide, BD Diagnostics, Plymouth, UK) and a 4mL EDTA tube (Vacutainer, Plymouth, UK). The blood sample was analysed in an automated cell counter (Coulter Counter System, Model Act Diff, Coulter Electronics, UK). Data for the variables haemoglobin ($g.dL^{-1}$), haematocrit (%), red blood cell count ($x10^{12}.L^{-1}$) and white blood cell count ($x10^{9}.L^{-1}$) were recorded. Each individual's haematological report was reviewed by the attending medical practitioner to confirm absence of anaemia and sub-clinical infection pre-test.

2.9: Hydration

Hydration status was assessed as urine specific gravity (USG) from a collected mid-stream urine sample using an Eclipse Professional Optical Refractometry, verified using UKAS Certified Reference Materials (Bellingham & Stanley, Kent, UK, see Plate 2.10). The instrument had a measurement range for USG of 1.00 to 1.04, samples above 1.02 were considered hypohydrated, and those below 1.02 were considered euhydrated.

Plate 2.10: Eclipse Professional Optical Refractometry.

2.10: Power

2.10.1: Wattbike ergometer

The Wattbike ergometer (Wattbike, Nottingham, UK; see Plate 2.11) has both an air resistance and magnetic resisted flywheel manufactured with zinc anodised iron and steel. The air resistance ranges from 1 to 10 and magnetic resistance from 1 to 7. The load ranged from 20 to 5000 W and was measured using a force strain gauge at the chain at a rate of 100 samples.min^{-1}. The Wattbike operates in temperatures ranging 1 to 50 °C and relative humidity 10 to 95%. The Wattbike was fitted with an LED console that facilitated visual feedback of current power (W), mean power (W) and elapsed time (h:mm:ss) during trials. Endeavouring to adhere to the open-cadence test protocols as described by the FTP test originators (Allen & Coggan, 2010), participants were requested to manoeuvre the damper forwards or backwards during trials as they wished, causing the resistance to increase or decrease, respectively. The power output was measured using a load cell located next to the chain. As the chain runs over the load cell, it calculates the sum of all the forces applied to the chain through the cranks (Hopker *et al.*, 2010).

Plate 2.11: The Wattbike ergometer (Wattbike, Nottingham, UK).

2.10.2: The Lode Excalibur Sport

The Lode Excalibur Sport (Lode, Groningen, The Netherlands; see Plate 2.12) is a programmable electromagnetically braked cycle ergometer with a workload capacity up to 2500 W, a moment of inertia at the crank axis of 24 $kg.m^2$ ± 5 % and a maximum torque capacity of 200 Nm. Power is calculated from the pedal angular velocity by the Lode Ergometry Manager (Lunn & Axtell, 2021). The reported accuracy is ± 2 W for a power output of less than 100 W, ± 2% within the range from 100 to 1500 W, and ± 5% for power outputs in excess of 1500 W (Lode, 2011). The operational temperature range is 14 to 40° and a humidity range of 30 to 90%. The programmed control panel was positioned to provided visual feedback to the athlete of current power (W), mean power (W) and elapsed time (h:mm:ss) during trials.

2.10.3: Garmin Vector 3 Pedals

Garmin Vector 3 pedals (Plate 2.13 a.) and a Lode bike (Figure 2.12) were used in the investigation described in chapters four and five. The Lode bike programmes do not facilitate "open pacing" without allotting a specific cadence to a predetermined power output (Linear mode), whereas the Garmin Vector 3 pedals facilitates open pacing, cadence and gear

selection. The Garmin Vector 3 pedals can also be placed on the Lode cycle and cross-calibrated. Consequently, both power-measuring devices were used in the current research. The power output measured by the Garmin Vector 3 pedals was recorded using the Edge 1030 device (Plate 2.13 b.) using ANT+ wireless sensor technology. Operating temperature range is -10 to 50 °C with a water rating of IEC 60529 IPX7 (up to 1-m for a 30-min period). A 15 mm pedal wrench was used to apply and remove the pedals. The pedals were fitted at a torque of 34 Nm. Vectors measure rotational velocity of the crank arm, force (N) and time (s). Angular velocity is determined using a magnet-activated sensor once per crank revolution. Torque is measured in the pedal spindle by eight strain gauges (Novak & Dascombe, 2016). During testing, the Edge 1030 device provided visual feedback to their current power (W), mean power (W) and elapsed time (h:mm:ss) during trials. Participants used their own bicycle gears to increase or decrease the resistance during the exercise trial.

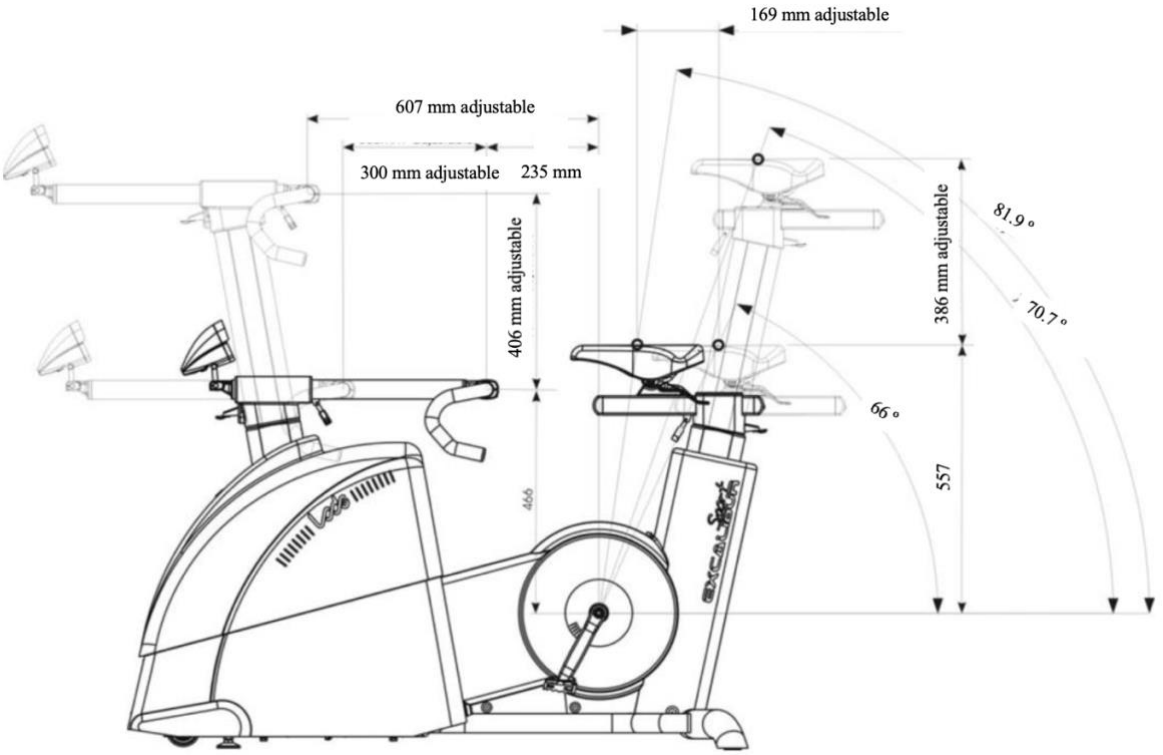

Plate 2.12: Lode Excalibur Sport (Lode, Groningen, The Netherlands) electromagnetically braked cycle ergometer illustrating individual cyclist adjustment.

a.  **b.** 

Plate 2.13: a. Garmin Vector 3 pedal and **b.** Garmin Edge 1030 device.

2.10.4: Concept 2 rowing ergometer with PM5

The Concept 2 (C2) rowing ergometer (see Plate 2.14) has a fully enclosed steel flywheel driven by a chain and resisted by air. The seat moves on a stainless-steel monorail. The PM5 screen facilitated visual feedback to the rower of current power (W), mean power (W), power per stroke (W), stroke rate (stroke.min^{-1}) and elapsed time (h:mm:ss) during trials and used ANT+ and Bluetooth technology to export data file to Excel. The footboard system was adjustable to the comfort and foot size of the rower. The C2 is an air-braked ergometer and resistance is created by a flywheel that becomes accelerated via a handle that is attached to a chain. During each rowing cycle, the rower pulls the handlebar, while moving backward on a sliding seat (drive phase), thereby accelerating the flywheel. Subsequently, the direction of movement is reversed and the rower moves forward to the starting position (recovery phase). During the recovery phase, the flywheel decelerates due to the resistance of the circulated air, but it does not stop immediately. That is due to the rotating mass of the flywheel and the energy stored (Treff *et al*., 2022). The rower determines resistance via stroke force, rate and length (Treff *et al*., 2022) using the following equation;

$$P_{ergo} = \frac{\int_{t_1}^{t_2} C_1 \dot{\theta}^3 dt + \frac{1}{2} J(\dot{\theta}_3^2 - \dot{\theta}_1^2)}{t_3 - t_1}$$

Where θ: angular position of the flywheel, J: moment of inertia of the flywheel (kg.m^2), t_1: starting time of the rowing cycle, namely the catch (s), t_2: end of the pull phase; namely the finish (s), t_3: end of the rowing cycle; namely, the next catch, C_1: constant (kg.m^2) calculated for each stroke on the previous recovery phase.

$$C_1 = -\frac{\int_{t_2}^{t_3} J\frac{\ddot{\theta}}{\dot{\theta}^2}}{t_3 - t_2}$$

Summarily, the power at the level of the flywheel is considered to be the sum of the power dissipated by air resistance and the power developed to accelerate the flywheel between two successive strokes.

Plate 2.14: Concept 2 rowing ergometer with PM5 LED display.

Chapter 3: Is the FTP test a reliable, reproducible and functional assessment tool in highly-trained athletes?

3.1: Introduction

Functional threshold power (c-FTP) is defined as the uppermost power sustainable for 60-min in a quasi-steady state (Allen & Coggan, 2010). Data for c-FTP was calculated as 95% of the mean power output during a maximal 20-min time-trial effort, the sole outcome measure assessed is power, see Table 1.1. This 20-min maximum effort does not reflect a specific energy system, rather a performance, derived from all available energetics. Dissimilarly, exercise physiologists commonly break-down the elements of whole-body energetics to enhance our understanding of how a competitive performance is derived, such as blood lactate (BLa) and ventilation to determine physiological thresholds; namely, load at lactate threshold (T_{Lac}), load at ventilatory threshold (T_{vent}) and load at Dmax (Cheng *et al*., 1992). Ordinarily these results are used to appraise the effectiveness of the preceding training and to direct future preparation. However, BLa and ventilation measures are impacted upon by test format; namely, increment duration and magnitude (Cheng *et al*., 1992; Stockhausen *et al*., 1997). A new power based test may add insight into these already established physiological test indices. The authors of the FTP test (Allen & Coggan, 2010) stated that the test can be trialled satisfactorily in the field. Irrespective, we felt it prudent, at this juncture, to appraise the FTP test in a controlled laboratory setting. The complexities of controlling the multitude of variables required for ecological validation were beyond the scope of the current investigation.

The first hypothesis of the current study was that, in a highly-trained athletic cohort, repeated 20-min FTP tests would be reliable and reproducible. The second hypothesis was that the computed cycling load (c-FTP) test was sustainable for 60-min. The prefatory description "quasi-steady-state" BLa and VO_2 was assessed using already established definitions of steady state BLa (Palleres *et al*., 2016) and VO_2 (Vanhatalo *et al*., 2011). The interchangeability of c-FTP with the following mathematical calculations of a threshold intensity; T_{vent}, T_{Lac} and Dmax were examined. The aim was to find a comparable intensity to c-FTP. The variation in each calculation (T_{vent}, T_{Lac} and Dmax) was foreseen to add a range of threshold powers and therefore enhance the likelihood of a possible match. The computations of T_{vent}, T_{Lac} and Dmax are shown in the data reduction section below. For statistical reasons, the null hypothesis was that no significant differences ($P > 0.05$) would be detected between the load at c-FTP and T_{Lac}, Dmax and/or T_{vent}. Where the null hypothesis

was accepted, agreement between tests was assessed using statistical measures of reliability and reproducibility.

3.2: Methods

3.2.1: Participants

The current study obtained ethical approval from the Faculty of Health Sciences Research Ethics Committee in Trinity College Dublin, see Appendix 9.1, and was performed in accordance the ethics standards of the International Journal of Exercise Science (Navalta *et al*., 2019). Participants completed a consent form prior to beginning any trials (Appendix 9.2). Nineteen (12 male, 7 female) highly-trained cyclists and triathletes, mean age 28-yr (± 6) participated. The mean VO_2peak, body mass, body mass index (BMI) and % body fat of enlisted participants are presented in Table 3.1, raw data are presented in Appendix 9.3.

Table 3.1: Mean (± SD) VO_2peak, mass, BMI and % body fat data for participants.

	GxT VO_2peak ($mL.kg^{-1}.min^{-1}$)	VO_2peak FTP ($mL \cdot kg^{-1} \cdot min^{-1}$)	Mass (kg)	BMI ($kg \cdot m^{-2}$)	Body fat (%)	Age (yr)
Female	59.3 ± 6.9	57.2 ± 3.3	57.0 ± 4.1	20.1 ± 1.2	16.3 ± 1.4	28 ± 6
Male	66.3 ± 5.5	65.1 ± 5.5	66.1 ± 4.9	22.0 ± 1.0	10.5 ± 1.3	28 ± 7

3.2.2: Protocol

Participants attended the laboratory on four occasions, in a rested, carbohydrate loaded and well-hydrated state, having abstained from alcohol and caffeine in the 24-h prior to testing. Trials were separated by a minimum of 6 and maximum of 10-day. Training load was agreed with both athletes and coaches prior to commencing the study, with weekly training load and stimulus remaining as constant as possible for the testing period. Exercise was limited to aerobic work for 48-h prior to each test. A 24-h food diary was completed prior to the first trial (Appendix 9.2). A copy of the food diary was retained by both the researcher and the participant. Each participant was requested to replicate their food intake prior to all tests, or if different, to consume comparable carbohydrate quantities. When necessary, participants were helped to plan their meals. Pre-test hydration status was assessed as urine specific gravity (USG) by refractometry (Bellingham & Stanley, Kent, UK) prior to all tests, euhydration was

defined as USG < 1.020 (Hamouti *et al.*, 2012). In addition, a full blood count was performed to screen for sub-clinical anaemia and infection.

Visit one involved a detailed medical assessment and a 3-min graded incremental test (GxT) to volitional exhaustion. Participants completed a 10-min warm-up on an air-braked cycle ergometer (WattBike, Nottingham, UK) below the initial power output required for the GxT (female < 90 W, male < 120 W). This time interval allowed participants to make minor adjustments to their cycling position (saddle height and fore-aft position, handlebar height and reach); these individual positions were noted and replicated during subsequent visits. The increments for the female and male cohort were 20 and 25 W, respectively, and cadence was controlled between 75 and 110 rev.min^{-1}. Finger-tip capillary blood samples for lactate analysis were collected at 2-min into each 3-min increment and assessed using a calibrated YSI 1500 Sports Lactate analyzer (YSI, OH, USA). Breath-by-breath ventilatory ($\dot{V}E$, $\dot{V}O_2$ and $\dot{V}CO_2$) and heart rate (HR) data, recorded using a calibrated cardio-metabolic cart (CPET; Cosmed, Rome, Italy), were averaged across the final minute of each increment. Each participant's $\dot{V}O_2$peak was determined as the highest consecutive ten breath average during the final test increment (Midgley *et al.*, 2007).

All participants had previously completed an FTP test prior to participation in the current study. During visits two and three, 20-min FTP time-trial tests were completed in the laboratory and projected 60-min FTP (c-FTP) was computed (c-FTP = 95% of the 20-min time-trial). Five participants were available for 3 visits only due to race commitments; therefore, they completed the GxT, one 20-min FTP time-trial test and the 60-min c-FTP test. Data for these five participants were omitted from all analyses pertaining to test-retest reliability and repeatability. However, their data were included in the assessment of the validity of the assertion that c-FTP could be sustained in a quasi-steady state for 60-min. Endeavouring to adhere as closely as possible to the construct of the FTP warm-up, the first FTP test warm-up used 65% Dmax as a proxy for 65% c-FTP (Table 3.2), the 5-min time-trial effort during the second FTP test was controlled at the same power attained during the initial FTP test and cadence during the warm-up was un-controlled. Table 3.3 outlines the timelines for capillary blood sample collection and measurement of ventilatory variables during all test sessions.

Table 3.2: FTP test protocol with amended warm-up.

	Duration	Description	% Dmax
Warm-up	20-min	Endurance pace	65
	3 by 1-min	Fast pedalling,	Not applicable
	with 1-min recoveries	100 rev·min^{-1}	
	5-min	Easy riding	65
	5-min	Time-trial	Maximum effort
	10-min	Easy riding	65
FTP test	20-min	Time-trial	Maximum effort
Cool-down	10 to 15-min.	Easy riding	65

During visit four, participants (n=19) were tasked with sustaining their c-FTP power for 60-min. The pre-test warm-up was standardised as 7-min at 55% of Dmax, 5-min at 65% of Dmax, 3-min at c-FTP and 3-min stationary rest. On-line VO_2 and HR data were recorded during the 60-min c-FTP test at the start and end (0 to 10 and 50 to 60-min). The facemask was removed from 11 to 49-min to facilitate participants drinking carbohydrate beverage *ad libitum*. Participants were asked to bring their normal race beverage, with the only stipulation being that the drink contained carbohydrate. Fingertip capillary blood samples were collected for lactate analysis at 10-min intervals throughout the 60-min trial.

3.2.3: Data reduction

Threshold loads (W) for T_{vent}, T_{Lac} and Dmax were determined from the recorded GxT data. VO_2 was used as the dependent variable; the associated power output was used to estimate T_{vent} and Dmax (Cheng *et al.*, 1992). Load at T_{vent} data were identified using a segmented regression model minimising the squared sum of the residuals following logarithmic transformation of VO_2 and load data (SigmaPlot 13.0; Systat, IL, USA). Load at T_{Lac} and Dmax was identified using "Lactate E" software (Newell *et al.*, 2007). The line of best fit for the Dmax calculation was calculated using third order curvilinear regression using VO_2 and BLa data at each workload. Thereafter, the maximum perpendicular distance to the straight line between the lowest and highest BLa data identified load at Dmax (Cheng *et al.*, 1992). The calculation of T_{Lac} was accomplished using a linear spline minimising the sum of the squared differences between workload and BLa, the workload preceding a departure from the straight line was identified as T_{Lac} (Lundberg *et al.*, 1986). A single factor repeated measures

ANOVA, quantified using *post-hoc* Bonferroni tests with $P < 0.05$ inferring significance, compared threshold data and was used to cull variables on the basis of there being a statistically significant difference compared to c-FTP (Bland & Altman, 1986).

3.2.4: Statistical analysis

An *a priori* statistical power test was conducted for expected outcomes with a Type 1 error probability of 0.05, a power of 0.85 and a projected effect size 0.3. This analysis indicated that n = 19 would provide a statistical power of 85% (G*Power v3.0.10 free software; Institute of Experimental Psychology, Heinrich Heine University, Dusseldorf, Germany). All data were checked for normality using both the D'Agostino and Pearson, and the Shapiro-Wilk tests. The reliability of repeat c-FTP tests was assessed using intra-class correlation (ICC), standard deviation of the residuals ($s_{y.x}$), coefficient of determination (r^2) and computing 95% confidence intervals of r (95% CI). The reproducibility of the c-FTP test was assessed using relative technical error of the measure (% TEM) and Bland Altman 95% limits of agreement (95% LoA). These analyses were performed using Prism 7 (Graph Pad, CA, USA).

Group data are presented as mean and standard deviation (SD). VO_2 measured during the 60-min trial was classified as steady-state if it remained significantly lower ($P < 0.05$, paired Student's T test) than VO_2peak, a specific demarcation used in identifying critical power (CP), a metric described as the boundary between steady- and non-steady-state cycling (Vanhatalo *et al*., 2011). Steady-state BLa data were assessed using maximal lactate steady state (MLSS) criteria, that is, an increase in BLa < 0.05 $mmol \cdot L^{-1} \cdot min^{-1}$ (Heck *et al*., 1985). We hypothesised that peak 60-min BLa would be significantly ($P < 0.05$) lower than GxT peak BLa. This might be sufficient to affirm Allen and Coggan's (2010) assertion that the load at c-FTP elicits a steady-state VO_2 response. However, this would not elucidate whether the intensity was the upper-limit intensity. MLSS can be identified using increases of 0.2 $W \cdot kg^{-1}$ until the load destabilised BLa data (Padilla *et al*., 2000). The difference in power output between the 20-min time-trial and c-FTP was 5%. Consequently, we reasoned that if the 5% difference in power equated to ≤ 0.2 $W.kg^{-1}$ and marked the boundary between steady and non-steady state, then the 60-min c-FTP power was the upper limit of steady-state.

For the purpose of comparing c-FTP data with alternate threshold tests, acceptable 95% LoA were set as ± 20 W. These LoA were considered appropriate for clinical use (Bland & Altman, 1986); namely, to discern biological change whilst mitigating against the risk of erroneous or misleading results. "Performance VO_2" was calculated by expressing VO_2 data during the 60-min test at c-FTP as a percent of VO_2peak (Costill, 1970). During the 60-min test, HR data were recorded during the initial and final 10-min of exercise, individual changes in mean HR data are reported. Peak HR measures were assessed for significant differences ($P < 0.05$, paired Student's T test) with GxT HR maxima.

Table 3.3: Time intervals during 60-min tests when BLa and ventilatory data were measured.

Test	Lactate sample	Ventilatory data
GxT	2-min into each workload	Continuously
FTP1 and FTP2	Post 5-min time-trial	From 31 to 66-min
	Pre 20-min time-trial	
	Post 20-min time-trial	
60-min at c-FTP	10, 20, 30, 40, 50 and 60-min	Start (0 to 10-min)
		End (50 to 60-min)

3.3: Results

A repeated measures ANOVA test identified no significant ($P > 0.05$) difference in power output between c-FTP (259 ± 40 W) and Dmax or T_{Lac} (246 ± 38 and 244 ± 47 W, respectively). However, the load at T_{vent} (197 ± 43 W) was significantly lower ($P < 0.01$) than c-FTP, consequently, T_{vent} data were excluded from further data analysis, see Figure 3.1, raw data are presented in Appendix 9.3. Mean group and gender specific power, normalised to body mass ($W \cdot kg^{-1}$) at Dmax, T_{Lac}, c-FTP and the last completed GxT stage (peak GxT) are listed in Table 3.4, raw data are presented in Appendix 9.3. The 95% LoA, mean bias, r^2, $s_{y.x}$ and 95% CI associated with; c-FTP1 vs. c-FTP2, c-FTP vs. Dmax and c-FTP vs. T_{Lac} are detailed in Table 3.5.

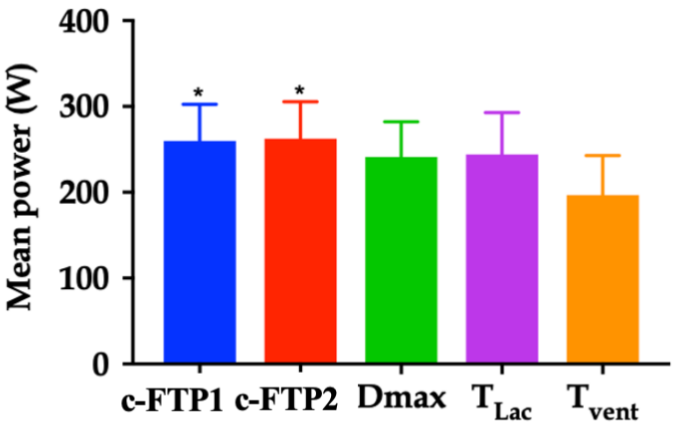

Figure 3.1: Bar graph of load at computed thresholds, bars denote SD, n=15. Asterisk symbol (*) infers significantly higher than T_{vent}, $P < 0.01$.

Table 3.4: Mean power ($W \cdot kg^{-1}$) associated with load at Dmax, T_{Lac}, c-FTP and peak GxT load. Columns indicate the whole population sample, female only and male only.

	Group	Female	Male
Dmax ($W \cdot kg^{-1}$)	3.5 ± 0.4	3.2 ± 0.3	3.7 ± 0.4
T_{Lac} ($W \cdot kg^{-1}$)	3.6 ± 0.6	3.2 ± 0.3	3.8 ± 0.6
c-FTP ($W \cdot kg^{-1}$)	3.9 ± 0.5	3.5 ± 0.5	4.1 ± 0.5
Peak GxT ($W \cdot kg^{-1}$)	4.8 ± 0.5	4.3 ± 0.4	5.0 ± 0.4

Table 3.5: Results of comparisons for c-FTP, Dmax and T_{Lac} computing % TEM, ICC, r^2 and 95% CI.

	c-FTP1 vs. c-FTP2	c-FTP vs. Dmax	c-FTP vs. T_{Lac}
95% LoA (W)	+ 13 to -17	+ 43 to - 7	+ 68 to – 37
Mean bias (W)	-2	18	16
% TEM	2.3	7.1	8.5
ICC	0.980	0.832	0.791
r^2	0.96	0.89	0.64
95% CI	0.87 to 1.11	0.72 to 1.10	0.51 to 1.33
$s_{y.x}$ (W)	9	14	30

No significant difference ($P > 0.05$) was detected comparing GxT peak BLa data with 20-min FTP BLa maxima (6.9 ± 1.3 vs. 6.9 ± 1.9 $mmol.L^{-1}$, respectively). However, peak BLa data

were significantly lower ($P < 0.05$) during the 60-min c-FTP test than peak GxT BLa (4.0 ± 1.1 vs. 6.9 ± 1.3 mmol.L^{-1}, respectively). The average BLa data across the final 50-min of the 60-min trial was 3.7 mmol.L^{-1} (± 1.2). Individual BLa data can be reviewed in Appendix 9.3. During the 60-min test, mean HR after 10-min at c-FTP (158 ± 14 beats.min^{-1}) increased across time by 9% (14 ± 7 beats.min^{-1}), however, mean HR between 50 and 60-min at c-FTP remained significantly ($P < 0.05$) lower (178 ± 11 beats.min^{-1}) than peak HR data recorded during the GxT (186 ± 12 beats·min^{-1}). In addition, mean VO_2 data increased by 6% from start to end of the c-FTP test (52.0 ± 6.4 vs. 55.0 ± 5.7 mL.kg^{-1}.min^{-1}, respectively), but similarly to HR data, remained significantly ($P < 0.05$) lower than peak GxT data (62.9 ± 6.2 mL.kg^{-1}.min^{-1}). The 5% power output difference between the 20 and 60-min trials equated to an average of 0.19 ± 0.02 W.kg^{-1}. "Performance VO_2" increased from 84% at 10-min to 88% of VO_2peak during the last 10-min of the 60-min cFTP trial.

In the current study, individual power at c-FTP was sustained for 60-min by seventeen (89 %) of nineteen athletes assessed; the two athletes unable to complete the c-FTP trial aborted at 35 and 52-min, respectively. Analysis of their BLa kinetics from 10 to 60-min indicated that the rate of change in BLa data from 10-min onwards remained below 0.05 mmol.L^{-1}.min^{-1} (Figure 3.2). The two athletes that could not complete the 60-min trial had their BLa data assessed at test termination. Neither participant's BLa had increased by > 0.05 mmol·L^{-1}·min^{-1} upon termination. As the facemask was removed to facilitate drinking, determination as to whether their VO_2 was also in a steady-state was not possible. Individual BLa data measured at 10-min intervals during the 60-min trial at c-FTP are presented in Figure 3.2; tabulated data across time are presented in Appendix 9.3.

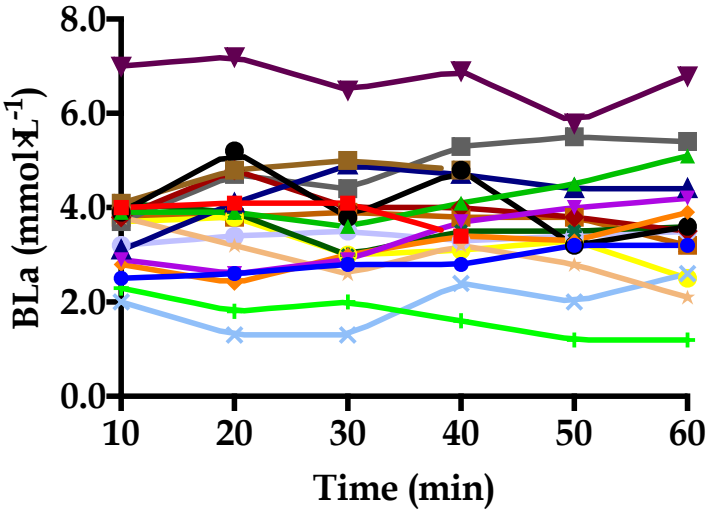

Figure 3.2: Individual BLa data at 10-min intervals during the 60-min trial at c-FTP (n=19).

3.4: Discussion

The results of the current study demonstrate that c-FTP is a reliable test. Both ICC and r^2 were high, while the corresponding residuals had a low standard deviation (ICC = 0.98 r^2 = 0.96, $s_{y.x}$ = 9 W). The c-FTP test was also found to be repeatable with satisfactory limits of agreement (+13 to -17 W, mean bias -2 W) and a low relative TEM of 2.3%. Consequently, the reliability and repeatability of the FTP test supports the inclusion of the 5 participants who completed a single c-FTP prior to the validity trial.

The FTP test was shown to identify a cycling power output that could be sustained for 1-hour in seventeen of nineteen (89%) athletes. Participants were asked to stop cycling after 1-hr as this met the criteria specified as c-FTP (Allen & Coggan, 2010). The purpose of the trial was not to determine a time to exhaustion. This eliminates the establishment of an absolute 60-min limit of tolerance. However, the FTP test protocol itself provides a 20-min limit of tolerance, supporting the contention that 60-min maximum power is < 5 % above the 20-min FTP time-trial power. Of note, this study group were highly-trained, mean fraction of VO_2max sustained during the 60-min trial was 84 % (using the first 10-min rather than the last 10-min VO_2 data as the numerator), a fraction reflective of elite endurance athletes (Heck *et al*., 1985). The high sustained fraction of VO_2 at c-FTP is particularly relevant if percentages of c-FTP are subsequently used to formulate exercise prescription, as currently recommended by Allen and Coggan (2010). Were a trained and untrained cyclist to train at the same

percentage of their c-FTP, each would likely be cycling at different percentages of absolute maximum 60-min power. In the context of training at percentages of maximum, overtraining and / or a poor response to training zones has previously been described (Olbrecht, 2007). The cause of volition exhaustion appears beyond the scope of this investigation. The two unsuccessful participants were euhydrated; reportedly carbohydrate loaded and adhered to all pre-trial exercise controls. The two participants also met the definitions of steady state BLa. The average and standard deviation of the participants BLa recorded during the 60-min trial (3.7 ± 1.2 mmol.L^{-1}) appear consistent with other research on continuous exercise tests examining MLSS (Heck *et al*., 1985). As a consequence of the face mask being removed to allow drinking, it cannot be discerned whether VO_2 was steady state on cessation. However, both participants maintained steady-state VO_2 for in excess of 30-min. Both cyclists were observed to be under a lot of stress on volitional exhaustion and consequently motivation did not appear to be the limiting factor. These investigators would recommend future research include an examination of the reliability of the 60-min trial. Additionally, future research into the trained state of the cyclist may prove insightful. The distinction between an index for a 35- versus a 60-min limit of tolerance is worth considering. In the context of exercise prescription, where the ideal intensity is to be steady-state, one might suggest the c-FTP metric adequate.

Strategies taken from investigations into MLSS and CP were used to measure whether quasi-steady-state VO_2 and BLa data were attained, not to expound whether c-FTP data were interchangeable with MLSS or CP. The BLa and VO_2 responses in this investigation support the concept of a steady-state being reached at c-FTP. Furthermore, the ≤ 0.2 W·kg^{-1} increment required to destabilise BLa and VO_2 support the claim that c-FTP was the uppermost intensity whereby a quasi-steady-state could be maintained.

The strength of the relationship between c-FTP and Dmax was stronger than the relationship between c-FTP and T_{Lac} ($r^2 = 0.89$, $s_{y.x} = 14$ W, 95% CI = 0.72 to 1.10 vs. $r^2 = 0.73$, $s_{y.x} = 26$ W, 95% CI = 0.64 to 1.38, respectively). Nonetheless, the LoA associated with c-FTP and Dmax were greater (+ 43 to – 7 W) than the LoA set *a priori* (+20 to –20 W). As such, we recommend that c-FTP should not be used interchangeably with Dmax or T_{Lac}. These metrics Dmax and T_{Lac} are commonly used to determine physiological thresholds, but do not have

associated limits of tolerance; namely, a defined upper limit duration (time) associated with a specific power output. This potentially highlights another likely function for the FTP test. A uniform racing pace tactic has been reported to be the fastest strategy where terrain is even, conditions still and duration extensive (Fukuba & Whipp, 1999). Under these circumstances, c-FTP is most likely a superior index to T_{Lac} or Dmax as a uniform power output pacing strategy is possible, unlike pacing using physiological indices, which are susceptible at some level to temporal changes (Jeukendrup & van Diemen, 1998).

An investigation into the interchangeability of c-FTP with CP may be worthwhile. CP "is mathematically defined as the power-asymptote of the hyperbolic relationship between power output and time to exhaustion" (Vanhatalo *et al*., 2011). However, of note, CP is reported sustainable for < 30-min (Poole *et al*., 2016), although this disparity may be explained in part by the untrained status of the participants in investigations (Poole *et al*., 1988). The landmark paper by Monod and Scherrer (1965) stated that exercise at CP could be sustained indefinitely, although the context was in respect to local muscle work, illustrated as being equivalent to "one leg" exercises, independent of respiratory and cardiovascular factors. The determination of CP also furnishes a metric named W′ which represents the fixed amount of work that can be performed above CP (Poole *et al*., 1988). The energy provided by W′ is likely to include anaerobic substrates and energy derived from oxygen stores, although, the exact physiological underpinnings of W′ are unknown (Poole *et al*., 2016). In the circumstance that CP and c-FTP were found to be interchangeable, one might posit that the difference between quasi-steady-state (c-FTP) and maximum power to be correlated with the size of W′. The FTP test has been appraised elsewhere, whereby participants were tasked with completing a 60-min time-trial as fast as possible, and the mean power achieved said to reflect c-FTP (Borszcz *et al.,* 2019). This methodology appears to consider c-FTP as the maximum intensity a participant can maintain, rather than that of a quasi-steady-state. Vanhatalo *et al.* (2011) categorised a W′ of 25 kJ as "large", however, extrapolated across a 1-h period a W′ of 25 kJ equates to 7 W, this is equivalent to a 2.3 % increase in power above c-FTP for an elite rider weighing 60-kg with a cFTP of 5 $W \cdot kg^{-1}$. The reproducibility in common performance cycling tests is typically 2 to 3% (Lamberts *et al*., 2009) and meaningful change in elite sport is suggested as being approximately 0.4 to 1.5 % (Lamberts *et al*., 2009; Pyne, 2013). The practical and or experimental significance of a 2.3%

differential between c-FTP and maximum power should perhaps be considered in the context of the purpose of the test.

The current investigation used the upper-limit of BLa change in MLSS to establish a tenet criteria to assess the claim that c-FTP was a quasi-steady-state intensity. Currently, there is a scarcity of peer-reviewed investigations into FTP. A single investigation into the interchangeability of c-FTP and MLSS reported "trivial" differences between c-FTP and MLSS (Borszcz *et al*., 2019). The associated LoA in "well trained" and "trained" populations (11.8 and 6.4 %, respectively) were reported in percentage format (Borszcz *et al*., 2019). The determination of absolute differences (W) versus percentages of differences likely requires deliberation, as a higher c-FTP would result in larger absolute LoA.

Researchers have indicated that maximum sustainable power can only be achieved with the concession of aerodynamic position (Fintelman *et al*., 2014; Padilla *et al*., 2000; Underwood *et al*., 2011). If the FTP test data were derived from a power maximised position, consideration would need to be given when applying c-FTP to a less powerful drag-optimised position. Beyond the cycling position adopted by the cyclist, part of our reluctance to appraise FTP in the field was that the average power might be affected negatively by the topography of the testing environment. Allen and Coggan (2010) introduce a non-validated algorithm termed "normalised power" (NP), which purportedly overcomes underestimates of mean power as a consequence of stochastic cycling. If validated, this weighted average could potentially facilitate the appraisal of the FTP test in the field. To compute NP the power data are smoothed using a 30-s moving average, raised to the fourth power, averaged over time and lastly the fourth root computed (Jobson *et al*., 2009). The adopted pacing strategy in the Borszcz *et al.* (2019) investigation was open and variable. This strategy is very clear but may overlook the negating effect of a variable versus a uniform pacing strategy (Fukuba & Whipp, 1999). The current study required position and power output to be held constant, and as such, our findings only reflect similar pacing strategies and conditions. Our focus was to determine whether it was possible physiologically to maintain c-FTP power for 60-min rather than to factor in "all" pacing strategies and / or positions.

In conclusion, the c-FTP test was shown to be a reliable and repeatable test. The current investigation demonstrated that the c-FTP test successfully determined 60-min power in 89% of assessed participants and prompted a quasi-steady-state BLa and VO_2 in all assessed participants. These findings are however limited to a similarly highly-trained, highly-motivated cohort. Extrapolation to lesser-trained groups would require fresh investigation. The findings herein support the utility of c-FTP as part of a pacing strategy in competition. Proceeding forwards, it appears that research into the interchangeability of c-FTP with MLSS and or CP may be worthwhile. In the instance that these tests were found interchangeable with c-FTP, the benefits would include more affordable and less time consuming testing. Noteworthy, the disadvantages of using the c-FTP test *in lieu* of physiological data is the lack of insight as to where performance gains might be made. A performance is the sum of whole body energetics that does not provide information such as fuel use, efficiency, aerobic versus anaerobic capacity. The principle limitation of the current study is that FTP was not assessed outside; where for the most part the majority of cycling is performed. However, the current investigation provides a starting point for further ecological assessment, given the demonstrated efficacy of the test. Inevitably, as Morton (2006) stated, "the single most remarkable conclusion is on the one hand such a plethora of models fit the real world so well, yet there is so much more to discover".

Chapter 4: Do Critical and Functional Threshold Power equate in highly-trained athletes?

4.1: Introduction

Critical power (CP) is the uppermost exercise intensity that a cyclist can maintain without the necessity for maximum oxygen uptake (VO_2max) and can be maintained in steady-state for up to approximately 30-min (Poole *et al.*, 1985). Although CP is associated with a physiological demarcation (the upper limit intensity that does not cause a VO_2max response), it is frequently calculated using a choice of mathematical models (Gaesser *et al*., 1995; Jones *et al*., 2010; Screedhara *et al*., 2019), see Figures 4.1 a, b and c. In contrast, c-FTP is the "uppermost power a cyclist can maintain in a quasi-steady-state for 60-min" (Allen & Coggan, 2010; Mc Grath *et al*., 2019). Similarly to CP, c-FTP is not determined using a physiological test rather using a percentage of mean mechanical power output maintained over a 20-min time-trial (Allen & Coggan, 2010).

The gold standard protocol for determining CP involves multiple cycling trials (Screedhara *et al*., 2019). Fixed power trial intensities are orchestrated with the goal of attaining volitional exhaustion, or an inability to sustain a predetermined cadence, after a minimum of 2-min and a maximum of 15-min (Poole *et al*., 1988). The fixed power trial exercise intensities may be calculated by adding power at ventilatory threshold (T_{vent}) to percentages of the difference data between power at T_{vent} and maximum power (Pmax) attained during a VO_2max test (Black *et al*., 2015; Vanhatalo *et al*., 2007). There are multiple equations that can then be applied to this data to estimate CP, with varying results (Gaesser *et al*., 1995). In this investigation, three equations were initially applied to data to determine if there was an optimal model for comparison with FTP.

The first model applied to compute CP plots power (W) against time (s) on a scatter plot, creating a hyperbolic curve (H_{model}) (Gaesser *et al*., 1995). There is a theoretical upper-limit power output on this hyperbolic curve that a cyclist can sustain indefinitely (Figure 4.1a). In mathematical modelling this point on the hyperbolic curve is termed an asymptote, and in the context of energetics reflects CP (Figure 4.1a). The second model that was applied (J_{model}) converts the hyperbolic curve to a straight-line format by plotting the product of the fixed power output assessed and duration (W_{Lim} in kJ) against time (T_{Lim} in s) (Monod & Sherrer, 1965), see Figure 4.1b. Graphically, the identification of the independent and dependent variable of these variables is difficult to discern as the W_{Lim} in this instance includes both an

independent fraction (power) and a dependent fraction (time). Nevertheless, the alternate axis is the open-ended time that a cyclist can sustain a fixed load (T_{Lim}). Consequently, W_{Lim} is placed on the abscissa and time is placed on the ordinate axis. In this linear J_{model} format, CP is equal to the inverse of the slope of the line fitted to minimise the squared errors (Bishop *et al*., 1998). The third and final model (I_{model}) applied to compute CP data also converts the hyperbolic power-time relationship into a linear arrangement (Figure 4.1c). This linear transformation is achieved by plotting power (W) against the inverse of time (s^{-1}). The I_{model} also uses linear regression to fit the data and the point of intercept with the abscissa determines CP.

The J_{model} was first introduced as a model for dynamic exercise, and plotted T_{Lim} (X-axis) against W_{Lim} (Y-axis) (Monod & Sherrer, 1965) to identify CP. This seminal paper also highlighted an "energetic reserve", a source of energy distinct from CP, as the point of the Y-intercept (W_{Lim}). This energetic reserve was later renamed W′, pronounced W-prime (Poole *et al.,* 2016). Researchers are currently unable to measure W′ directly, or indeed to define the index physiologically. Broadly, W′ purports to reflect a "finite energy store comprising O_2 stores, a phosphagen pool, aerobic and a source of anaerobic glycogenolysis" (Bishop *et al.*, 1998). The variable W′ is reportedly a fixed constant and will only replenish if power output is reduced to a level below CP (Chidnok *et al*., 2013). Practically, each Joule contained in W′ equates to one Watt for one second. The quantum of energy (J) available is limited by the magnitude of W′. The rate at which W′ is used is dependent on the amount of power produced above CP. In the current investigation, W′ data from the H_{model} equates to the integrated area between an X-intercept above CP and the associated Y-intercept on the fitted hyperbola, see Figure 4.1a. Using the J_{model}, W′ is the point of intersection of the line of best fit through the abscissa, see Figure 4.1b. In respect to the I_{model}, W′ is computed from the inverse slope of the line of best fit where power is the independent variable and the inverse of time the dependent variable, see Figure 4.1c.

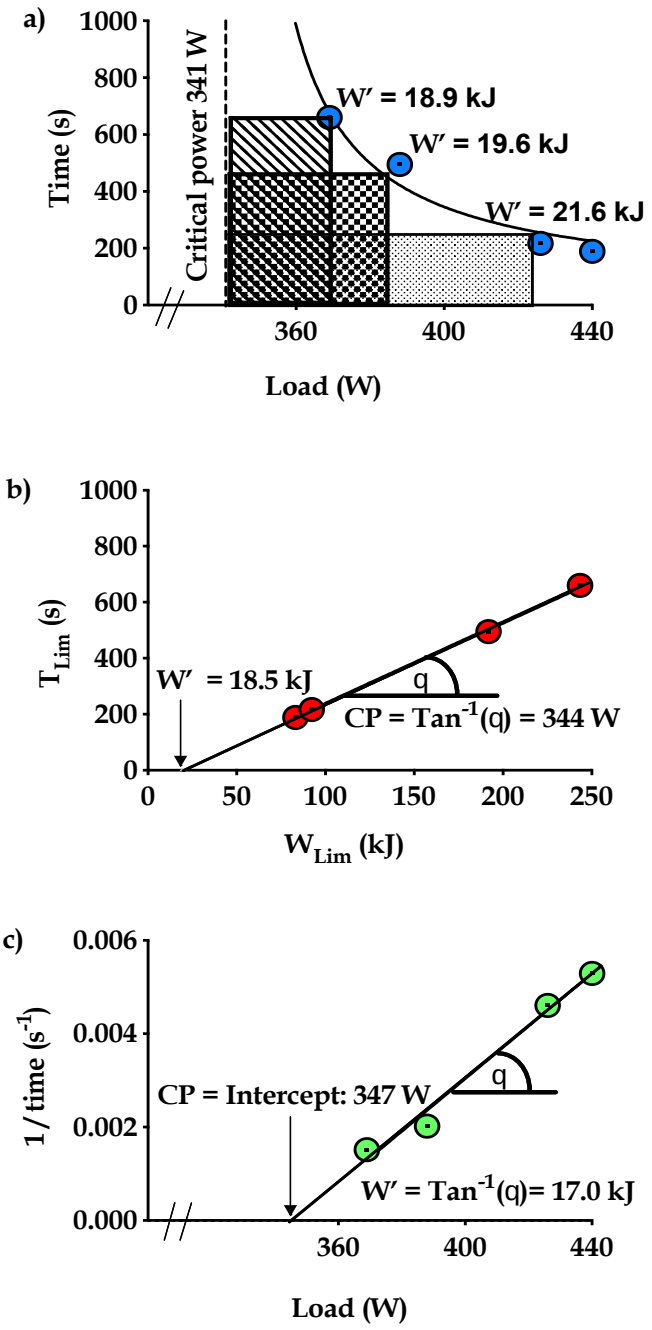

Figure 4.1: Plots of models used to compute CP and W′ for athlete "A" identifying CP and W', a) H_{model}; CP of 341 W, and three measures of W′ derived from three alternate coordinates (19.0, 19.6 and 21.6 kJ), b) J_{model}; CP of 344 W (inverse of slope of line of best fit; solid black line) and W′ of 18.5 kJ by point of intersection with the X-axis and c) I_{model}; CP of 347 W by point of intercept with the X-axis and a W′ of 17.0 kJ (inverse of slope of the line of best fit; solid black line).

Although a stand-alone index, CP is purportedly used principally in conjunction with W′ to predict the time duration a specific power output can be sustained in competition using Equation 4.1:

Equation 4.1: $T_{Lim} = W' / (P - CP)$

Where T_{Lim} is the limits of tolerance, P = power above CP, and CP is critical power.

Alternatively, rearranging Equation 4.1; the upper limit power that can be sustained for a given time can be calculated using Equation 4.2.

Equation 4.2: $P = (W' / T_{Lim}) + CP$

The foundation of these theoretical equations is that there is a power output that can be sustained indefinitely; namely, CP, and that any power output above CP is limited by the magnitude of W′. The kernel here is that if W′ lacks foundation or is variable, the predictive capacity of CP in competition is defunct. That stated our limited understanding of the underpinnings of W′ should not impact upon resolution of the relationship, if any, between CP and c-FTP.

The mean power during a self-paced 20-min time-trial is reduced by 5 % to identify c-FTP (Table 1.1). In a trained cohort, c-FTP has been shown to be sustainable for 60-min with VO_2 and BLa data remaining in a metabolic steady-state (Mc Grath *et al.*, 2019). Borszcz *et al.* (2018) investigated whether c-FTP and a 60-min time-trial could be used interchangeably. Their study concluded that these indices should not be used interchangeably as they reported wide T_{Lim} data (50.9 ± 15.7 min). The cyclists in the Borszcz *et al.* (2018) study adopted an open-paced strategy for their 60-min time-trial; however, a variable paced strategy is likely to produce a smaller mean power than a uniform power output (Fukuba & Whipp, 1999). Indeed, the creators of the FTP test furnished an incipient un-validated algorithm, "Normalised Power", that claimed to convert the additional stress of a variable power output into a constant power output equivalent (Allen & Coggan, 2010). The cyclists assessed by Mc Grath *et al.* (2019) were tasked with sustaining c-FTP uniformly for 60-min. These participants appeared to have had more success, as of the nineteen athletes assessed seventeen completed the 60-min at c-FTP, while two were unable to maintain c-FTP beyond 35-min and 52-min, respectively. Borszcz *et al.* (2018) questioned whether the first 46-min of the

FTP protocol (Table 1.1) negated the c-FTP index. These authors (Borszcz *et al.*, 2018) pointed to the FTP warm-up being too long and reported that blood lactate data were too high between the end of the 5-min maximal effort trial and the commencement of the 20-min time-trial. One might argue that the impact of the warm-up, whether positive or negative, is part of the FTP test protocol. Consequently, the adequacy of the recommended warm-up should perhaps be assessed by the outcome of the FTP test as a whole, that is, the ability to predict an upper-limit 60-min steady-state power. The nutrition strategies in these investigations may also have partly impacted on T_{Lim} data (Borszcz *et al.*, 2018; Mc Grath *et al.*, 2019), as participants drank carbohydrate beverages between minutes 10 and 50 (Mc Grath *et al.*, 2019) versus water alone (Borszcz *et al.*, 2018).

The null hypothesis of the current study was that, at the very least CP and c-FTP would correlate, as both indices (CP and c-FTP) propose to demark a change from steady to non-steady-state metabolism. Sequentially, we proposed that anticipated narrow limits of agreement (LoA) between CP and c-FTP would support the respective tests being used interchangeably.

4.2: Methods

4.2.1: Participants

The current study obtained ethical approval from the Faculty of Health Sciences Research Ethics Committee in Trinity College Dublin, see Appendix 9.1, and was performed in accordance with the ethics standards of the International Journal of Exercise Science (Navalta *et al.*, 2019). Participants completed a consent form prior to beginning any trials (Appendix 9.2). Fifteen (8 female, 7 male) highly-trained cyclists and triathletes, mean age 28 ± 6 yr participated. Mean VO_2max data ($mL \cdot kg^{-1} \cdot min^{-1}$) were 58.8 ± 4.5 and 65.4 ± 7.9 for the female and male cohorts, respectively. Mean anthropometric and related training data are presented in Table 4.1 and raw data are presented in Appendix 9.4.

Table 4.1: Mean ± standard deviation anthropometric, weekly training duration, and training experience for male (n = 7) and female (n = 8) participants.

Gender	Mass (kg)	Height (m)	BMI ($kg \cdot m^{-2}$)	Weekly volume (h)	Training (yr)
Male	74.6 ± 6.2	1.80 ± 0.05	23.1 ± 2.5	18.3 ± 2.8	5.7 ± 1.9
Female	57.5 ± 6.5	1.69 ± 0.07	20.1 ± 1.0	19.1 ± 3.1	5.9 ± 1.5

4.2.1: Protocol

Participants attended the laboratory on seven to eight occasions, in a rested, carbohydrate loaded and euhydrated state, having abstained from alcohol and caffeine in the 24-h prior to testing. A 24-h food diary (Appendix 9.2) completed prior to the first trial identified that enlisted participants were consuming a training load adjusted isocaloric diet (macronutrient breakdown; ≥ 60% carbohydrate, ≤ 20% fat and ≤ 20% protein). Each food diary was duplicated, and a single copy retained by both the researcher and participant (Appendix 9.2). Each participant was requested to replicate their food intake prior to all subsequent tests, or if different, to consume comparable carbohydrate quantities. When necessary, participants were helped to plan their pre-test meals. A full blood count was performed to screen for sub-clinical anaemia and infection. Trials were separated by a minimum of 2 and maximum of 7-day. Training loads were agreed with both athletes and coaches prior to commencing the study, with weekly training load and other stimuli remaining as constant as possible during the testing period. Exercise was limited to aerobic work for 24-h prior to each test. Prior to testing, participants endeavoured to duplicate their own bicycle geometry on an electromagnetically braked cycle ergometer (Lode Excalibur Sport; Groningen, The Netherlands), adjusting saddle height and fore-aft position, handlebar height and reach. Individual participant ergometer geometry was recorded and replicated during all subsequent ergometer tests. The same Lode cycle ergometer was used for all test sessions with the exception of the FTP test (athlete's own bicycle).

The first two tests performed were a 3-min graded incremental test (GxT) and a VO_2max test. Thereafter, two CP tests, an FTP test and two more CP tests were completed. The order of the respective CP tests was agreed with the athlete, and/or coach, so as to balance the athlete's training programme. Earlobe blood samples for lactate analysis were collected during all tests and analysed using an Arkray Lactate Pro 2 (Arkray, Shiga, Japan), which required 0.3 μL

whole blood samples and had an operating range of 0.5 to 25 mmol·L^{-1}. During all tests, breath-by-breath ventilatory (VE, VO_2 and VCO_2) and heart rate (HR) data were recorded using a calibrated cardio-metabolic cart (CPET; Cosmed, Rome, Italy).

The GxT test commenced with a 10-min warm-up at 100 and 120 W for female and male participants, respectively. The increments for the female and male cohorts were 20 and 25 W, respectively, cadence was controlled between 75 and 110 rev.min^{-1} and increment duration was 3-min. Blood samples for lactate analysis were collected at 2.5-min into each 3-min increment. Breath-by-breath ventilatory (VE, VO_2 and VCO_2) and HR data were averaged across the final minute of each increment.

The VO_2max test commenced with a 4-min load of 20 W. The female participant protocol stepped the load up to 100W in 1-s and ramped up at a rate of 25 W.min^{-1} thereafter. The male participant protocol stepped the load to 170 W in 1-s and ramped up at a rate of 30 W.min^{-1} thereafter. Tests were continued to volitional exhaustion or until cadence dropped below 70 rev.min^{-1}. VO_2max was classified as the highest mean VO_2 response across ten consecutive breaths. Data recorded during the VO_2max test data were also used to identify ventilatory threshold (T_{vent}) using the volume of the slopes of O_2 and CO_2 (V-slope method) described by Beaver *et al.* (1986). The mechanistic basis of this determination is that "excess CO_2 is generated when lactate concentration is increased during exercise because extracellular [H^+] is buffered primarily by HCO_3^- (22 mL for each mEq of lactate)" (Beaver *et al*., 1986). Prior to analysis, metabolic data were filtered into 10-s windows to compensate for breathing irregularities (Beaver *et al*., 1986). A double linear regression model was used to identify this metabolic transition from aerobic to anaerobic exercise. However, prior to applying these two lines of best fit, it was necessary to remove data at the start and end of the test to ensure the two lines of best fit were not affected by irrelevant datum points. Recorded data during the 20 W load period and the first minute of the exercise ramp were therefore excluded, facilitating an initial adjustment in CO_2 stores (Beaver *et al*., 1986). Later, if the participant commenced hyperventilation, demarked as the point of respiratory compensation (RC), the data above this point were excluded as these data did not reflect metabolic and buffering events in the tissues (Beaver *et al*., 1986). Hyperventilation was identified using a scatter plot of VCO_2 and VE, with a double linear regression applied with a constraint of > 15

% change in the slope prior to the second line being fitted (Beaver *et al*., 1986), see graphic in Appendix 9.4. The remaining VO_2 and VCO_2 data were assessed for a change in the expected slope of > 10 % to demark a transition in metabolism, see graphic in Appendix 9.4. This constraint, namely, an increase of > 10 % above that expected was built into the modelled regression lines to obscure misleading respiratory data (Beaver *et al*., 1986). The load for the CP trials was calculated by adding the load at T_{vent} minus two-thirds of the ramp rate (25 or 30 $W.min^{-1}$) to 65, 75, 85 and 90% of the delta power between T_{vent} and the maximum power achieved in the VO_2max test (Griffin *et al*., 2018). In circumstances where the participant could not complete a minimum of 2-min or exceeded 15-min, a fifth CP trial was completed to fill the pertinent void. The fifth trial was set at a load that was informed by the four pervious trials, using Equation 4.1, and the experience of the researchers (Gaesser *et al.*, 1995). Each CP trial was preceded by a 10-min warm-up at 100 W and a 5-min seated rest. Trials commenced with a low-intensity phase (4-min at 20 W, cadence of 90 $rev.min^{-1}$), the applied load then increased to the desired CP trial intensity over 1-s and thereafter remained constant for the test duration. CP trials continued to volitional exhaustion or until cadence dropped below 70 $rev.min^{-1}$. The VO_2 on cessation had to have reached 95% of that attained in the VO_2max test to be considered maximal (Jones *et al*., 2010).

The FTP test was performed on the athlete's own bicycle using Garmin pedals (Garmin, KA, USA) to measure power, with the bicycle mounted on an indoor trainer (LeMond Revolution, WA, USA). All pedals used were calibrated prior to each trial as per the manufacturer's instructions to zero offset. Having completed the FTP test, the Garmin pedals were subsequently placed on the Lode cycle ergometer and calibrated at their ascertained c-FTP to mitigate any differences in the respective devices. The corrected c-FTP (that measured on the Lode ergometer) was subsequently used for all proceeding analyses throughout the current investigation.

Endeavouring to adhere as closely as possible to the construct of the FTP warm-up, the warm-up intensity was set at 65% of Dmax as a proxy for 65% c-FTP (Mc Grath *et al*., 2019), see Table 3.2. The line of best fit for the Dmax computation was determined using third order curvilinear regression using VO_2 and BLa data at each workload during the GxT test. Thereafter, the maximum perpendicular distance to the straight line between the lowest

and highest exercise BLa data identified load at Dmax (Cheng *et al*., 1992). The athlete's c-FTP was determined by reducing the mean power across the 20-min time-trial by 5% (Allen & Coggan, 2010). In addition, all participants were fully familiarised with the FTP protocol having previously completed a FTP test prior to participation in the current study.

4.2.2: Statistical analysis

All CP and c-FTP data were analysed using Prism 7 (Graph Pad, CA, USA). Each participant's c-FTP datum was corrected to the calibrated Lode ergometer equivalent prior to any data reduction and subsequent statistical analyses. Data normality was confirmed using D'Agostino and Pearson's omnibus normality test. Group data are presented as mean and standard deviation (SD). Group comparisons were performed using one-way repeated measures ANOVA with detected differences quantified using *post-hoc* Tukey HSD testing and statistical significance was set at $P < 0.05$. ANOVA was applied to CP derived data from the H_{model}, J_{model}, I_{model} and c-FTP to identify potential differences between derived CP and c-FTP data. Derived W′ data from the H_{model}, J_{model} and I_{model} were compared (ANOVA) to assess differences, if any, between models. The results of both ANOVA calculations are presented graphically in Figure 4.2. The coefficient of determination (r^2) was calculated for the identification of CP using the H_{model}, J_{model} and I_{model} for each individual athlete. The average r^2 for all athletes within each of the three models is reported. The standard deviation of the residuals ($s_{y.x}$) between the three CP models and FTP is stated.

W′ from the H_{model} is the integrated area between an X-intercept above CP and the associated Y-intercept on the fitted hyperbola (Chidnok *et al*., 2013). The size of the integrated area changed depending on which sets of coordinates were used. Consequently, 1000 X- and Y-intercepts were interpolated permitting 1000 measures of area between 2-min and 12-min; the mean of these 1000 iterations was subsequently used as each participant's W′ datum for the H_{model}. Participant W′ data were determined as the X-intercept of the line of best fit and as the inverse slope of the line of best fit for the J_{model} and I_{model}, respectively, see Figures 4.1b and 4.1c.

Regression analysis to identify line of identity (Figure 4.3); and Bland Altman analysis with computation of 95% limits of agreement (95% LoA) were used to assess agreement between

the H_{model}, J_{model} and I_{model} with c-FTP. The 95% LoA were set a priori at + 20 and – 20 W to satisfy agreement between CP and c-FTP as these limits previously conferred c-FTP reproducibility (Mc Grath *et al.*, 2019). Bland Altman 95% LoA was also used to assess agreement between models (H_{model}, J_{model} and I_{model}) in their determination of W′. The load at Dmax was determined using the Lactate-E software (Newell *et al.*, 2007) further data analysis derived from blood lactate sampling is presented currently, as these data form part of an on-going cardio-metabolic study.

4.3: Results

Mean power ($W \cdot kg^{-1}$) at exhaustion during VO_2max testing for female and male cohorts were 6.0 ± 0.6 and 6.1 ± 0.7, respectively. The mean power at Dmax ($W \cdot kg^{-1}$) for female and male cohorts were 3.7 ± 0.5 and 4.0 ± 0.5, respectively. Mean powers ($W \cdot kg^{-1}$) during the final incremental step of the GxT for female and male cohorts were 4.9 ± 0.6 and 5.2 ± 0.6, respectively. The mean c-FTP normalised to body mass ($W.kg^{-1}$) for female and male cohorts were 3.9 ± 0.4 and 4.3 ± 0.6, respectively. See Appendix 9.4 for individual data. Detected differences between Garmin pedal and Lode ergometer power assessments were on average 1.0 ± 3.3 W (Appendix 9.4).

Mean power at CP derived from the J_{model} was significantly higher than c-FTP (282 ± 53 vs. 266 ± 55 W, $P < 0.001$), see Appendix 9.4 for individual participant data. The final comparisons between CP and c-FTP were refined to the J_{model} on the basis of the following data analyses. A one-way repeated measures ANOVA comparing CP from the H_{model}, J_{model}, and I_{model} detected significant differences ($P < 0.05$) between the H_{model} versus the I_{model}, no significant differences ($P > 0.05$) were detected comparing H_{model} and J_{model} or J_{model} and I_{model} (Figure 4.2a). The 95% LoA between the H_{model} and J_{model} were more favourable (+ 21 to -21 W) than between the H_{model} and the I_{model} (+13 and - 31 W) and between the J_{model} and I_{model} (+21 and -38 W), see Table 4.2. The calculated r^2 associated with the estimation of CP were very high, for J_{model} 99.7% (CI = 99.5 to 99.8), for H_{model} 94.3% (CI = 90.7 to 97.8) and for I_{model} 92.9 % (CI = 89.4 to 96.3). The r^2 and $s_{y.x}$ between c-FTP and the H_{model} was 0.95 and 13 W, between c-FTP and J_{model} was 0.97 and 10 W and between c-FTP and I_{model} was 0.93 and 15 W, respectively. The 95% LoA comparing CP derived from H_{model}, J_{model} and I_{model} versus FTP are presented in Figure 4.4. The tightest LoA were observed between the J_{model}

and c-FTP (+4 W to -36 W), see Figure 4.4b. The differences between all CP models and c-FTP were homoscedastically distributed. The 95% LoA for W′ were tightest between the J_{model} and the H_{model} (+5.83 and -4.61 kJ), as compared with the H_{model} and I_{model} (+19.51 and -11.02 kJ) or the J_{model} and I_{model} (+15.54 and -9.27 kJ), see Table 4.2.

The line of equality, depicted by the dashed black line in Figure 4.3, provides a visual representation of the theoretical instance whereby CP and c-FTP data equate. The blue, green and red identity lines (Figure 4.3) represent the actual relationships between loads at CP for H_{model}, I_{model} and J_{model}, respectively, and c-FTP. For the majority of assessed data pairs CP exceeded c-FTP data.

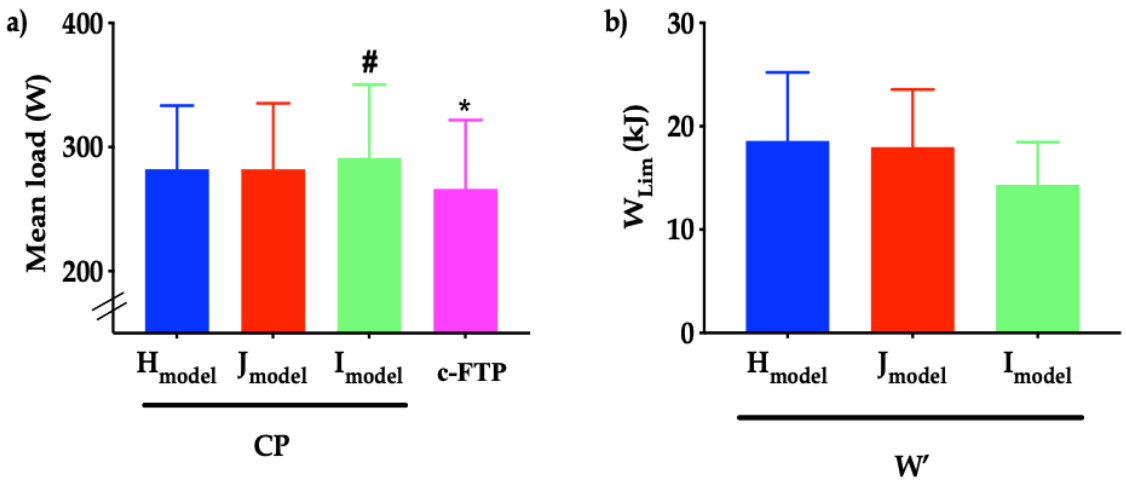

Figure 4.2: Bar graphs of mean and standard deviation data for a) CP using H_{model}, J_{model}, and I_{model} versus c-FTP and b) W′ using H_{model}, J_{model}, and I_{model}. Asterisk (*) symbol infers significantly lower than CP using H_{model}, J_{model}, and I_{model}, * infer $P < 0.001$, hash-tag (#) symbol infers CP significantly higher than H_{model}, # infer $P < 0.05$.

Table 4.2: Bland-Altman computed 95% LoA and mean bias for CP and W' using three CP models (H_{model}, J_{model} and I_{model}).

	CP 95% LoA (W)	CP mean bias (W)	W′ 95% LoA (kJ)	W′ mean bias (kJ)
H_{model} vs. J_{model}	+21 to -21	0	+5.8 to –4.6	+0.6
H_{model} vs. I_{model}	+13 to -31	-9	+19.5 to –11.0	+4.3
J_{model} vs. I_{model}	+ 21 to - 38	-9	+15.5 to –9.3	+3.6

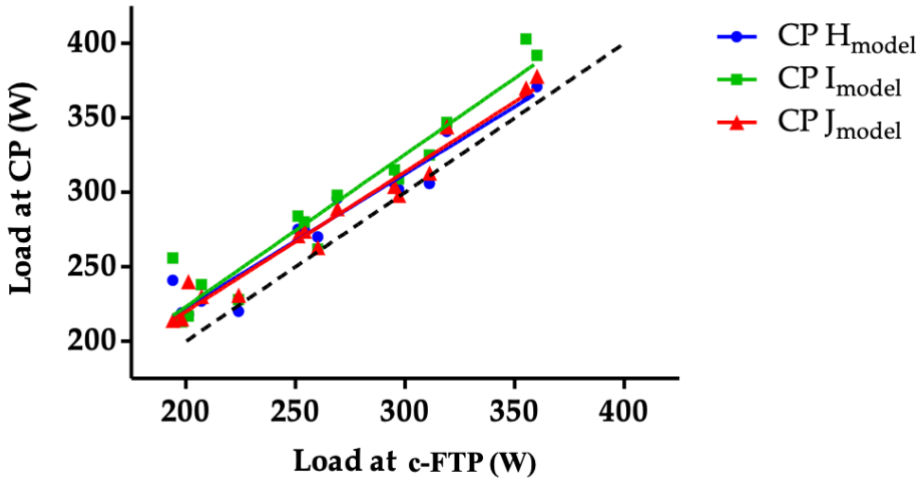

Figure 4.3: Scatter plot of CP data using H_{model}, J_{model} and I_{model} versus c-FTP. Dashed black line represents line of equality.

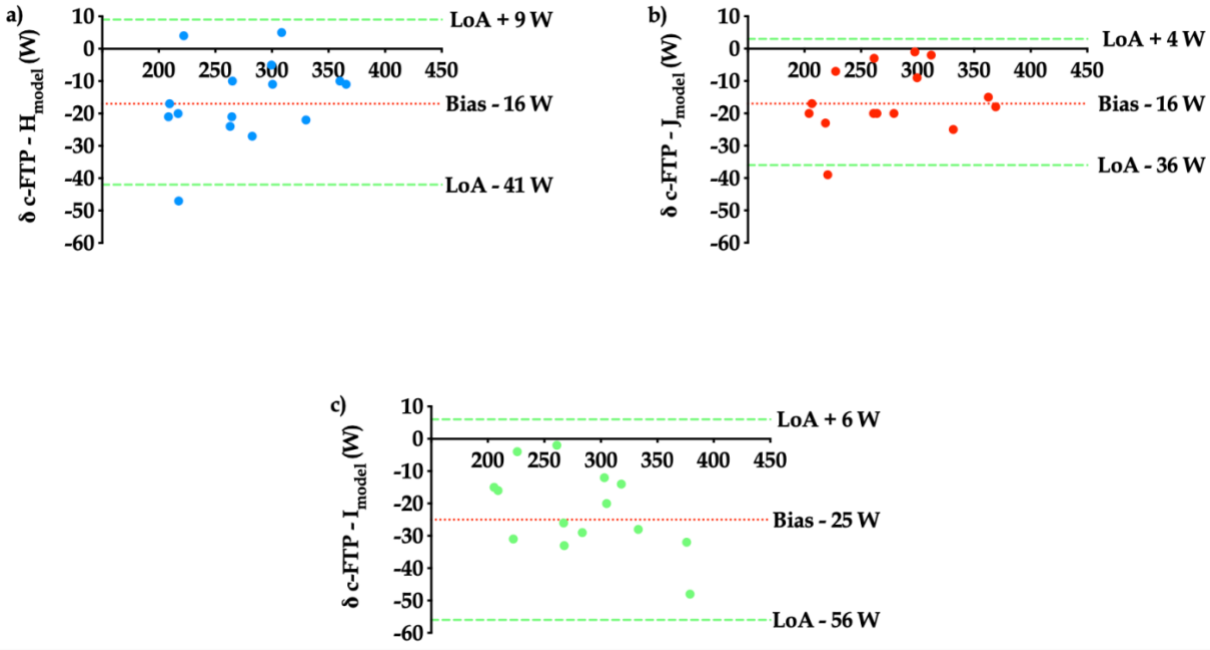

Figure 4.4: Bland-Altman plots for a) H_{model} vs. c-FTP, b) J_{model} vs. c-FTP and c) H_{model} vs. c-FTP identifying mean bias (dashed red line) and upper and lower 95% LoA (dashed green lines).

4.4: Discussion

Given the disagreement associated with disparities between fitness test indices (Cheng *et al*., 1992), three CP models were thoroughly assessed to elucidate any rationale to support the incorporation of one CP model over another, for subsequent statistical comparison with c-FTP. The correlation coefficient for the determination of CP using all three models was high and therefore we proceeded to analyse agreement between CP models and c-FTP. Having considered the results as a whole, the J_{model} was identified as the model of choice for the purpose of comparing CP and c-FTP. Chronologically, the basis of this decision was firstly that the r^2 for the J_{model} in determining CP was itself almost "perfect". Inter-CP model comparisons of r^2 is inappropriate (Gaesser *et al*., 1995), however, the J_{model} r^2 of almost 1 is reassuring. Next, the computed r^2 between c-FTP and the J_{model} was highest and yielded the lowest $s_{y.x}$ data (10 W) compared to 13 and 15 W for the H and I_{model}, respectively. Previous research (Bishop *et al*., 1998; Gaesser *et al*., 1995) concluded that the selection of a linear model (J_{model}) over the hyperbolic model (H_{model}) to determine CP might result in an overestimation of CP. The explanation for this possibility was that a fitted straight line may be projected above the longest CP trial, whereas the final datum point on the hyperbolic H_{model} is forced through the centre of the longest trial (Bishop *et al*., 1998; Gaesser *et al*., 1995), thereby, precluding an overestimation of the longest trial. However, this scenario was not apparent in the current investigation when comparing the linear J_{model} versus the hyperbolic H_{model}.

CP data derived from all three models were found to be significantly higher ($P < 0.05$) than c-FTP and consequently we can reject the null hypothesis that the two tests can be used interchangeably in a highly-trained athletic cohort. However, the range of the 95%LoA set *a priori* between computed CP using the J_{model} and c-FTP were deemed somewhat satisfactory (a range of 40 W between upper and lower 95% LoA). Consequently, if a simple correction factor was applied then either test could potentially be estimated using the alternate test. In the current study, as the individual error data between computed CP using the J_{model} and c-FTP was homoscedastically distributed (Figure 4.4b), we consequently and tenuously suggest that any correction factor should be an integer rather than a percentage. In the current cohort of highly-trained athletes the mean bias of 16 W would approximately equate to a suitable correction factor. However, given the small homogenous sample (n = 15) assessed in the

current study we suggest that further investigation is warranted evaluating other athletic cohorts of varying fitness.

The principal focus of the current study was to determine the interchangeability of CP and c-FTP, which we currently report to be inappropriate. The relevance of W′ here pertains to the natural discourse as to whether the CP or c-FTP is a "better test". If the principle use of CP is pacing or the ability to extract the minutia from exercise tests, the LoA associated with W′ in the current study may not always support this role. Ideally, 95% LoA should be rationalised *a priori* and this was not undertaken prior to commencing data collection for the current study. On reflection, we would venture to suggest that 95% LoA would need to be addressed relative to specific time epochs. The narrowest LoA, derived from the H_{model} and J_{model} were equivalent to +5.83 and -4.61 kJ. In the context of a 2-min maximal effort this equates to +48 and –38 W, whereas over a 12-min window this equates to +8 and -6 W. Applying the same concept to the wider 95% LoA reported between the H_{model} and I_{model} equates to +162 and –92 W over 2-min, and +27 and -15 W over 12-min. Therein, it is apparent that the application of CP to competition from *a priori* 95% LoA must consider individual competition duration.

The J_{model} and c-FTP both purport to represent a breakpoint between steady and non-steady-state exercise, but the J_{model} can only be sustained for up to 30-min (Jones *et al.*, 2010) whereas c-FTP has been demonstrated to be sustained for 60-min (Mc Grath *et al.*, 2019). Prior to the current investigation, we reasoned that training status might account for this disconnect as participants in many CP trials are recreational or untrained (Table 4.3), whereas recently c-FTP was sustained for 60-min in highly-trained athletes (Mc Grath *et al.*, 2019). However, the current investigation using a cross-over design infers that training status does not account for diverging T_{Lim}, rather, CP is "simply" higher than c-FTP (Figure 4.3). The confusing common description of both CP and c-FTP demarking a transition from steady-state VO_2 however remains. One might posit this may be a consequence of VO_2 measures being insufficiently sensitive to quantify the small, yet important, power difference apparent between CP and c-FTP. Although there is a 30-min difference (< 30-min vs. 60-min), the respective epochs lie at the nadir of the asymptote of the hyperbolic curve, resulting in a minimum change in load. This concept is of course speculative and requires further scientific investigation.

CP is a variable not used routinely in performance sport, possibly as a consequence of the cumbersome multiple trials required (Jones *et al*., 2010). The function of T_{vent} in the current study was to determine the appropriate load for the four subsequent CP trials. The CP trial loads derived from T_{vent} resulted in four of the fifteen participants being required to complete an additional trial as their T_{Lim} were outside of the 2- to 15-min boundary. Similarly, other investigations have reported the necessity to wait until the penultimate trial is completed to decide on the appropriate intensity of their final trial (Jones *et al*., 2007; Vanhatalo *et al*., 2007).

The cause of erroneous predictions can only be posited, but may include potential errors associated with determination of T_{vent}. The landmark paper (Beaver *et al*., 1986) that originally introduced the V-slope method for determining T_{vent} used an indwelling brachial catheter to derive blood samples from 10 healthy male participants to identify lactate threshold. Concurrently, ventilatory data were collected to identify T_{vent} comparing two methodologies, a visual inspection of data versus the objective V-slope calculation. Visual inspection of metabolic data by six experts resulted in T_{vent} being identified in just five of the ten participants, nevertheless the visual method is commonly used in CP testing (Griffin *et al*., 2018; Jones *et al*., 2007). In addition, the application of T_{vent} to well-trained athletes has been documented as questionable if the objective is to reflect blood lactate changes as a consequence of athletic training (Gaesser *et al*., 1995; Hughes *et al*., 1982). Given that the preliminary VO_2max test was performed to predict CP trial intensities, we propose that the option of a GxT based determination of CP trial loads would potentially furnish the athlete with an alternative test format deriving additional physiological and pertinent collateral performance information; namely, a lactate profile. Consequently, we trialled this concept using retrospective data gleaned from our current study data. In keeping with the calculation for CP trial intensities, whereby a fraction of a metabolic turning point in conjunction with peak power are used to project T_{Lim}, the variable T_{vent} was substituted by Dmax (a marker commonly used in athletic populations). The peak power at VO_2max was replaced by the power sustained during the final increment of the GxT. The original T_{vent} method of anticipating CP trial-loads subtracts 66% of the ramp rate power from T_{vent} prior to determining a delta calculation. This amendment reportedly accounts for the time delay in VO_2 data as a response to changes in external work (Whipp, 1987). This methodology was

not applied to the fraction of Dmax based calculation as a 3-min step rate is sufficient for VO_2 to meet the external work-load (Whipp, 1987). Load at Dmax was added to 55, 80, 105 and 130% of the power difference between Dmax and the last completed increment of the GxT. When applied retrospectively to the GxT data this proposed methodology correctly predicted all four exercise intensities that participants actually completed in the current investigation. Finally, these GxT derived calculations of appropriate exercise intensities also concurred with the predicted epochs within the 2- and 15-min limitations using Equation 4.1.

The exercise physiology literature is currently littered with numerous examples of individual physiological markers of a metabolic transition that cannot be reconciled with one another (Cheng *et al.*, 1992). The shared description, in the literature, of a metabolic transition between CP and c-FTP might be observed similarly. However, the apparent sensitivity of both the CP and FTP tests to small changes in position on the power-time curve is nevertheless exciting.

The current study is not without limitations. Although the number of participants in the current investigation is comparable to other CP studies (Table 4.3), it could still be deemed potentially statistically under-powered. However, the current homogenous athletic cohort while mitigating for this, unfortunately limits extrapolation to dissimilar individuals or groups. The adoption of two power-measuring devices is also not ideal; however, we would argue that the robust compromise used eliminated potential discrepancies. The Lode cycle ergometer is considered a gold standard in cycling research studies and was ideal for the fixed pace trials, GxT and VO_2max tests. Although it is possible to complete the FTP test on the Lode cycle ergometer using the linear mode, the cyclist's c-FTP would have to be anticipated prior to the test. Thereafter, any divergence from this pre-ordained c-FTP could only be achieved if the cyclist changed their self-selected "preferred cadence". Although this methodology has been used previously (Vanhatalo *et al.*, 2007) such a study design might be considered to bias the results. In addition, Garmin pedals can be calibrated independently and assessed on the Lode cycle ergometer to eliminate any potential power errors.

Table 4.3: Summary table of study population sizes and backgrounds in highlighted CP studies.

Author	Population Size	Study Participants
Mc Grath *et al.* (2021)	15	Highly-trained cyclists and triathletes
Bishop *et al.* (1988)	10	PE students
Black *et al.* (2015)	10	Physically active
Chidnoc *et al.* (2013)	8	Recreationally active
Gaesser *et al.* (1995)	16	Non-sports
Jones *et al.* (2007)	6	Recreationally active
Moritani *et al.* (1981)	8	Students
Vanhatalo *et al.* (2007)	10	6 cyclists, 2 runners, 2 generally fit

The current investigation clarifies that CP is a higher cycling intensity than c-FTP. Previous findings that the linear J_{model} resulted in an overestimation of CP were not borne out in our findings. The current investigation does not support the posited notion that differences between c-FTP and CP are based on trained status, as differences remained within this cross-over design study. Although CP and c-FTP share the common description of being the upper-limit in steady-state oxygen consumption, were the indices used interchangeably, the precision of tracking changes in fitness, particularly in a highly-trained cohort where the anticipated changes are smaller, is likely inadequate. Moreover, the assimilation of test data into the ensuing program would be confounding. Current results do indicate that it is possible to anticipate CP from c-FTP (or c-FTP from CP) in a homogenous group of elite-athletes. Plainly, this does not reconcile CP and c-FTP; it simply facilitates acquisition of a second physiological demarcation without additional testing.

Chapter 5: Prediction of Functional Threshold Power from Graded Exercise Test Data in highly-trained individuals

5.1: Introduction

The Graded Exercise Test (GxT) has been used both to assess clinical issues relating to health, and evaluate exercise performance (Beltz *et al*., 2016). The measured responses to each step-increase in exercise intensity typically include; heart rate, fuel utilisation, oxygen cost, and during the final stage measurement of peak oxygen consumption, and frequently in an exercise setting an athlete's blood lactate profile. A key characteristic of the GxT is that it appraises contributions from multiple individual physiological indices concurrently at each exercise intensification. Moreover, as the derived step-data is interpolated using all of the performance markers listed above, exact cycling intensities can be identified between the predefined GxT step-increases. Commonly used indices of physical conditioning derived from a GxT such as lactate threshold (T_{Lac}), load associated with 2 mmol.L^{-1} blood lactate concentration (FBLC-2), load associated with 4 mmol.L^{-1} blood lactate concentration (FBLC-4), workload preceding a fixed rise of 1 mmol.L^{-1} in blood lactate concentration (FRBL) and the maximum distance from a curve representing ventilatory and metabolic variables (Dmax), reflect specific "micro-occurrences", which infer the capacity of a subset of actual performance. Conversely, the FTP test is a 20-min maximum effort; reflecting the sum total of whole-body energetics, see Table 1.1. The computation of c-FTP is calculated by simply reducing the average power sustained over a 20-min time-trial period by 5 %. Allen and Coggan (2010) suggested that the minor reduction of the 20-min power equated to an output that could be sustained for 60-min. This proposition has been demonstrated both valid and reliable (Mc Grath *et al*., 2019), without these measurement qualities, a prediction equation would not be warranted. The basis of the small (5%) reduction in power between the 20- and 60-min cycling intervals is conjectured to be a consequence of the respective time periods being positioned close to the lowest point of the hyperbolic curve and therefore the 40-min differential (20-min test versus 60-min limits of tolerance) being associated with only a minor (5%) reduction in load (Mc Grath *et al*., 2021).

The goal of the current investigation was to derive an empirical equation to predict c-FTP from the gold standard GxT. In some respects, the strengths and weaknesses of the GxT and FTP tests appear to compliment one-another. The FTP test requires a power meter but does not require the more elaborate equipment commonly associated with a GxT; namely, a metabolic cart and lactate analyser. The FTP test does not provide any physiological data,

rather power output alone. The proponents of the FTP test highlight the advantage of using power output to pace time-trial efforts as this constant analogue is unaffected by time (Allen & Coggan, 2010). Conversely, the multiple physiological variables derived from a GxT can be influenced by a multitude of variables, for example if heart rate is used for pacing the associated power is likely to reduce over time (Coyle & Gonzalez-Alonzo, 2001). Given that the two tests (GxT and c-FTP) in their current guise provide mutually exclusive information; there is a rationale for predicting c-FTP from GxT derived data. The purpose of the current study was to identify an effective prediction model for c-FTP from GxT data from a combination of both robust statistical analyses and using established physiological principles. Published articles demonstrate variations in the GxT increments and durations can affect the gleaned data (Beltz *et al*., 2016; Jamnick *et al*., 2020). These differences may have benefited a particular circumstance but limit inter-investigation comparisons (Beltz *et al*., 2016). The derivation of a model from the current research would be limited to the same test protocols, ancillary calculations and highly-trained populations. The hypothesis of the current investigation was that a prediction model could be trained to predict c-FTP for highly-trained athletes using GxT data.

5.2: Methods

The current study obtained ethical approval from the Faculty of Health Sciences Research Ethics Committee in Trinity College Dublin, see Appendix 9.1, and was performed in accordance with the ethics standards of the International Journal of Exercise Science (Navalta *et al*., 2019). An *a priori* linear multiple regression power test was conducted with a Type 1 error probability of 0.05, a power of 0.85 and a projected effect size of 0.1. This analysis indicated that n = 74 would provide a statistical power of 85% for 2, 3 and 4 parameter models (G*Power v3.0.10 free software; Institute of Experimental Psychology, Heinrich Heine University, Dusseldorf, Germany). Inclusion criteria were that participants were; aged 18-35 years; healthy and injury free as assessed by medical questionnaire and medical assessment; competing in triathlon or cycling for a minimum of 2-years. Exclusion criteria included the following: outside the age range of 18-35 years old; high blood pressure or found to have high blood pressure during pre-screening assessment; a bleeding or clotting disorder; any diagnosed cardiac or ECG abnormalities; respiratory difficulties (based on spirometry data) or symptoms of colds/influenza on the day of testing; acute or chronic

musculoskeletal injury limiting exercise capacity; disease that would prevent participation in an maximal exercise test; deemed unfit to participate on completion of a medical questionnaire and medical examination due to an on-going illness, or having any of the following; diabetes, hypertension, heart defects, metabolic disorders or other contraindications to maximal exercise testing.

Participants VO_2peak, body mass, height, BMI and age can be viewed in Table 5.1. Participants completed an informed consent form, see Appendix 9.2, prior to beginning any trials. All enlisted participants (male n = 50, female = 20) attended the laboratory on two occasions, in a rested, carbohydrate loaded state to control for dietary induced elevations or reductions in BLa data (Maassen & Busse, 1989) and consequently maintain the power versus BLa relationship (Maassen & Busse, 1989). Athletes were requested to arrive hydrated, having abstained from alcohol and caffeine in the 24-h prior to testing. Hydration status was assessed as urine specific gravity (USG) using a mid-stream urine sample and an optical refractometry (Eclipse Professional, Bellingham & Stanley, Kent, UK). A 24-h food diary, see Appendix 9.2, completed prior to the first trial identified that enlisted participants were consuming a training load adjusted isocaloric diet (macronutrient breakdown; ≥ 60% carbohydrate, ≤ 20% fat and ≤ 20% protein). Each participant was requested to replicate their food intake prior to both tests, or if different, to consume comparable carbohydrate quantities. When necessary, participants were assisted in planning their pre-test meals. The two trials were performed within a two-week period, at least 7-days apart. Training loads were agreed with both athletes and coaches prior to commencing the current study, with weekly training load remaining as constant as possible preceding both tests. Exercise was limited to aerobic work for 48-h prior to each test.

The GxT was performed on an electromagnetically braked cycle ergometer (Lode Excalibur Sport; Groningen, The Netherlands) as this ergometer is considered the gold standard for GxT data collection (Earnest *et al.*, 2005) and can be adapted to replicate the angles of an alternate bicycle. The GxT test commenced with a 10-min warm-up at 90 and 110 W for female and male participants, respectively. The increments for female and male cohorts were 20 and 30 W, respectively, cadence was controlled between 75 and 110 rev.min^{-1} and increment duration was 3-min. Earlobe blood samples for lactate analysis were collected at

2.5-min into each 3-min increment. These blood samples were analysed using an Arkray Lactate Pro 2 (Arkray, Shiga, Japan), which required 0.3 μL whole blood samples and had an operating range of 0.5 to 25 mmol.L^{-1}. Breath-by-breath ventilatory (VE, VO_2 and VCO_2) and heart rate (HR) data, recorded using a calibrated cardio-metabolic cart (CPET; Cosmed, Rome, Italy), were averaged across the final minute of each increment. The Lode Excalibur Sport automatically adjusted the power throughout the GxT (hyperbolic mode), therefore controlling the participants power output. Participants were instructed to continue to exhaustion or until cadence dropped below 70 rev.min^{-1}. VO_2peak was classified as the highest mean VO_2 response across ten consecutive breaths (Mc Grath *et al*., 2019). The distinction between VO_2peak rather than VO_2max was on the basis of the GxT test construct exceeding 10-min, which has been demonstrated to significantly impact on the magnitude of the measured VO_2max (Buchfuhrer *et al*., 1983). The selection of a 3-min incremental test duration was on the basis that metabolic data is stable and, consequently, threshold scores are not overestimated (Foxdal *et al*., 1994).

Table 5.1: Mean (± SD) VO_2peak, mass, height, BMI and age data for participants.

	VO_2peak ($mL \cdot kg^{-1} \cdot min^{-1}$)	Mass (kg)	Height (m)	BMI ($kg \cdot m^{-2}$)	Age (yr)
Female	58.9 ± 5.1	57.8 ± 7.6	1.69 ± 0.7	20.1 ± 1.9	29.1 ± 5.0
Male	62.7 ± 8.8	75.0 ± 8.9	1.79 ± 0.7	23.8 ± 2.5	27.4 ± 5.7

The FTP test protocol was performed on the athlete's own bicycle using Garmin pedals (Garmin, KA, USA) to measure cycling power output, with the bicycle mounted on an indoor trainer (LeMond Revolution, WA, USA). The Lode Excalibur Sport ergometer facilitates self-paced time-trial efforts in "Linear Mode". However, this requires the practitioner to predetermine a specific power and associated cadence prior to testing. We considered the risk of bias to supersede the benefits of performing both the GxT and FTP test protocol on one ergometer, particularly given that the Garmin power pedals could be used on both ergometers and cross-referenced. Garmin pedals were calibrated prior to each trial as per the manufacturer's instructions to zero offset. Having completed the FTP test, the Garmin pedals were subsequently placed on the Lode cycle ergometer and calibrated at their ascertained c-FTP to mitigate against any differences in the respective devices (Mc Grath *et al*., 2021). The

corrected c-FTP (namely, that corrected to the Lode ergometer) was subsequently used for all proceeding analyses throughout the current investigation.

All participants had completed an FTP test prior to enlistment into the current study. The 20-min FTP test protocol can be viewed in Table 3.2. The order of the two cycle tests was not randomised as the GxT data was used to identify the appropriate warm-up intensity for the FTP test. The warm- up intensity was set at 65% of the alternate threshold index "Dmax" (derived from the GxT data) in keeping with previous research (Mc Grath *et al*., 2019), and utilising the recent fitness test (< 2-weeks between tests). The line of best fit for the Dmax computation was determined using a third order curvilinear regression using VO_2 and BLa data at each workload during the GxT test. Thereafter, the maximum perpendicular distance to the straight line between the lowest and highest exercise BLa data identified load at Dmax (Cheng *et al*., 1992). The instruction given to participants for the 20-min FTP time-trial was "a strong, steady effort for the entire 20 min. Do not start out too hard! Get up to speed (power) and then try to hold that speed (power). Your goal is to produce the highest average wattage over the entire period" (Allen & Coggan, 2010). Subsequently, c-FTP was determined by reducing the mean power output across the 20-min time-trial by 5% (Allen & Coggan, 2010).

5.2.2: Statistical analysis

Data normality was assessed using D'Agostino and Pearson's omnibus normality test. A single factor repeated measures ANOVA, quantified using *post-hoc* Bonferroni tests with $P < 0.05$ inferring significance, compared c-FTP versus all of the model parameters (T_{Lac}, Dmax, FBLC-2, FBLC-4 and FRBL) using Prism 9 (Graph Pad, CA, USA). For the purpose of identifying the agreement between cFTP and T_{Lac}, Dmax, FBLC-2, FBLC-4 and FRBL, acceptable 95% LoA were set as ± 20 W using Prism 9 (Graph Pad, CA, USA).

A list of potential c-FTP prediction variables from GxT data was compiled. The workloads (Watt) at the following indices were included; load at T_{Lac}, Dmax, FBLC-2, FBLC-4 and Pmax. Additionally, body mass (BM in kg) and absolute VO_2peak ($mL.min.^{-1}$) were included in the initial data gathering phase, as these data were deemed relevant to both the GxT and cycling performance. The relationship between each of these potential independent variables

(IV) versus c-FTP was first checked using scatter plots to visualise each relationship. Correlation coefficients (r) and the corresponding coefficients of determination (r^2) were calculated using Prism 9 (Graph Pad, CA, USA). Two iterations of all of these initial plots and calculations were prepared. The first used absolute data and the second used data scaled to body mass. Computed correlation coefficients of $\geq$ 0.84, and accompanying coefficients of determination $\geq$ 0.70 were determined as a minimum inclusion requirement (Bland & Altman, 1995). The interpretation of r^2 was also considered from the context of the specific field of application (Hamburg, 1983). In elite sport, meaningful improvements are relatively small (Lamberts *et al.*, 2009), and, therefore any prospective model would need to be sensitive to small biological changes.

Each of the independent variable (IV) were then correlated with one another, the rationale here was to avoid any potential distortion of the line of best fit that could not be explained because two or more parameters were measuring the same quantity within one equation. The researchers were alert specifically to the risk of collinearity between; T_{Lac}, Dmax, FBLC-2, FBLC-4 and FRBL versus Pmax or VO_2peak. For physiological reasons explained in the discussion below, the combinations of either T_{Lac}, Dmax, FBLC-2 or FBLC-4 versus Pmax or VO_2peak was permitted. This caveat was not afforded to statistical evidence of collinearity between T_{Lac}, Dmax, FBLC-2 and FBLC-4. In respect to collinearity, the following responses were considered indicators; high variation inflation factor (VIF), a sizeable drop-off between r^2 and r^2 adjusted (r^2adj) to the number of parameters included, and an increase in the *P*-value to > 0.05.

A stepwise regression, using an entry and exit α of $P < 0.05$ and 0.1, respectively, was applied to all of the non-redundant IV correlates versus c-FTP using JMP 16 (SAS Institute, NC, USA). Every permutation of the non-redundant IV correlates that passed this initial cull was further assessed as a potential parameter of a single or multi-parameter predictive equation. The following indicators were used to evaluate each equation; namely, relationship of the β-coefficient to FTP; VIF; r^2; r^2adj; the root mean square of the error with the number of parameters inserted into the equation ($s_{y.x}$); Akaike Information Criterion (AIC); and an estimation of the prediction error using a Leave One Out (LOO) cross-validation technique. The iterative process of stepwise regression facilitated the combined interpretation of

statistical results with physiological tenets. The objective of this phase of the analysis was solely to identify the apparently most suitable parameters for estimating c-FTP. LOO cross-validation was included in the model selection criteria to validate the ability of the model to predict to unseen data (athlete). The mean-squared-error (MSE) was used as the evaluation criterion. In LOO cross-validation, for each observation (athlete) in the dataset, say the i^{th} observation, the same model is fitted keeping aside the i^{th} observation and using the remaining observations (athletes) to train the model. The MSE is then calculated from the model prediction for the i^{th} observation. Finally, the average of the individual MSE is calculated, which corresponds to the LOO cross-validation metric. For linear regression, we do not need to refit the model n-times, where n is the number of observations (James *et al*., 2013). The predictive capacity of gender on the predictive model for c-FTP was assessed using comparisons of the AIC and LOO cross-validation technique.

5.3: Results

As only 70 participants met the strict inclusion criteria a subsequent *post-hoc* power analysis indicated that the current study achieved an overall statistical power of 83.5%. The calculated mean and standard deviation of power output data at T_{Lac}, Dmax, FBLC-2, FBLC-4, FRBL and Pmax can be viewed in Table 5.2. The power output at c-FTP was significantly different to Dmax (P <0.0001), FBLC-2 (P <0.0001), FBLC-4 (P <0.0001), FRBL (P <0.0001), however c-FTP was not significantly different to T_{Lac} (P > 0.99). The 95% LoA between c-FTP and T_{Lac} were +56 W to – 59 W; between c-FTP and Dmax were +60 W to – 26 W; between c-FTP and FBLC-2 were +88 W to -33 W; between c-FTP and FBLC-4 were +26 W to -60 W.

The scatter plots representing FTP versus each IV are presented in Figure 5.1. The correlation matrix of all IV that were used to give insight as to potential collinearity is documented in Table 5.3. The results of the initial regression analyses of FTP versus each IV are documented in Table 5.4, the four strongest correlates of c-FTP with the smallest $s_{y.x}$ and most favourable 95% CI were; Dmax, Pmax, FRBL and FBLC-4. These indices remained topmost when rescaled to body mass: Dmax ($s_{y.x}$ = 0.28 W.kg^{-1}, r = 0.87, 95% CI of 0.78 to 0.93); Pmax ($s_{y.x}$ = 0.26 W.kg^{-1}, r = 0.89, 95% CI of 0.81 to 0.94); FRBL ($s_{y.x}$ = 0.32 W.kg^{-1}, r = 0.74, 95% CI of 0.76 to 1.03) and FBLC-4 ($s_{y.x}$ = 0.33 W.kg^{-1}, r = 0.88, 95% CI of 0.9 to

1.2) albeit slightly inferior to their un-scaled equivalents. The results for the same analyses versus c-FTP for T_{Lac}, FBLC-2, VO_2peak and BM are also presented in Table 5.4. Four prospective model parameter options were extricated using stepwise regression. The formulae and associated $s_{y.x}$, r^2, r^2adj, VIF and AIC are presented in Table 5.5. The reported VIF and AIC for Model 4, see Table 5.5, without and with gender as a parameter were AIC 399 versus 596 and VIF 288 versus 296, respectively.

Table 5.2: Mean power (in W and W.kg^{-1}) associated with load at c-FTP, T_{Lac}, Dmax, FBLC-2, FBLC-4, FRBL and Pmax, SD in parentheses.

	c-FTP	**T_{Lac}**	**Dmax**	**FBLC-2**	**FBLC-4**	**FRBL**	**Pmax**
Male (W)	298	297	277	265	314	274	371
(SD)	(34)	(41)	(32)	(39)	(35)	(32)	(40)
Female (W)	215	222	207	200	232	205	267
(SD)	(22)	(34)	(27)	(33)	(29)	(29)	(30)
Male (W.kg^{-1})	4.0	4.0	3.7	3.5	4.2	3.6	4.9
(SD)	(0.6)	(0.8)	(0.7)	(0.7)	(0.7)	(0.6)	(0.8)
Female (W.kg^{-1}).	3.8	3.9	3.7	3.6	4.1	3.6	4.7
(SD)	(0.4)	(0.6)	(0.5)	(0.7)	(0.7)	(0.7)	(0.7)

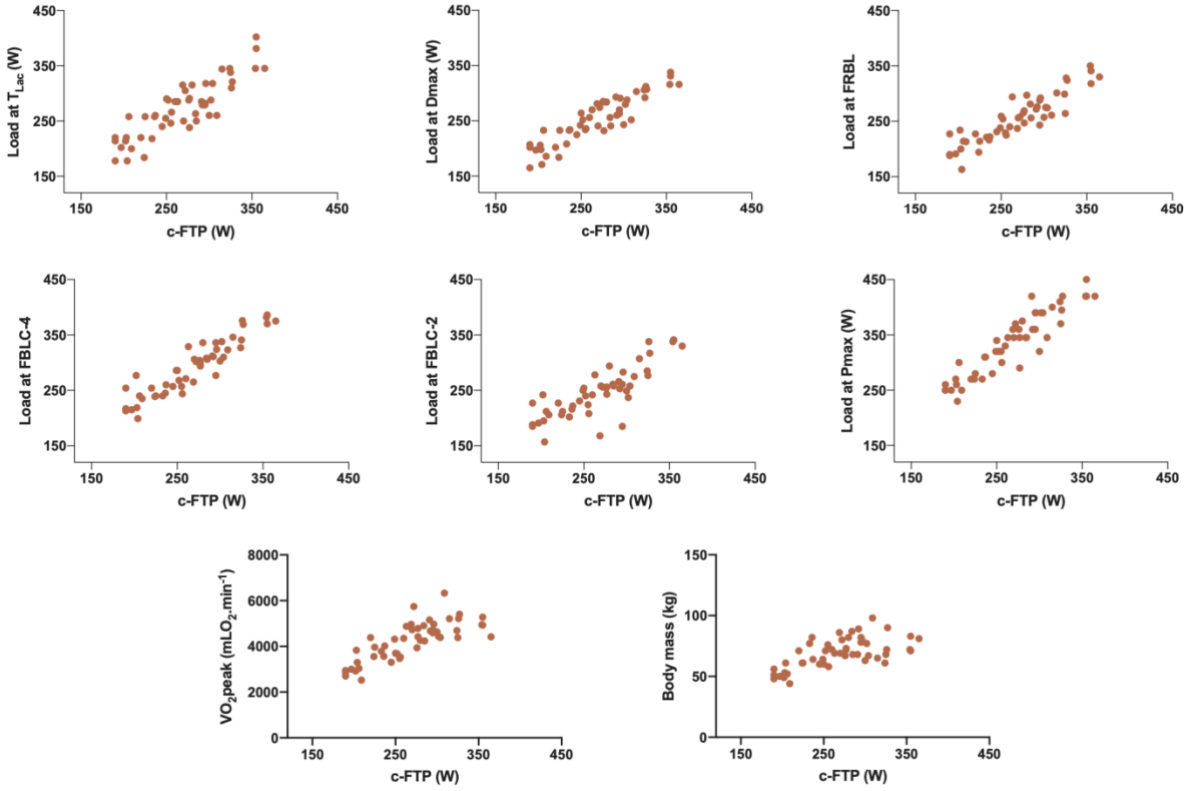

Figure 5.1: Scatter plots of c-FTP versus each individual IV

Table 5.3: Correlation matrix of IV.

	T_{Lac} (W)	**Dmax (W)**	**FBLC-2 (W)**	**FBLC-4 (W)**	**FRBL (W)**	**VO_2peak (mL.min.$^{-1}$)**	**Pmax (W)**	**BM (kg)**
T_{Lac} (W)	-	0.97	0.78	0.84	0.85	0.67	0.90	0.50
Dmax (W)		-	0.81	0.89	0.90	0.74	0.94	0.56
FBLC-2 (W)			-	0.94	0.94	0.64	0.79	0.40
FBLC-4 (W)				-	0.97	0.75	0.90	0.55
FRBL (W)					-	0.71	0.89	0.54
VO_2peak*						-	0.76	0.75
Pmax (W)							-	0.60
BM (kg)								-

*(mL.min.$^{-1}$)

Table 5.4: Regression analyses of c-FTP versus each individual IV.

	r	r^2	$s_{y.x}$ (W)	95% CI of r	*P*
c-FTP vs. T_{Lac} (W)	0.87	0.76	25	0.78 to 0.92	<0.0001
c-FTP vs. Dmax (W)	0.91	0.83	18	0.85 to 0.95	<0.0001
c-FTP vs. FBLC-2 (W)	0.83	0.68	26	0.71 to 0.90	<0.0001
c-FTP vs. FBLC-4 (W)	0.93	0.86	19	0.83 to 0.94	<0.0001
c-FTP vs. FRBL (W)	0.90	0.81	19	0.83 to 0.94	<0.0001
c-FTP vs. Pmax (W)	0.92	0.85	22	0.87 to 0.96	<0.0001
c-FTP vs. VO_2peak ($mL.min^{-1}$)	0.78	0.61	30	0.64 to 0.87	<0.0001
c-FTP vs. BM (kg)	0.63	0.40	37	0.43 to 0.77	<0.0001

Table 5.5: Prospective parameters derived from a stepwise multiple regression analyses of non-redundant IV

	c-FTP prediction equation	$s_{y.x}$ (W)	r^2	r^2adj	VIF	AIC	LOO	*P*
Model-1	13.4 + 0.64 Pmax + 0.16 Dmax	18	0.87	0.87	8.6 8.6	410	345	0.0004 0.0300
Model-2	16.7 + 0.75 Pmax	18	0.86	0.86	-	409	501	0.0001
Model-3	21.6 + 0.98 Dmax	22	0.80	0.79	-	438	334	0.0001
Model 4	-6.6 + 0.32 FBLC-4 + 0.42 BM + 0.46 Pmax	15	0.89	0.89	-	399	288	0.0001

5.4: Discussion

The requirement for this study was on the basis that our previous investigation was unable to identify a comparable threshold intensity to FTP using data derived from a GxT (Mc Grath *et al.*, 2019). To this end, a predictive model seemed to be an alternate approach, again utilising GxT data. Given the larger participant numbers in this investigation (n = 70) versus the cited previous investigation (n = 19) by McGrath *et al*. (2019), it seemed worthwhile to repeat the same statistical analyses to ensure these indices were not in agreement with FTP. Our current findings support the previous conclusion that there was unsatisfactory agreement between FTP and Dmax or T_{Lac}. This investigation concluded that Model-4 (-6.6 + 0.32 FBLC-4 + 0.42 BM + 0.46 Pmax) was the prediction model of choice. This assertion was borne from multiple statistical decisions coupled with actualities of exercise physiology. As might be

expected, the study design commenced by identifying potential correlates to be used to predict c-FTP, whilst remaining alert to the potential of collinearity in the instance that more than one prediction variable be included in a final equation. As mentioned in the methods section, scope for potential collinearity was afforded to the combinations of T_{Lac}, Dmax, FBLC-2 or FBLC-4 versus Pmax or VO_2peak. This exemption was on the basis that the power output associated with these four indices changes with aerobic fitness without an obligatory concomitant change in Pmax or VO_2peak (Olbrecht, 2007). Figure 5.2 illustrates this scenario whereby a lower power output at FBLC-4 may be observed when an athlete is in a deconditioned versus well-conditioned state, pivotally all the while Pmax conceivably remaining constant (Olbrecht, 2007). In this scenario, if for example Pmax alone were used to prescribe training, the athlete would be required to train at the same intensity whether they were well-conditioned or deconditioned. Alternatively, if FBLC-4 (or T_{Lac}, Dmax, FBLC-2) were used in conjunction with Pmax (or VO_2peak), the training load would be proportionately lower for the deconditioned athlete. As the current study population were highly-trained and all in competition-phase at the time of testing; T_{Lac}, Dmax, FBLC-2 and FBLC-4 were likely to equate to a similarly high fraction of Pmax or VO_2peak (Mc Grath *et al*., 2019). Without variation in this fraction, these four prospective IV will exhibit a statistically linear relationship with Pmax. Importantly however, these indices still provide unique insight not afforded by Pmax alone. Similarly, it was anticipated that gender would likely enhance the predictive model given findings in the literature that female athletes have lower relative VO_2max data but higher thresholds relative to their VO_2max (Stoa *et al*., 2020). However, the addition of gender did not significantly improve the error associated with future predictions. Notably, the number of females was limited as compared to the male group (n = 20 versus 50, respectively), this may have had an impact on our results.

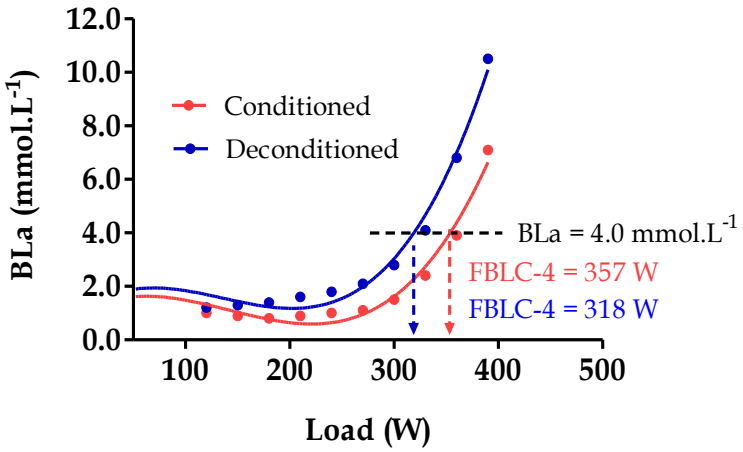

Figure 5.2: Illustrative data recorded in our laboratory depicting a change in power output at FBLC-4 whilst maintaining the same absolute Pmax load.

The study design used stepwise regression to identify the best predictor variables for c-FTP. The findings derived from each regression analysis were considered from the purview of physiology prior to being accepted or rejected as being the best prediction equation. A purely statistical comparison of Model-1 versus Model-2 would likely favour the latter equation as a consequence of the apparently similar predicative capacity and parsimony, see Table 5.5. However, the two parameters of Model-1 engaged two principle demarcations of physical conditioning; namely, aerobic fitness by using load at Dmax (Cheng *et al*., 1992) and aerobic capacity *vis-à-vis* Pmax (Bishop *et al*., 1998). Conversely, the single parameter Model-2 is limited to peak power, not necessarily an indicator of training status and not convergent with the quintessence of a GxT.

The single-parameter Model-3 was expected to reflect the trained state in the guise of Dmax, a kernel marker for current training status associated with a GxT (Cheng *et al*., 1992). However, the statistical findings herein are less favourable as the $s_{y.x}$ and AIC were higher than the other prospective models, see Table 5.5. Although the bivariate Model-1 contained succinct measures of training status, the results of the stepwise regression (Table 5.5) favoured the alternative Model-4 parameters; FBLC-4, BM and Pmax. This Model-4 yielded the lowest $s_{y.x}$ and AIC, see Table 5.5. Model-4 also demonstrated the lowest LOO,

indicating the best equation for predicting the performance of an athlete not included within a data set.

From a statistical perspective, caution should be taken when analysing these findings. Firstly, the β-coefficients cannot be used for explanatory purposes, as a consequence of some collinearity, although not enough to diminish the principles of the regression equation. Notably, the three explanatory parameters in Model-4 were still found to be significant, see Table 5.5, irrespective of the likely inflated *P*-value associated with co-variance. The IV of Model-4 can be partitioned to illustrate the redundant explanatory function of Model-4. If FBLC-4 and the Y-intercept are held constant, FTP will only increase by 0.46 W (the slope coefficient for Pmax) for every 1 W increase in Pmax. This is proportionately at odds with the relative intensity of power output at FTP versus Pmax. This can be seen in Model-2 where c-FTP equated to more than 75% of Pmax (the sample slope coefficient of 0.75 plus the constant of 17 W) and has been demonstrated elsewhere to occur at approximately 80% of the peak power reached during the same GxT protocol in a similarly trained athletic cohort (Mc Grath *et al*., 2019). That stated the main purpose of this regression model was to predict c-FTP rather than to explain the relationships of the already well-established and reliable equation parameters.

There were some decisions that were taken from the perspective of exercise science that are worth highlighting. Firstly, the GxT derived measurements of T_{Lac}, Dmax, FRBL-2 and FRBL-4 each serve similar functions physiologically; namely, to track lactate kinetics. Without any unique predictive capacity, only one of these measures was anticipated to be included in any single equation. This point did not preclude the inclusion of all four indices prior to data reduction as the purpose was to commence the regression analyses with the strongest predictors of c-FTP, rather than cherry-picking any particular marker. The merits of each of these four measurements (T_{Lac}, Dmax, FRPB-2 and FRBL-4) has polarised opinions (Cheng *et al*., 1992; Heck *et al*., 1985), and we acknowledged that some researchers may have a preference for one particular BLa calculation, hence the initial inclusion of each of them. Secondly, cycling data is frequently normalised to body mass as a way of making intra- and inter-individual comparisons. Data for c-FTP were reported in $W.kg^{-1}$ facilitating the tabulation of categorisations of the cyclist's performance capacity (Allen & Coggan,

2010). Herein, normalised data were also assessed with the view that a relationship between variables may have existed that may not have been evident when expressed in absolute terms. However, this conjecture was not reflected in our current findings. Scaling data to body mass did not appear to have any additional predictive capacity for c-FTP in this cohort of well-trained triathletes. This may have been impacted by the participants having similarly low BMI data and might differ if cyclists / triathletes with a wider range of BMI data were evaluated.

Previous investigations have sought to associate GxT derived indices with FTP, apparently unsuccessfully (Mackey & Horner, 2021), and, therefore, supporting the notion that a prediction equation was necessary. One previous investigation, by Denham *et al.* (2017), generated two relevant prediction equations, one to predict c-FTP from GxT data and the second to predict VO_2max from c-FTP (scaled to BM) and age data. The models were trained using twenty-one (n=21) inactive non-cyclists and nineteen (n=19) self-reported recreational cyclists collectively. The age profile ranged from 19 to 55 years and included just three female participants. The model to predict c-FTP from GxT data was FTP = -56.5 + 0.86 Pmax. Their computed Y-intercept will likely have a sizeable proportional effect on the data given that the reported mean c-FTP in their investigation was 200 ± 58 W (2.6 ± 0.7 $W.kg^{-1}$). This relationship might be explained in some way by the untrained group having their c-FTP occurring at a very low percentage of their Pmax, however, this is difficult to generalise to trained athletes. The equation stipulated that c-FTP had a set position in excess of 57 W lower than Pmax (the constant – 56.5 W plus the 0.86 W coefficient of Pmax using the lowest possible Pmax value of 1 W).

In respect to predicting VO_2max from c-FTP, Denham *et al.* (2017) suggested that, although the bivariate model (using c-FTP and age) to predict VO_2max was trained on a combination of recreational cyclists and sedentary individuals, the model appeared to "provide robust estimates of VO_2max even for those at the upper end of the fitness spectrum". This claim was based on Denham *et al.* (2017) applying their predicative equation to a single elite athlete from another researchers findings (Bell *et al*., 2017). Therein, Denham *et al.* (2017) used the reported power at FBLC-4 as a proxy for the individual athlete's c-FTP (as c-FTP was not actually reported). The premise of this proxy calculation was that an alternate investigation

by Gavin *et al.* (2012) had reported that c-FTP and FBLC-4 were interchangeable. Again, confoundingly, the c-FTP reported in the Gavin *et al.* (2012) study was computed using an uncontrolled 8-min field test for c-FTP and the FBLC-4 data were derived from altogether different GxT protocols. Specifically, Gavin *et al*. (2012) commenced their test at 150 W and increased power output at a rate of 25 W every 3-min, whereas Denham *et al*. (2017) commenced at 100 W and increased power output at a rate of 20 W every minute. Given that modelling already has inherent error, consistent discrepancies can only compound model inadequacies. In our investigation one particular female triathlete (swimming, cycling running) competed in the recent Olympics in Tokyo and this investigation in the same year. This provides a useful comparison with Denham *et al*. (2017) proposition of using a single elite-athlete case study to test an algorithm. This female triathlete had a body mass of 45.4 kg, a measured Pmax of 270 W (5.9 $W.kg^{-1}$) and a c-FTP of 229 W (5 $W.kg^{-1}$), Model 4 accurately predicted her FTP. This paradigm cannot be accommodated in the proposed Denham *et al.* (2017) model for c-FTP as the difference between Pmax and c-FTP was less than 56.5 W and of course the magnitude of the delta value will only increase as the coefficient of Pmax in their predictive model is 0.865. This scenario is usual where highly-trained endurance athletes have c-FTP data that occur at high c-FTP fractions of VO_2peak (Mc Grath *et al*., 2019).

The approach taken herein is unusual insofar as each statistical and physiological step is described and each decision explained. A wide variety of GxT indices were included so as to create a model that was not biased to any particular GxT metric, a contentious topic ever-present in exercise science literature (Cheng *et al*., 1992; Heck *et al*., 1985). Stepwise regression afforded the combination of science and statistics. The heuristic LOO cross-validation approach permitted better usage of the limited number of high-performance athletes available, a population sample that can be more difficult to recruit for scientific research studies.

There is nothing startling in the statement that models are imperfect (Hamburg, 1983; Morton, 2006) and that physiological tests of physical fitness have limitations (Cheng *et al*., 1992). The approach of the current investigation was in the words of Anscombe (1967) "weighing of evidence in the light of circumstances, available knowledge and theory". To

quote Anscombe (1967) a second time, “The word 'valid' should be better dropped from the statistical vocabulary. The only real validation of a statistical analysis, or of any scientific enquiry, is confirmation by independent observations." The development of this model would likely benefit from an increased number of female athletes to ensure the current analysis is accurate and gender does not enhance the model’s predictive capacity. The application of the predictive model to an alternate sport such as rowing, which uses power as an analogue and does not require the athlete to carry their entire weight (Nevill *et al*., 1992) may prove beneficial to rowers and would provide a measure of external validity for the deduced m-FTP equation.

Chapter 6: Prediction of rowing Functional Threshold Power using body mass, blood lactate and GxT peak power data.

6.1: Introduction

Functional Threshold Power (c-FTP) is the uppermost bicycling power sustainable for 60-min in a quasi-steady state (Allen & Coggan, 2010) and has been demonstrated to be valid and reliable (Mc Grath *et al.*, 2019). Undoubtedly, one advantage of the FTP test (Table 1.1) is its simplicity and accessibility (Gavin *et al.*, 2012). The creators of the test published the FTP test with details on the testing protocol; directions as to how to implement the test result into a training plan; clear strata to identify energy systems; tabulated power profile data to identify performance level; and highlight the scope of using c-FTP to monitor changes in fitness. Furthermore, the authors developed software that could be used by the athlete to record their training, retain archives, and highlight personal bests and measure of exercise stress. The inference here being, perhaps the test attributes extend beyond the FTP tests simplicity. The limitation in the context of academia to the afore-listed attributes is that these functions are hitherto unvalidated.

Comparisons have been made between the intensity associated with c-FTP and alternate endurance tests. The interchangeability of c-FTP and Critical Power (CP) was investigated as a consequence of similar physiological identifiers; namely, CP reportedly demarking the boundary between steady- and non-steady-state cycling (Vanhatalo *et al.*, 2011). However, a comparison of c-FTP and CP in a trained cohort of cyclists concluded that the tests could not be used interchangeably, although a correction factor between the indices appeared effective in predicting one test measure from the alternate test measure (Mc Grath *et al.*, 2021). Maximum lactate steady-state (MLSS) is the maximum intensity that BLa concentration increases by < 1 mmol.L^{-1} over a 20-min epoch (Beneke *et al.*, 2001). Investigators have suggested MLSS could be used interchangeably with c-FTP (Borszcz *et al.*, 2019). However, the MLSS marker is not frequently used in the field because of the number of discrete test sessions required (Lillo-Bevia *et al.*, 2022), a problem perhaps overcome by using the FTP test.

Table 6.1: Protocol used for performing the rowing FTP (r-FTP) test

		Description	Intensity
Warm-up	10 min	Endurance pace	65 % Dmax
	3 by 1 min, rest 1-min	Race cadence	2000-m race-rate
	5 min	Easy rowing	65% Dmax
	20 min	Time-trial	Maximum effort
	10 to 15 min.	Easy rowing	65% Dmax

The graded exercise test (GxT) has maintained a prevalent position for the assessment of aerobic exercise fitness. There are reported variations in the GxT protocols according to the researcher's needs or leanings. These variations highlighted by Cheng *et al.* (1992) include; the number of incremental steps, the duration of discrete steps and the magnitude of the increase in load (W). The garnered raw data are routinely collated, and an array of computerised metrics ensue (Mc Grath *et al.*, 2019). There have been attempts to identify an equivalent of c-FTP derived from a GxT, but without success (Mc Grath *et al.*, 2019). Recently, an equation to model the output at FTP from GxT (m-FTP) data was constructed and reported (Mc Grath *et al.*, 2022), furnishing another GxT-derived metric. The m-FTP equation was trained and tested on highly-trained cyclists, and reported favourable root mean square of the error ($s_{y.x}$) of 15 W; a low estimation of the error associated with the prediction derived from a Leave One Out (LOO) cross-validation technique; a strong r^2 (0.89) and r^2adj remaining unchanged to two decimal places indicating that the favourable error was not a consequence of overfitting. The m-FTP variables were; power (W) at 4 mmol.L^{-1} BLa (FBLC-4), maximum power (W) achieved during the GxT (Pmax) and body mass (BM in kg). See Equation 6.1. The m-FTP equation was derived from cycling data in highly-trained cohort of cyclists and triathletes.

Equation 6.1: m-FTP = -6.6 + 0.32 FBLC-4 + 0.42 BM + 0.46 Pmax

Where m-FTP = Functional Threshold Power modelled, 6.6 = Y-intercept, FBLC-4 = power at 4-mmol.L^{-1} blood lactate, BM = body mass (kg), Pmax = maximum 3-min power completed during the GxT.

The null hypothesis for the current investigation was that the equation m-FTP equation could accurately predict a rowing FTP (r-FTP) data in a more heterogeneous cohort of club-level male and female rowers.

6.2: Methods

Participants

The current study obtained ethical approval from the Faculty of Health Sciences Research Ethics Committee in Trinity College Dublin, see Appendix 9.1, and was performed in accordance with the ethics standards of the International Journal of Exercise Science (Navalta *et al.*, 2019). Initially, nineteen (n = 8 female, n = 11 male) club-level rowers of wide-ranging abilities were enlisted in the current investigation. Participants completed a consent form; see Appendix 9.1, prior to beginning any trials. The mean VO_2peak ($mL.kg^{-1}.min^{-1}$), body mass (kg), body mass index ($kg.m^{-2}$), % body fat and age (yr) of enlisted rowers are presented in Table 6.2. Inclusion criteria were that participants were; aged 18 to 35 years; healthy and injury free as assessed by medical questionnaire, see Appendix 9.1, and medical assessment; competing in rowing for a minimum of 2-yr. Exclusion criteria included the following: outside the age range of 18 to 35 years old; high blood pressure or found to have high blood pressure during pre-screening assessment; a bleeding or clotting disorder; any previous history of cardiopulmonary disease; respiratory difficulties or symptoms of colds/influenza on the day of testing; acute or chronic musculoskeletal injury limiting exercise capacity; disease that would prevent participation in a maximal exercise test; deemed unfit to participate on completion of a medical questionnaire and medical examination due to an on-going illness, or having any of the following; diabetes, hypertension, heart defects, metabolic disorders or other contraindications to maximal exercise.

Participants attended the laboratory on two separate occasions having abstained from alcohol and caffeine for the 24-h prior to testing. The rowers were required to attend test days in a rested, carbohydrate replete and euhydrated state. A 24-h food diary, see Appendix 9.2, completed prior to the first trial (3-min GxT) identified that enlisted participants were consuming a standard training load adjusted isocaloric diet (macronutrient breakdown; ≥ 60% carbohydrate, ≤ 20% fat and ≤ 20% protein) to control for dietary induced elevations or reductions in BLa data (Maassen & Busse, 1989). Each participant was requested to replicate

their food intake prior to the r-FTP test, or if different, to consume comparable carbohydrate quantities. Trials were separated by a minimum of 4 and maximum of 10-day.

Table 6.2: Mean (± SD) VO_2peak, mass, BMI, % body fat and age of enlisted participants.

	GxT VO_2peak ($mL.kg^{-1}.min^{-1}$)	Mass (kg)	BMI ($kg.m^{-2}$)	Body fat (%)	Age (yr)
Female (n=7)	52.0 ± 7.7	71.3 ± 11.7	23.4 ± 3.5	25.3 ± 5.6	22.6 ± 3.2
Male (n=11)	55.6 ± 9.9	85.6 ± 11.6	24.5 ± 2.4	13.8 ± 5.8	25.5 ± 6.5

The Concept2 rowing ergometer (Concept2 model D; VT, USA) does not have a calibrating option, the power output display on the PM5 is coded internally and generic among all Concept2 ergometers (Lindenthaler *et al.*, 2018). The drag factor was set for each participant according to their weight category or fitness; 130 W for heavyweight, 120 W for lightweight (Lindenthaler *et al.*, 2018). The drag factor sets the rate of deceleration of the flywheel after each drive phase of the rowing stroke is complete (Lindenthaler *et al.*, 2018). The foot-stretcher was adjusted appropriately for each participant for both tests. The first test was a 3-min graded incremental test (GxT) with a 1-min break between increments to facilitate collection of earlobe blood samples for lactate analysis. The load commenced at 100 and 120 W for the lightweight and heavyweight rowers, respectively, or on the basis of their anticipated fitness. The load increased by 20 W and 30 W every 3-min in the respective groups. To minimise measurement error on the ergometer for each 3-min segment, each rower took their initial 3 to 5 strokes to accelerate the flywheel prior to the commencement of each stage (Treff *et al.*, 2022; Boyas *et al.*, 2006). Collected earlobe blood samples were processed using an Arkray Lactate Pro 2 (Arkray, Shiga, Japan), which required 0.3 μL whole blood samples and had an operating range of 0.5 to 25 $mmol \cdot L^{-1}$. During the GxT, breath-by-breath ventilatory (VE, VO_2 and VCO_2) data were recorded using a calibrated cardio-metabolic cart (CPET; Cosmed, Rome, Italy). Heart rate (HR) data were recorded by radio-telemetry using a Cardiosport GT1 HR monitor (Cardiosport, Hampshire, UK), consisting of a coded transmitter belt and monitor.

The second test completed by each rower was the rowing FTP (r-FTP) test, adapted from the original cycling protocol (Allen & Coggan, 2010) to rowing, see Table 6.1. The test order

was not randomised as the warm-up intensity for the FTP test was set using fractions of load at Dmax calculated from the GxT (Mc Grath *et al.*, 2019). The instruction given to participants for the 20-min FTP time-trial was the same as that recommended for the cycling test, "a strong, steady effort for the entire 20-min. Do not start out too hard! Get up to speed (power) and then try to hold that speed (power). Your goal is to achieve the highest average wattage over the entire period" (Allen & Coggan, 2010). Throughout the 20-minute r-FTP test, HR data were recorded and the mean and maximum data noted. An earlobe blood sample for BLa analysis was collected at baseline (pre-test); prior to commencing the 20-min trial and having completed the 20-min time-trial. Peak BLa was compared with peak GxT data to ensure the 20-min effort was maximal. The power data was recorded on the PM5 throughout each test and transmitted via Bluetooth to Concept2 Software.

On an air-damped ergometer, the rower determines the accuracy of the targeted mechanical output via stroke force, rate and length (Treff *et al.*, 2022). Consequently, the actual power rather than the anticipate power output at each stage was used for all calculations. Breath-by-breath ventilatory (VE, VO_2 and VCO_2) and HR data were averaged across the final minute of each 3-min increment. Blood samples for lactate analysis were collected immediately following each 3-min increment.

Lactate E software was used to interpolate the power associated with a 4 $mmol.L^{-1}$ BLa concentration (FBLC-4) and the threshold index Dmax (Newell *et al.*, 2007). The power associated with FBLC-4 was identified from a third order polynomial line of best fit using least squares regression. The load (W) at Dmax was identified as the maximum perpendicular distance to the straight line between the lowest and highest exercise BLa (Cheng *et al.*, 1992). Pmax was identified at the final 3-min average load completed during the GxT. Each participant's VO_2peak was determined as the highest consecutive 60-second average during the final test increment. The description "VO_2peak" is distinct from "VO_2max" on the basis of the GxT test construct was selected to derive steady-state data, thereby exceeding 10-min in total duration, which has been demonstrated to significantly impact on the magnitude of the measured VO_2 data (Denham *et al.*, 2017). The r-FTP warm-up intensity was set at 65% of Dmax as a proxy for 65% c-FTP (Mc Grath *et al.*, 2019), see Table 6.1. The load (W) for the 3 by 1-min intervals (Table 6.1) required by the FTP test (Allen & Coggan, 2010) were

adapted to rowing using race stroke-rate as the controller. All participants were fully familiarised with 20-min time-trials prior to testing. The load at r-FTP was calculated by reducing the mean power sustained during the 20-min time-trial by 5% (Allen & Coggan, 2010).

Statistical analysis

Data normality was assessed using D'Agostino and Pearson's omnibus normality test. A single factor repeated measures ANOVA, quantified using *post-hoc* Bonferroni tests with $P < 0.05$ inferring significance, compared r-FTP versus each of the potential model parameters (T_{Lac}, Dmax, FBLC-2, FBLC-4 and FRBL) using Prism 9 (Graph Pad, CA, USA). For the purpose of identifying the agreement between r-FTP and T_{Lac}, Dmax, FBLC-2, FBLC-4 and FRBL, acceptable 95% LoA were set as ± 20 W using Prism 9 (Graph Pad, CA, USA).

An *a priori* power test was conducted for highly correlated variables with expected outcomes of a Type 1 error probability of 0.05, a power of 0.95 and a projected effect size 0.1. This analysis indicated that n = 19 would provide a statistical power of 95% (G*Power v3.0.10 free software; Institute of Experimental Psychology, Heinrich Heine University, Dusseldorf, Germany). All data were checked for normality using the D'Agostino and Pearson Omnibus normality test. Comparisons between m-FTP versus r-FTP were made using repeated measures ANOVA test with significant differences set at $P < 0.05$; intra-class correlation (ICC); standard deviation of the residuals ($s_{y.x}$); coefficient of determination (r^2) and the computed 95% confidence intervals of r (95% CI) were computed. For the purpose of comparing m-FTP with r-FTP, a Bland-Altman plot was constructed and the acceptable 95% LoA were set *a priori* as ± 20 W (Mc Grath *et al*., 2019). All analyses were performed using Prism 9 (Graph Pad, CA, USA) and group data are presented as mean and standard deviation (SD).

6.3: Results

Data checks using the D'Agostino and Pearson Omnibus normality test classified that all data were normal distributed. The power output at r-FTP was not significantly different to Dmax ($P = 0.94$), FBLC-4 ($P = 0.99$) or T_{Lac} ($P = 0.14$). The power output at r-FTP was

significantly different to FBLC-2 (P = 0.0001), FRBL (P = 0.0002). The 95% LoA between r-FTP and Dmax were +45 W to – 37 W; between r-FTP and FBLC-2 were +100 W to -2 W; between r-FTP and FBLC-4 were +34 W to -32 W and between r-FTP and T_{Lac} were +19 W to – 34 W.

One of the nineteen study participants was unable to complete the second trial due to an illness; a *post-hoc* power analysis indicated an amended overall power of 94.6%. The mean power at m-FTP, r-FTP and the predictive parameters body mass (kg), FBLC-4 (W) and Pmax (W) for the female, male and grouped cohorts are presented in Table 6.3, individual results are tabulated in Appendix 9.6. The results of comparisons between m-FTP (W) vs. r-FTP (W) including the computed 95% LoA (W), mean bias (W), relative technical error of the measurement (% TEM), ICC, r^2, 95% CI of regression and $s_{y.x}$ (W) are presented in Table 6.4. Computed variables m-FTP and r-FTP were highly correlated (r = 0.99, $P < 0.0001$, see Figure 6.1a) and no significant difference was detected between them *(*P = 0.26*;* F = 1.13, P = 0.80, repeated measures ANOVA). The computed 95% LoA were – 18 to + 15 W with a mean bias of 2 W, see Figure 6.1b, and an associated $s_{y.x}$ of 7 W. There were no significant differences detected comparing BLa data on cessation of the 20-min r-FTP test time-trial and Pmax (12.4 ± 2.7 versus 11.5 ± 3.7 mmol.L^{-1}, F = 1.84, P = 0.22) or HR data (190 ± 9 versus 183 ± 8 beats.min^{-1}, F = 1.35, P = 0.63).

Table 6.3: Mean power at m-FTP, r-FTP, and the predictive parameters body mass (kg), FBLC-4 (W) and Pmax (W) for female (n = 7), male (n = 11) and grouped (n = 18) cohorts.

	r-FTP (W)	m-FTP (W)	Body mass (kg)	FBLC-4 (W)	Pmax (W)
Female	176 (± 24)	182 (± 23)	71 (± 12)	181(± 30)	224 (± 27)
Male	265 (± 57)	265 (± 54)	86 (± 12)	260 (± 68)	331 (± 70)
Grouped	230 (± 64)	233 (± 60)	80 (± 13)	226 (± 67)	286 (± 77)

Table 6.4: Results of comparisons using regression analysis between m-FTP (W) vs. r-FTP (W) computed 95% LoA (W), mean bias (W), % TEM, ICC, r^2, 95% CI and $s_{y.x}$ (W).

	95% LoA (W)	Mean bias (W)	% TEM (%)	ICC	r^2	95% CI of r	$s_{y.x}$ (W)
m-FTP vs. r-FTP	-18 to + 15	-2	2	0.99	0.98	0.97 to 0.99	7

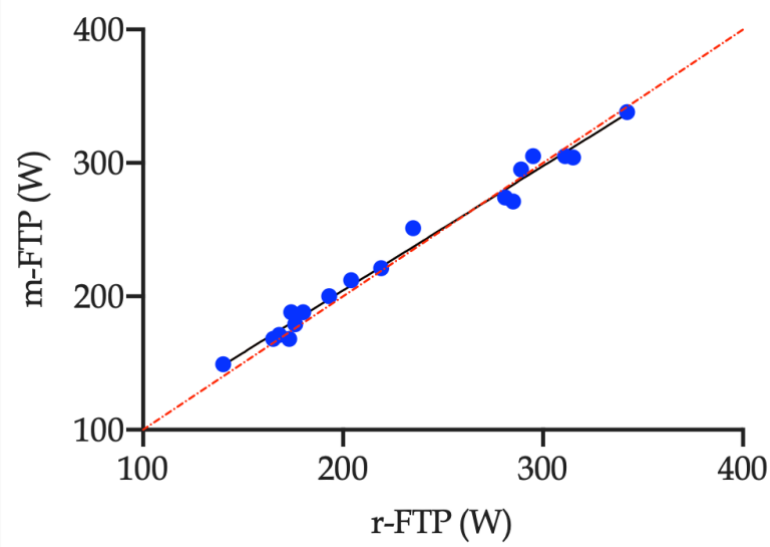

Figure 6.1a: Regression analysis of m-FTP (W) versus r-FTP (W) data. Dashed red line represents line of equality.

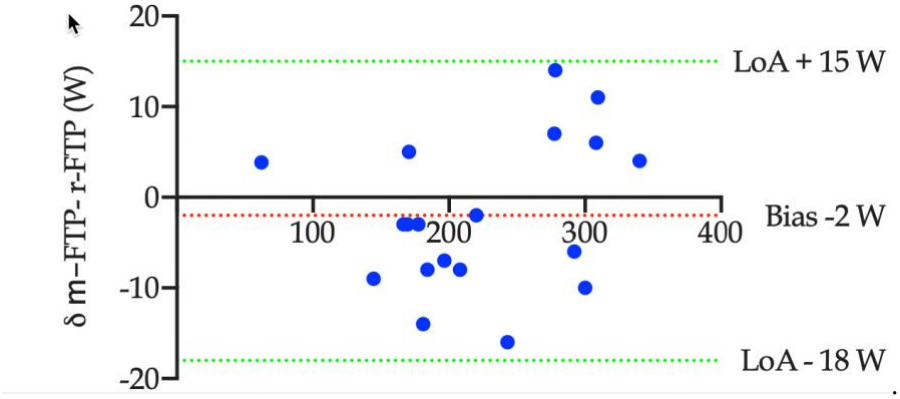

Figure 6.1b: Bland-Altman plot for m-FTP versus r-FTP identifying mean bias (dashed red line) and upper and lower 95 % LoA (dashed green line).

6.4: Discussion

The initial results of this investigation on a heterogeneously trained cohort of rowers, mirror previous finding derived from well-trained cyclists whereby BLa threshold indices were not in agreement with the respective FTP (r-FTP and c-FTP, respectively) intensities (Mc Grath *et al.*, 2019). Unsurprisingly, GxT computed m-FTP and measured r-FTP were, as anticipated, highly correlated (r^2 = 0.98). More insightfully, the 95 % LoA (-18 W to + 15 W) between m-FTP and r-FTP were comparable to those associated with repeating the same cycling c-FTP test on two occasions; namely, -17 to + 13 W (Mc Grath *et al.*, 2019). Furthermore, the 95 % LoA were found to be narrower than the limits set *a priori*, therefore supporting the usage of the cycling trained m-FTP equation to accurately predict r-FTP on a rowing ergometer. A comparison of the $s_{y.x}$ determined from the rowers data (7 W) compared favourably (15 W) with the original cycling validation study reported by Mc Grath *et al.* (2019). Lastly, the 95 % CI of regression in the current rowing investigation were much tighter than those previously derived from the determination of the repeatability of the c-FTP testing when cycling; namely 0.97 to 0.99 versus 0.87 to 1.11, respectively. These results as a whole may be interpreted as there being equivalence in completing or repeating an FTP test versus predicting FTP from GxT data. Practically, however, in a circumstance where a rower only wishes to determine their r-FTP, there is an argument for choosing the r-FTP test rather than using m-FTP equation derived from GxT data.

All rowing races at international regattas are staged on a 2000-m course (Smith & Hopkins, 2011) where time rather than power is the determinant of success. Smith and Hopkins (2011) highlighted that performance-times would be impacted by environmental changes. The sensitivity of time as an analogue for performance may also be blunted as a consequence of fluid resistance; as a 3 % change in physiological output is associated with a diminutive 1 % change in the velocity of a rowing boat (Smith & Hopkins, 2011). The limited sensitivity of time to changes in fitness provides a rationale for the inclusion of power (W) based assessment such as the r-FTP test.

The determination of the external validity of the cycling m-FTP equation was feasible as the analogue power is used on both cycling and rowing ergometers. Rowing ergometers are widely used by recreational to elite-level rowers (Mentz *et al.*, 2020). The Concept2 rowing

ergometer used in the current investigation is air-braked and resistance is created by a flywheel that is accelerated during the drive-phase and decelerated during the subsequent recovery phase of a stroke. The flywheel decelerates due to the resistance provided by the circulating air but it does not stop immediately due to the rotating mass of the flywheel and the energy stored therein (Treff *et al.*, 2022). The ergometer determines resistance via stroke force, rate and length (Treff *et al.*, 2022) using the following equation (Boyas *et al*., 2006);

$$P_{ergo} = \frac{\int_{t_1}^{t_2} C_1 \dot{\theta}^3 dt + \frac{1}{2} J(\dot{\theta}_3^2 - \dot{\theta}_1^2)}{t_3 - t_1}$$

Where θ: angular position of the flywheel (rad), J: moment of inertia of the flywheel (kg.m^2), t_1: starting time of the rowing cycle, namely the catch (s), t_2: end of the pull phase; namely the finish (s), t_3: end of the rowing cycle; namely, the next catch, C_1: constant (kg.m^2) calculated for each stroke on the previous recovery phase.

$$C_1 = -\frac{\int_{t_2}^{t_3} \frac{J\ddot{\theta}}{\dot{\theta}^2}}{t_3 - t_2}$$

Summarily, the power at the level of the flywheel is considered to be the sum of the power dissipated by air resistance and the power developed to accelerate the flywheel between two successive strokes (Boyas *et al.*, 2006).

Rowing power outputs are reportedly comparatively lower than those recorded when cycling (Steinacker *et al.*, 1986). The associated VO_2 at a fixed load (W) is therefore unsurprisingly higher when rowing (Cunningham *et al.*, 1975). Given that the predictive equation m-FTP comprises the parameter Pmax, the impact of a lower Pmax on a rowing ergometer versus a cycle ergometer was identified as a possible influence on the equations efficacy. However, this risk was considered low as Pmax and FBLC-4 are both contained in the predictive equation and the relative relationship between the indices was anticipated to be more important than the independent parameters (Equation 6.1). Previous research has argued that Pmax could be used as a standalone marker of performance. Pmax has been demonstrated to be a more stable marker than VO_2max for predicting performance as a consequence of a lower coefficient of variation (4.99 versus 7.89 %, respectively) (Kuipers *et al.*, 1985) and

there is some evidence to suggest that a higher Pmax can be associated with lower HR, BLa and oxygen uptake data (Kuipers *et al.*, 1985). However, a lack of concordance between Pmax and both peak blood lactate and VO_2max limits this association (Kuipers *et al.*, 1985). c-FTP represents a change in the upper-limit quasi-steady-state intensity an athlete can sustain for 60-min, whereas the insight derived from Pmax (Kuipers *et al.*, 1985) is that performance has changed with the absence of any insight as to the mechanistic basis. The argument for a single parameter model for m-FTP has been argued previously on the basis of parsimony (Mc Grath *et al.*, 2022), however, the authors conceded that the addition of a second parameter reflecting the more oxidative energetics was, nevertheless, worthwhile.

Mc Grath *et al*. (2022) reported that the inclusion of FBLC-4 in their m-FTP equation was questionable as a consequence of high correlation of FBLC-4 with Pmax (r = 0.90). The premise for retaining the parameter (FBLC-4) was that the relationship between FBLC-4 and Pmax varies with fitness, and therefore both indices provide unique predictive capacity. The current investigation findings appear to support this argument where FBLC-4 expressed as a fraction of Pmax ranged between 60 and 93% (mean 78 ± 7%). As it stands, the identification of the m-FTP equation was based on its predictive capacity and minimising of errors (Mc Grath *et al.*, 2022). Other investigators surmise that the errors associated with the parameter FBLC-4 versus a "turning point" (Dmax, T_{vent} and T_{Lac}) could be theoretically lower as a consequence of the calculation design (Heck *et al*., 1985). An elevated baseline BLa could impact on the identification of a turning point as this initial datum point is included in the calculation. Given that FBLC-4 is not impacted by baseline BLa data, it is insusceptible to this particular source of error. The magnitude of the errors in BLa at FBLC-4 versus "a turning point" should also be smaller as FBLC-4 is positioned on the steeper region of the BLa curve (Heck *et al.*, 1985). The premise of this conjecture is that changes in the Y-coordinate decrease relative to the independent X-coordinate as a consequence of the exponential relationship between BLa and load (W).

The third equation parameter; namely BM, has been demonstrated to have a meaningful impact on both cycling (Lamberts *et al.*, 2012) and rowing (Nevill *et al.*, 1992), as both modalities require the athlete to carry only a portion of their body mass. As such, both modalities have been scaled using a variety of models including: simple ratio; linear regression and a power function (Nevill *et al.*, 1992; Swain *et al.*, 1987). The weighting of

the individual predictive parameters can be identified by the product of the coefficient and the magnitude of the parameter. Consequently, the m-FTP equation can be considered most heavily weighted to Pmax, followed sequentially by FBLC-4 and BM.

In conclusion, r-FTP in a heterogeneous cohort of female and male club-level rowers can be accurately derived from GxT rowing data using the m-FTP equation computed from cycling GXT data recorded in highly-trained cyclists and triathletes. The application of the m-FTP to an alternate fully weight-bearing sports is possibly limited as a consequence of the coefficient of BM but this conjecture requires further investigation.

Chapter 7: General discussion

7.1: Test reliability and validity

The c-FTP test has been shown to be reliable test in a mixed gender group of highly-trained cyclists, ascertained using appropriate and rigorous statistical tools including, Bland and Altman LoA and $s_{y.x}$, rather than significance testing alone (Chapter 3). The c-FTP intensity was also observed to be a valid representation of the anticipated upper-limit steady-state intensity that a cyclist could maintain for 60-min. The homogenous groups of highly- trained cyclists from Chapters 3, 4, 5, can be considered both a weakness and strength of the study designs; findings are limited to a similar cohort but data on highly-trained cohorts are sparse (Jukendrup & van Diemen, 1988). During the c-FTP 60-min trial, power (W) was the fixed measure and HR data responded to this constant stress with a 9% (14 ± 7 beats·min^{-1}) drift across the 60-min effort, similarly to findings reported elsewhere (Mogoni *et al*., 1990). If the heart rate data associated with c-FTP was used to control a 60-min exercise bout, the inverse relationship would inevitably be observed whereby the power output would be observed to reduce over time (Boulay *et al*., 1997). This temporal relationship between power output and HR data provides a fundamental argument in favour of power output versus HR in achieving an even-pacing strategy in competition. However, in the circumstance that the target of the exercise indicator is to incur a constant physiological stress, HR is likely a superior index as it accounts for reductions in end diastolic volume (Souissi *et al*., 2021). Beyond the control of exercise intensity, HR has a role in detecting over-training using simple markers such as elevated morning HR and reduced maximal HR (Jeukendrup & van Diemen, 1998). The cyclists in the investigations described herein were positioned in a road-bike position that was consistent throughout all trials (Chapters 3, 4 and 5). The subsequent use of HR, VO_2 or power data for exercise prescription requires adaption to alternate bike positions. The variations are reportedly small; 2.2 % increase in heart rate, 2.5% in oxygen consumption moving from a seat tube angle of 69 to 83° (Heil *et al.*, 1995).

7.2: Exercise prescription

The power outputs derived from the BLa threshold calculations were not interchangeable with c-FTP (Chapter 3), whilst notably both are used to prescribe exercise (Allen & Coggan 2010; Jeukendrup & van Diemen, 1998). Allen and Coggan (2010) used percentages of c-FTP to create seven discrete zones for training (Table 1.2). Given the demonstrated validity and reliability of c-FTP, further studies directed towards the purported extracted training zones

might be worthwhile. Future research would likely require a gap to be inserted between each training zone to facilitate the sensitivity of the measurement error (Chapman *et al.*, 2011). Some of the findings herein provide some minor support for the tabulated training zones (Table 1.2). Firstly, the umbrella term "lactate threshold" (c-FTP is the multiplicand) or "Level 4" can be observed to have a 14 % range (Table 1.2). The range commences 9 % below c-FTP and continues to 5% above c-FTP. The laboratory BLa indices investigated in Chapter 3 were all lower than c-FTP and the corresponding "Level-4" range is weighted to a power output that is 9 % lower than FTP. Secondly, "Level 5" or the VO_2max training zone is identified as being 105 to 120% of c-FTP (Table 1.2). Cycling at a power output of 100 % of c-FTP was shown to be significantly below VO_2peak (Chapter 3) and therefore support the omission of 100% of c- FTP from the range of "Level 5" or VO_2max training. Also, the lower limit of Level 5 training (105 % c-FTP) was demonstrated as provoking VO_2max in Chapter 3 during the 20-min trial-trial component of the FTP test, supporting this lower limit required to provoke VO_2max.

There is, however, a converse argument that sustains if Dmax (a BLa measure of threshold, Chapter 3) reflects an exact measure of threshold. Using the data derived from the 70-participants reported in Chapter 5, the power output at 90 and 105 % of c-FTP exceeded BLa threshold in 23 (33%) and 65 (93%) and in the latter by an average 35 ± 21 W of the seventy participants, respectively. This scenario presents a risk of poorly targeted training, whereby the targeted training response (threshold) is not being appropriately stimulated. Instead, the athlete would adapt to the more anaerobic supra-threshold stimulus. There is also a potential risk of an imbalance between training and recovery if the athlete considers the required rest on the basis of a threshold workout, in other words "overtraining" (Kuipers & Keizer, 1988). The ever-continuing comparisons between BLa thresholds are discussed in Chapter 3. All of the BLa measures of threshold reported in this thesis are identified as a single unit of the independent variable rather than a range of intensities. The fervent discourse regarding the "best" threshold index is normally softened with the acknowledgement that no threshold measure is perfect. The posit therefore that threshold is not anticipated to be an unaltering single unit is rationale. The inexact derivation of the T_{Lac} threshold provides a clear example. The T_{Lac} calculation commences with the division of log-transformed VO_2 and BLa data points into two segments. The consequentially linear relationship is expressed

mathematically as the power-law in Equation 7.1. The point of intersection (Figure 7.1) "threshold" is assumed to belong to both segments rather being identified as "aerobic" or "anaerobic". This dichotomy cannot reportedly be solved with statistical reasoning (Beaver *et al*., 1986). A comparison of the c-FTP training Zone 4 with T_{Lac} threshold is impacted by the decision to appoint the line of intersection as "aerobic" or "anaerobic". The judgement to allocate threshold to the lower demarcation (Beaver *et al*., 1986; see Figure 7.1) seems sensible, given the far reaching health consequences of overtraining (Morton, 1996). To be clear, the suggestion here is not that an athlete should avoid supra-threshold training, nor that threshold training is recommenced. The point is that the intended training prescription needs to match the actual intensity, and that the impact of incongruencies is not limited to over-training but includes misdirected training adaptations. For example, BLa threshold might be used to stimulate a high oxidative metabolism but without a concomitant net lactate increase (Kindermann *et al*., 1979). Alternately, the LoT calculated from CP might be used to expose the athlete to a BLa equivalent to competition, whatever the quantum.

$$[La^{-}] = [La^{-}]_o \left(\frac{\dot{V}O_2}{\dot{V}O_{2\,o}}\right)^b$$

Equation 7.1: $[La^{-}]$ = lactate concentration; $[La^{-}]_o$ = lactate concentration at threshold; $\dot{V}O_2$ is the oxygen uptake; $\dot{V}O_{2\,o}$ = oxygen uptake at threshold

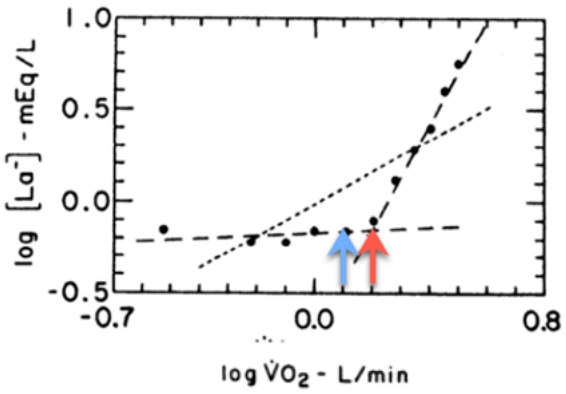

Figure 7.1: Log transformed oxygen consumption versus log transformed BLa data adapted from Beaver *et al*. (1985). The red arrow indicates the shared point of intersection. The blue arrow indicates the elected point preceding the point of intersection as "threshold".

The tabulated sub-threshold training zones, levels 1 to 3 in Table 1.3, were not directly appraised in the FTP test. In the current investigation (Chapters 3, 4, 5 and 6), the participants responses to these tiers were measured during the GxT using HR, BLa and VO_2 data. The measurement of BLa at these low intensities may inform the readiness of the athlete to proceed to higher intensity work. The acme of these comparisons is that power outputs equivalents may be derived from the c-FTP test but without inferences of the associated energetics. As described in Chapter 1, a consequence of endurance training is that more lactate is used as a fuel, and the lactate measured using the devices in this project (YSI 1500 Sport lactate analyser and Lactate Pro 2) quantify the net lactate, that is the amount of lactate produced minus that which has been recycled. In very highly-trained athletes this can manifest in close to maximum efforts being made by an athlete with low associated net BLa data. In the circumstance that the athlete has access to pulmonary data, the comparison of oxygen cost at a specific intensity versus VO_2peak or VO_2max, affords insight to the associated stress (Jeukendrup & van Diemen, 1998). The 20-min FTP trial may also give similar insight insofar as the effort is the sum of bioenergetics. Jeukendrup and van Diemen (1998) recommended that exercise stress is considered from the perspective of total ATP hydrolysed (see Chapter 1). Hydrolysed ATP is converted to mechanical energy per minute ($kJ.min^{-1}$), therein power output is posited to be the most direct indicator of energy expenditure *in vivo* (Gaesser & Brooks, 1975). The election of a particular method for controlling training intensity and training prescription is a decision for the athlete and is not limited to a single approach (*vide supra*).

The tabulated power-based training intensities (Table 1.2) are accompanied in Allen and Coggan's (2010) book with a "Power Performance Chart", see Appendix 9.3. The chart correlates competitive category (from untrained non-racer to world-class professional) with their power output scaled to body mass (kg) at; c-FTP; peak 5-s power and peak 5-min power. These unverified tables could be used out of competition to identify the athletes projected level of cycling performance, for example the power outputs associated with a world-class professional female for Zone-7 range from 17.7 to 19.4 $W.kg^{-1}$. Allen and Coggan (2010) suggested that the categorisations and classification of these epochs informed the cyclist as to their relative strengths and weaknesses. This categorisation could also feasibly inform a coach as to a cyclist's readiness to compete at a specific level of racing, a decision that a

coach might consider as a duty of care. There are however questions regarding the appropriateness of scaling power output to body mass without consideration for pertinent variables such as rolling resistance and varying drag (Swain *et al*., 1987). The use of BM as a scalar is reportedly more succinct to hill cycling where gravity is the primary limitation to travelling velocity (Swain, 1987). However, during higher-velocity flat cycling, the reliance on BM alone would likely result in imprecise projections, most notably as the ratio of surface area to body mass in not proportional (Swain, 1987). Theoretically, with all other considerations held constant, a cyclist with a body mass of 50-kg versus a cyclist with a body mass of 60-kg will travel at the same velocity on an incline if both cyclists produce a power output of 4 $W.kg^{-1}$. Conversely, if the same two cyclists maintained 4 $W.kg^{-1}$ on flat terrain, the heavier cyclist's velocity would exceed that of the lighter cyclist (Chapter 1). This inexhaustive allometric scaling (Huxley & Teissier, 1936) might then be considered a limitation of the "Power Performance Chart" (Appendix 9.3). The Power Performance Chart notionally provides the athlete with a measure of the required mechanical power outputs that are required for each stated level of competition. In circumstances where the athlete cannot produce the targeted power output for an equivalent time period, for instance 5-min (Appendix 9.3), the defined mechanical output could still be spliced into shorter intervals. This approach has been demonstrated effective from a mechanical power-output perspective (Astrand *et al*., 1960), and the ratios of work to rest can be adjusted to target suitable collateral circulatory and respiratory responses (Astrand *et al*., 1960). The oxygen intake during the initial period of an interval will not correspond to the energy demand due to a time lag in respiration and circulation (Astrand *et al*., 1960). The speed of the pulmonary response to match the energetics required for interval training varies with fitness (Berger & Jones, 2007). Unlike many single-variable scientific interventions, the athlete is required to combine and overlap multiple factors to derive a training outcome. A young male cyclist attended our laboratory for testing. The cyclist had received their first professional cycling contract that same year. In training, this cyclist was recommended to approach VO_2max intervals using a blend of laboratory measurements and Allen and Coggan's (2010) principles. One of the constructs of the VO_2max intervals was 6 by 4-min at 125 % of c-FTP, resting 5-min. Although this cyclist could stimulate VO_2max at <120 % of c-FTP as per the tabulated range (Appendix 9.3), the adoption of 125 % c-FTP was firstly on the basis that the pulmonary response to match the energetics (125 % of c-FTP) were sufficiently fast that each 4-min

interval derived a minimum of 2.5-min at VO_2max. The higher mechanical power associated with a 4-min interval versus a 5-min interval was considered necessary due to the cyclist smaller body mass (*vide supra*). The "World Class" 5-min power output was deemed to require inflating to 7.33 $W.kg^{-1}$ as compared to the cyclist's actual 5-min peak power of 7.10 $W.kg^{-1}$.

The same young cyclist described above competed in a multi-stage race that commenced with a prologue. The cyclists' CP and W′ were calculated and the winning time from the previous year's prologue was used to identify the required duration of the effort (LoT). Using Equation 4.2, the upper-limit power was anticipated. The cyclist superseded the power output by 40-W across the 330-s race, or 13.2 kJ (330-s multiplied by 40-W). From a performance perspective, were the cyclist not to have taken the initiative to ignore the planned power output, the result would have been underwhelming. The miscalculation measured in Joule, would be classified as lying outside the 95 % LoA in the comparison between the H_{model} and the J_{model} and inside the 95 % LoA between the H_{model} and I_{model}, and J_{model} and I_{model}. The context of the impact on performance to the cyclist in the field versus a statistical appraisal of a line of best fit in regression provides insight to the academic researcher.

The authors of the FTP test (Allen & Coggan, 2010) stated that c-FTP can be assessed outdoors. The approach herein was to appraise the FTP test in a controlled laboratory setting. The controlled setting permitted less confounding variables, and was judged as a better starting point than an attempt to satisfy ecological criteria and inevitably concluding that further data with tighter controls would be required. Proceeding forwards, an indoor FTP test could be compared with an outdoor test, plausibly without the necessity for expensive and the possibly risky carriage of costly mobile metabolic apparatus. Combining the metabolic and BLa data from the GxT, the 20-min test and the 60-min trial at c-FTP, it appears that criteria for MLSS were partly met (Chapter 3), apparently the second investigation to publish such findings and the first publication that had both male and female athletes. The findings hitherto (Chapter 3) informed the direction of Chapter 4 that proceeded to compare FTP and CP. In the event of FTP and CP being found to be interchangeable, the conjecture was that by default, the difference between FTP and 60-min maximum power output would be equivalent

to W′. However, the outcome of Chapter 4 was that CP and c-FTP were not the same exercise intensity, albeit that the single test format c-FTP could predict CP using a correction factor.

In Chapter 4, the ventilatory threshold was calculated to determine exercise intensities required to determine CP, rather than to derive any specific pulmonary response to exercise. The multistage process of determining T_{vent} appears to require more expertise and time as compared to other computerised indices of threshold. With this in mind, Chapter 4 retrospectively applied study data to an alternate calculation using the Dmax threshold to predict trial LoT. The endeavour therein was to set a precedent whereby future investigators would have the option of either index (Dmax or T_{vent}) depending on the particular study and athlete needs, to quote Astrand (1984), "At present there are many protocols applied for exercise testing. It will be difficult to get one internationally accepted standard methods, and I do not think that would be desirable. The purpose of an exercise test varies".

In Chapter 4, comparisons between c-FTP are reported using three different calculations for CP. The context of the results should be considered from the perspective of c-FTP versus the most statistically convergent iteration of CP ("J_{model}"), a best case scenario. The null hypothesis that CP and c-FTP would correlate was accepted but the associated LoA between CP and c-FTP tests were too wide for the calculations to be used interchangeably. A simple and presently unique correction factor is recommended to convert c-FTP to CP. Importantly; the power output at CP was reported to be higher than FTP, explaining the reported discrepancies in the LoT (Chapter 4). This fundamental finding provides clarity to a perpetual threshold-related question as to whether differences stem from power output or nomenclature.

The role of CP in pacing race outputs is based entirely on the validity of W′. There were differences in the magnitude of W′ between the three CP models, and within the H_{model} (Chapter 4). The findings of this investigation prompt the proposition of establishing LoA *a priori* that are considered from the perspective of the range of times 2-min to 15-min, an approach not seen in the observed CP literature to date.

The power output at FTP was not demonstrated to be convergent with T_{vent}, T_{Lac} or Dmax. The concept of repeating the process of the GxT but altering the GxT step increases was

considered from the perspective of changes in the step durations impacting of estimations of T_{vent}, T_{Lac} or Dmax (Heck *et al*., 1985). However, the 3-min steps were identified in this investigation as a minimum for the purpose of establishing a steady-state physiological response. Alternatively, the concept of increasing the step durations was also rebuked on the premise that c-FTP was shown to be higher than T_{vent}, T_{Lac} or Dmax and increasing the step duration beyond the 3-min would reduce the load associated with the BLa threshold measurements (Heck *et al*., 1985). Consequently, the research changed direction and developed a model (m-FTP model) to predict FTP from collected GxT data; namely, the three-parameter model developed in Chapter 5.

7.3: Rowing FTP

A search of the literature did not retrieve any studies examining the FTP test in the modality of rowing. The focus of Chapter 6 was the determination of the efficacy of the application of the m-FTP model to rowing (r-FTP). The predictive capacity and associated error reported in Chapter 6 support the implementation of the r-FTP model. The comparative LoA between the repeated c-FTP test (Chapter 3) versus the m-FTP (Chapter 5) and the r-FTP (Chapter 6) provide an ardent argument for the models efficacy. The participants in Chapter 6 were a more heterogeneous group than those that partook in the study to train the m-FTP (Chapter 5), but this variation does not appear to have negated the models performance. Although more is now understood about c-FTP in the context of cycling, and certain commonalities with rowing are likely, further research on c-FTP and rowing is required. Chapter 3 required cyclists to sustain c-FTP for 60-min in a quasi-steady state, this same assessment in rowing would be insightful. Rowing is reportedly associated with more injury-issues than cycling (Lindenthaler *et al*., 2018) and consequently there may be utility in assessing the rowers' VO_2 and BLa data for a shorter time-period such as 30 or 40-min rather than 60-min. This may mitigate the structural mechanical stress associated with rowing for protracted periods whilst still potentially achieving insight concerning MLSS over the latter 20-min epoch.

7.4: Study limitations

The study findings are limited by the number of participants that partook in the series of investigations detailed in Chapters 3, 4, 5 and 6. Some participants were unable to complete all of the required trials for reasons ranging from sickness to busy competitive schedules. In

Chapters 3, 4 and 5, the potential benefit of being a University based laboratory that could recruit varsity participants may have been compromised by the requirement for highly-trained participants. Chapter 4 sought to compare FTP with CP, which required a total of 7 to 8 visits to the laboratory on separate days. The requirement on particular test-days to complete a 2-min and 5-min (approximately) LoT trial may have been difficult for the potential participants to reconcile with the logistics of travel, forfeiting other exercise training, or other considerations such as the cumulative time requirements. Although the investigation comparing CP and FTP is apparently underpowered, Table 4.3 illustrates the alternate prominent and widely cited investigations on CP. Perhaps surprisingly, it is evident that the homogeneity and number of the study participants herein compares favourably with alternate CP investigations. This damning point highlights the potential merit in finding a comparable index to CP that requires less exercise trials.

The gender balance between studies was satisfactory in Chapters 3, 4 and 6 with a male to female ratio of 12 to 7; 7 to 8; and 11 to 8, respectively. The investigation in Chapter 5 was heavily weighted to male participants, 50 male to 20 female. Although gender was not found to add insight as a predicative parameter in the context of Chapter 5, this finding is undermined by the cohort's gender imbalance.

The requirement for a measure of aerobic fitness to control the warm-up intensity took precedence over the randomisation of tests. The potential negative impact of non-randomly assigned test sequences should be considered a study weakness. In Chapters 3 and 4, two alternate power measuring devices were used in each investigation. This study limitation was acknowledged but considered preferable given equipment limitations that would limit exercise trial design (*vide supra*). The assessment of the VO_2 response to the projected 60-min trial at c-FTP was limited as the facemask was deemed a sizeable burden to the participant for such a prolonged time-trial and as it would have prohibited the ingestion of fluids *ad-libitum*. The negative impact of removing the face mask for the middle section of the protracted trial was highlighted when the two participants that could not complete the entire time-trial retired at a time when VO_2 data were not being measured. The m-FTP was trained using potentially transiently collinear parameters (Chapter 5). The purpose of the ensuing model is therefore limited to the prediction of m-FTP and cannot be used to infer

individual relationships between Pmax, BM, FBLC-4 with m-FTP. The ecological validity of the c-FTP and r-FTP have not been demonstrated in this series of investigations. The findings are limited to indoor cycling and rowing ergometry.

7.5: Conclusions

The aim of the first investigation was to assess the reliability of the Functional Threshold Power test (FTP) and validity of the corresponding intensity, reportedly sustainable for 60-min in a "quasi-steady state". Satisfactory agreement between FTP tests was detected (95% LoA = +13 and -17 W, bias +2 W). The 60-min effort at c-FTP was successfully completed by 17 participants, and BLa and ventilatory data at c-FTP were classified as quasi-steady state. A 5% increase in power above c-FTP destabilised BLa data ($P < 0.05$) and prompted VO_2 data to increase to peak GxT rates. The FTP test was deemed representative of the uppermost power a highly-trained athlete can maintain in a quasi-steady state for 60-min. Agreement between repeated 20-min FTP tests was judged acceptable.

The purpose of the study presented in Chapter 4 was to determine whether Critical Power (CP) and c-FTP could be used interchangeably for a highly-trained group of cyclists and triathletes. The J_{model} and c-FTP were not found to be interchangeable as ANOVA detected significant differences (282 ± 53 vs. 266 ± 55 W, $P < 0.001$) between these indices and the associated Bland-Altman 95% limits of agreement exceeded those set *a priori*. As the J_{model} was found to be consistently higher than FTP, a correction factor was posited to anticipate CP from c-FTP in this homogenous group of athletes using the mean bias (16 W). An alternate method for assessing CP trial intensities using Dmax as a proxy for T_{vent} was proposed.

The findings from Chapter 4 prompted the study reported in Chapter 5. The purpose of this phase of the research project was to derive an equation that could predict c-FTP from GxT data. Previous investigations to determine a comparable marker derived from a GxT data have had limited success to date. Consequently, the investigation aimed to predict c-FTP from GxT data to provide an additional index of cycling performance. This investigation concluded the model "m-FTP" (FTP =-6.62 + 0.32 FBLC-4 + 0.42 BM + 0.46 Pmax) was the prediction model of choice.

The purpose of the final investigation (Chapter 6) was to appraise the efficacy of the m-FTP model in a more heterogeneously-conditioned group of rowers. The Bland-Altman 95 % limits of agreement between the r-FTP and the m-FTP were -18 W to + 15 W), the $s_{y.x}$ was 7 W and the 95 % CI 0.97 to 0.99. The m-FTP equation was demonstrated to be resilient to both the alternate modality and heterogeneously-trained cohort. The incorporation of the m-FTP equation to rowing is recommended.

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Wasserman K, Whipp B, Koyal S & Beaver W (1973). Anaerobic threshold and respiratory gas exchange during exercise. *J Appl Phsiol* **35**, 236-243.

Whipp B (1987). Dynamics of pulmonary gas exchange. *Circulation* **76**, VI18–28.

9.0: Appendix

Appendix 9.1: Ethics approval letter for study reported in Chapter 3

Coláiste na Tríonóide, Baile Átha Cliath
Trinity College Dublin
Ollscoil Átha Cliath | The University of Dublin

Eanna Mc Grath
Anatomy Department,
Trinity Biomedical Sciences Institute,
Trinity College,
152 -160 Pearse Street,
Dublin 2.

Ref: 170602

Title of Study: Assessment of the validity and reliability of the function threshold power (FTP) test as a measure of 60-min critical power.

Dear Eanna,

Further to a meeting of the Faculty of Health Sciences Ethics Committee held in June 2017, we are pleased to inform you that the above project has been approved without further audit.

Yours sincerely,

pp Brian Brown
Prof. Brian O'Connell
Chairperson
Faculty Research Ethics Committee

Dámh na nEolaíochtaí Sláinte
Foirgneamh na Ceimice,
Coláiste na Tríonóide,
Ollscoil Átha Cliath,
Baile Átha Cliath 2, Éire.

Faculty of Health Sciences
Chemistry Building,
Trinity College Dublin,
The University of Dublin,
Dublin 2, Ireland.

www.healthsciences.tcd.ie

Appendix 9.1: Ethics approval letter for study reported in Chapter 4

Coláiste na Tríonóide, Baile Átha Cliath
Trinity College Dublin
Ollscoil Átha Cliath | The University of Dublin

Eanna Mc Grath
School of Medicine
Anatomy Dept
Trinity Biomedical Sciences Institute
Trinity College
152-160 Pearse Street
Dublin 2

8th November 2019

Ref: 190602

Title of Study: An assessment of mathematical models of human performance as proxies for physiological tests.

Dear Eanna,

Further to a meeting of the Faculty of Health Sciences Ethics Committee held in June 2019. We are pleased to inform you that the above project has ethical approval.

We would advise you to seek review and comments on your DPIA, PIL and Consent forms from the DPO prior to study commencement. The revised PIL/Consent should be logged back with this ethics committee, not for review just for noting and filing.

Yours sincerely,

p.p. Gloria Bowen

Prof. Jacintha O'Sullivan
Chairperson
Faculty Research Ethics Committee

Appendix 9.1: Ethics approval letter for study reported in Chapter 5

Coláiste na Tríonóide, Baile Átha Cliath
Trinity College Dublin
Ollscoil Átha Cliath | The University of Dublin

Eanna Mc Grath,
Human Performance Laboratory, Level 2,
Watts Building,
Trinity College Dublin, the University of Dublin,
Dublin 2,
Ireland

8th February 2022

Ref: 211104
Title of Study: An assessment of mathematical models for human performance as proxies for physiological data.

Dear Eanna,

Further to a meeting of the Faculty of Health Sciences Ethics Committee held in November 2021. We are pleased to inform you that the above project has ethical approval to proceed.

This study has been ethically approved. We would advise you to seek review and comments on your DPIA from the DPO if required prior to study commencement'

As a researcher you must ensure that you comply with other relevant regulations, including DATA PROTECTION and HEALTH AND SAFETY.

Yours sincerely,

Prof. Jacintha O'Sullivan
Chairperson
Faculty Research Ethics Committee

Dámh na nEolaíochtaí Sláinte
Foirgneamh na Ceimice,
Coláiste na Tríonóide,
Ollscoil Átha Cliath,
Baile Átha Cliath 2, Éire.

Faculty of Health Sciences
Chemistry Building,
Trinity College Dublin,
The University of Dublin,
Dublin 2, Ireland.

www.healthsciences.tcd.ie

Appendix 9.1: Ethics approval letter for study reported in Chapter 6

Coláiste na Tríonóide, Baile Átha Cliath
Trinity College Dublin
Ollscoil Átha Cliath | The University of Dublin

Eanna Mc Grath,
Human Performance Laboratory, Level 2,
Watts Building,
Trinity College Dublin, the University of Dublin,
Dublin 2,
Ireland

8th February 2022

Ref: 211104
Title of Study: An assessment of mathematical models for human performance as proxies for physiological data.

Dear Eanna,

Further to a meeting of the Faculty of Health Sciences Ethics Committee held in November 2021. We are pleased to inform you that the above project has ethical approval to proceed.

This study has been ethically approved. We would advise you to seek review and comments on your DPIA from the DPO if required prior to study commencement'

As a researcher you must ensure that you comply with other relevant regulations, including DATA PROTECTION and HEALTH AND SAFETY.

Yours sincerely,

Prof. Jacintha O'Sullivan
Chairperson
Faculty Research Ethics Committee

Dámh na nEolaíochtaí Sláinte
Foirgneamh na Ceimice,
Coláiste na Tríonóide,
Ollscoil Átha Cliath,
Baile Átha Cliath 2, Éire.

Faculty of Health Sciences
Chemistry Building,
Trinity College Dublin,
The University of Dublin,
Dublin 2, Ireland.

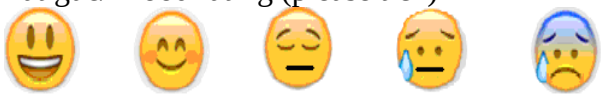
www.healthsciences.tcd.ie

Appendix 9.1: Pre-participation medical questionnaire for all reported studies

Pre-participation medical questionnaire *Date / /*

Name	Age of entry to sport
Date of birth	Category
Occupation	Contact Tel No
Address	Contact e-mail
	GP contact details

Training log

Last training session *(time & details):* Recent performance indicator (PB): Detail a typical training week:	Fatigue/ mood rating (please tick)  Resting morning HR beats.min^{-1} Sleep: Hours Quality Appetite

Personal History		***Family History***		***State details***
	Circle		*Circle*	
Smoking	Y N	Heart problem	Y N	
Alcohol	Y N	Strokes	Y N	
Tea	Y N	Diabetes	Y N	
Coffee	Y N	Asthma	Y N	
Vegetarian	Y N	Epilepsy	Y N	

Medical screening details	***Circle***	***State***
1. Has a brother, sister; cousin, parent or grandparent died suddenly under 45 years of age due to heart disease or no known cause?	Y / N	
2. Have you had a sudden blackout, loss of consciousness or fallen to the ground for no good reason in association with exercise?	Y / N	
3. Have you been diagnosed with a heart condition?	Y / N	
4. Do you get chest pain, chest tightness or shortness of breath during exercise that prevents you continuing?	Y / N	
5. Do you get sudden onset of very rapid heart beating that occurs for no obvious reason and which makes you feel unwell?	Y / N	
6. Have you been diagnosed previously with a mental illnesses	Y /N	

Medications supplements	*Circle*	***State details***
Medications (Prescribed or OTC)	Y / N	
Vitamins	Y / N	
Food supplements	Y / N	
Sports drinks	Y / N	
Allergies	Y / N	

Medical problems in the last 3 months	***State details***
Recent illnesses	**Recent injuries**

Female athletes only

At what age did your periods start ……	Date of 1st day of last period ..... /…./……,
How long are your periods……. (days)	How long between periods ……
Are you pregnant? Y / N	Have you missed periods recently? Y / N
Are your periods regular? Y / N	Any problems with your periods? Y / N

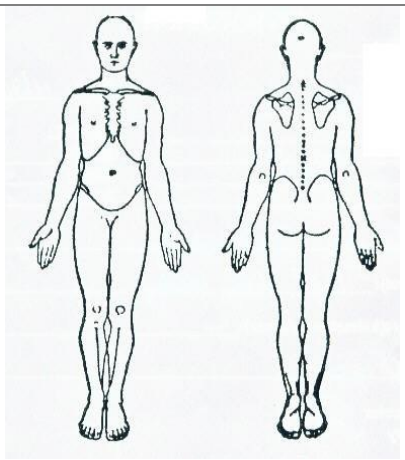
Have you had any of the following:				***State details***
last 7 days	**Circle**	***at any time***	**Circle**	
Flu symptoms	Y N	Hospital stay	Y N	
Sore throat	Y N	Operations	Y N	
Cough	Y N	Fractures	Y N	
Wheeze	Y N	Sports injuries	Y N	
Chest pains	Y N	Diabetes	Y N	
Palpitations	Y N	Asthma	Y N	
Nausea	Y N	Epilepsy	Y N	
Vomiting	Y N	Jaundice	Y N	
Diarrhoea	Y N	Kidney problem	Y N	
Headaches	Y N	Heart condition	Y N	
Fits or faints	Y N	Eye problems	Y N	
Others	Y N	Any other illness	Y N	

General Examination: Doctors Use Only

MSK Injury / NEURO Chart

Obs: Pulse beats.min^{-1} Reg/Irreg

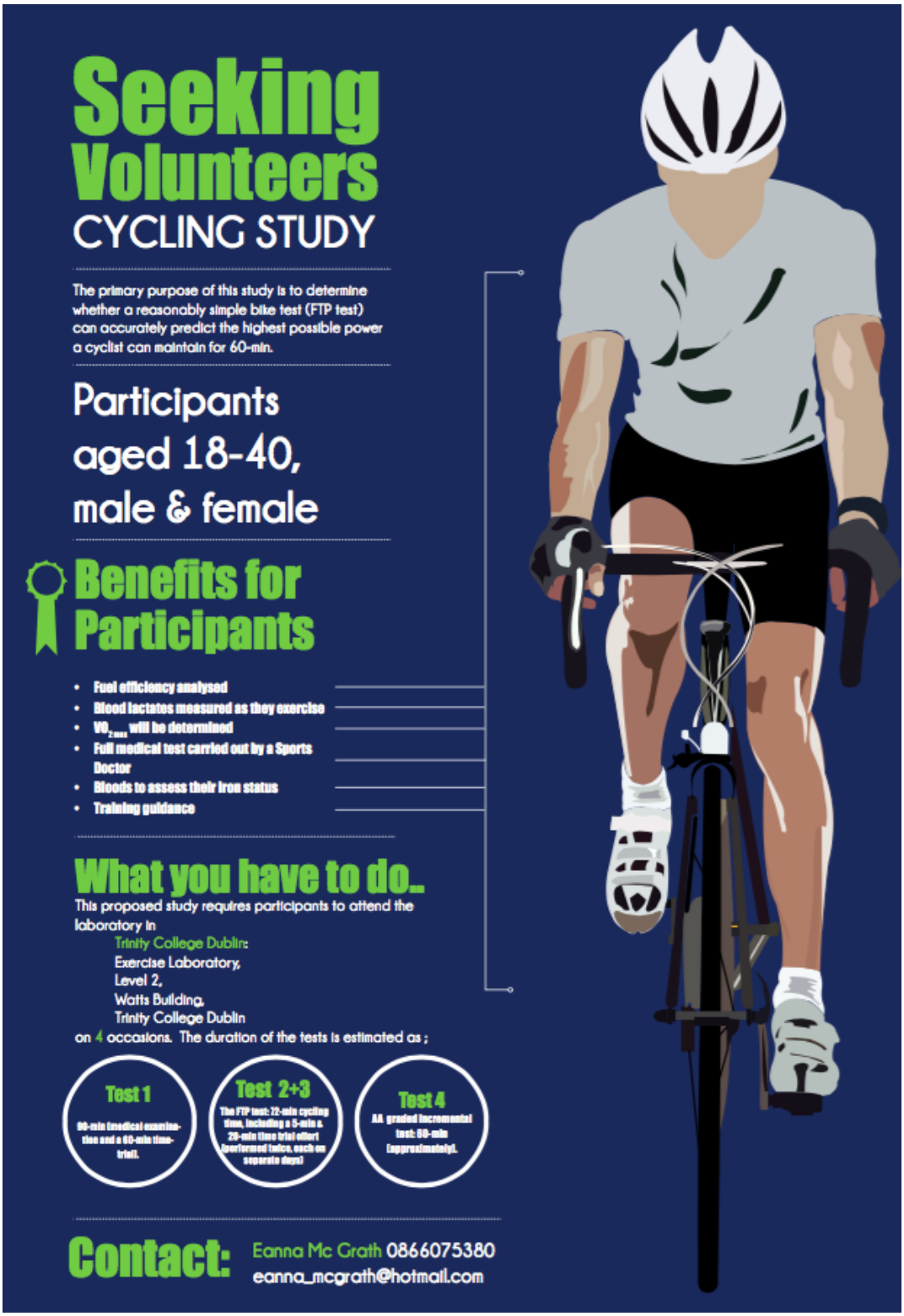
BP / mmHg (Temp ^{o}C)

Head: Nose Throat Neck: Nodes Thyroid CVS: Apex beat Heart Sounds RS: Exp^{n} Perc. / Ausc. Others *(ABDO/GU/Urinalysis)*: FBC result: Lung Function Result:	

Medical summary / Investigations / Recommendations to GP or Consultant

Fit for exercise test / Participation Y N Dr Signature……

Appendix 9.2: Poster seeking volunteers for study reported in Chapter 3



9.2: Letter to gatekeepers for study reported in Chapter 3

Anatomy Department, Level 2 Watts Building,
Trinity College Dublin,
Dublin 2.
Phone: 0866075380
Email: eanna_mcgrath@hotmail.com
Date: 26/05/2017

To …….

I am undertaking a PhD research project in Trinity College Dublin investigating methodologies for determining 60-min critical power on a bicycle. Functional threshold power (c-FTP) is a variable determined by performing a 20-minute all-out time-trial with a power-meter, averaging the power output throughout this time and taking 5% away. Many cyclists and triathletes are using their c-FTP as a training tool instead of undergoing multiple laboratory-based tests. This investigation will incorporate and overlap; laboratory measurements, the c-FTP test, and a full 60-min time-trial result.

The title of my proposed paper is "An assessment of the validity and reliability of the function threshold power (c-FTP) as a measure of 60-min critical power". I am looking for 20+ volunteers, between the ages of 18 to 40 years old to participate in this research. Study volunteers will partake in four separate tests, the trial details and benefits are outlined in the attached poster. I would very much appreciate if you could pass this on to any members of your club who you think may be interested in participating.

Sincerely,

Eanna Mc Grath

9.2: Participant information leaflet for study reported in Chapter 3

Participant Information Leaflet

1. Title: Assessment of the validity and reliability of the function threshold power (FTP) test as a measure of 60-min critical power.

2. Introduction: The primary purpose of this study is to determine whether a reasonably simple bike test (FTP test) can accurately predict the highest possible power a cyclist can maintain for 60-min. Scientific papers do not currently support this test. However anecdotally, many cyclists and triathletes use the test seemingly successfully. The use of blood lactate, heart rate and ventilatory data to find the same best possible performance over 60-min have their limitations and individual differences need to be determined on a case-by-case basis. This study will assess your performance during three different types of tests and will use all of the measurements assessed to give you detailed feedback on your current fitness level.

Prior to each test, you would undergo a medical screening to ensure you are in good health and that it is safe for you to exercise to exhaustion. There will be four testing days.

Test one: A 60-min time-trial.
Test two and three: The FTP test protocol
Test four: A graded incremental test to volitional exhaustion.

You will have a mask placed over your nose and mouth, which is securely tightened. This will be left on throughout one of the tests (the graded incremental test). During the remaining three tests, the mask will be taken off intermittently to facilitate drinking. A heart rate strap will be placed around your chest for all testing. A very small pinprick in your fingertip will be used to collect and assess changes in blood lactate concentration while you exercise.

3. Procedures: Each participant is required to fulfil the following inclusion criteria:

- Aged between 18 and 40 years.
- Pass the medical screening provided by a medical doctor.
- Have consistently partaken in organised cycling or triathlon training and competitive events for at least one year prior to study commencement.
- Are not pregnant, nor likely to become pregnant during the time span of the proposed study.

4. Benefits: The tests will give you information on your state of fitness. Using this information, you will be given feedback as to how best orchestrate your training.

5. Risks: This study requires you to exercise maximally and therefore is a risk of coronary attack associated with such exercise. In a young healthy population these risks are markedly reduced and considered minimal. In the unlikely event that you suffer from any adverse effects, medical supervision will be available during all elements of the study, and all study procedures will be supervised by the lead investigator who is certified in AED/CPR and first

aid. In addition, you will give a contact mobile phone number for usage at any time during your participation in the study, and you will be contacted 24 hour after each trial element by the lead investigator to enquire if you have experienced any adverse effects. You may experience some minor bruising on your fingertip from blood sampling, however, all blood samples will be collected from the same site to minimise the need for additional finger pricks. If any contra-indications to exercise are identified during the medical examination, this information will be forwarded, with your consent, to your designated GP by the study team.

6. Exclusion from participation: You cannot participate in this study if any of the following are true:

- You are outside the age range of 18 to 40 years old
- You have high or low blood pressure, or are found to have either during your pre-screening assessment
- You have a bleeding or clotting disorder
- You have any diagnosed cardiac or ECG abnormalities
- You have any respiratory difficulties (based on spirometry data) or symptoms of colds/influenza on the day of testing
- You have an acute or chronic musculoskeletal injury that could limit your exercise capacity
- You have a disease that would prevent you from participating in an exercise test
- You are deemed unfit to participate on completion of your medical questionnaire and medical examination due to an on-going illness, or if you have any of the following; diabetes, hypertension, heart defects, metabolic disorders or other contraindications to exercise testing.

7. Confidentiality: Your identity will remain confidential. Your name will not be published and will not be disclosed to anyone outside the designated study group. All your data collected during the study will be stored on a computer in a secure location which only the lead investigator will have access to. The computer will be password protected and only the investigator will have access to the password. All your hardcopy records will be kept in a secure storage place in the laboratory, which only the lead investigator will have access to. For additional security, your identity and data will be referenced under a study specific code number at all times. These security measures will stay in place during the study and after it has finished. Data will only be analysed in group format and no personal information or data relating to any participant will be disclosed. Your data will be kept for the duration of the study and until the work is fully reported and disseminated, and your data will then be kept in a locked cabinet for a further five years.

8. Compensation: This study is covered by standard institutional indemnity insurance. Nothing in this document restricts or curtails your rights.

9. Voluntary participation: If you decide to volunteer to participate in this study, you may withdraw at any time. If you decide not to participate or, if you withdraw, you will not be penalized and will not give up any benefits that you had before entering the study.

10. Stopping the study: You understand that the investigators may withdraw your participation in the study at any time without your consent.

11. Permission: This trial has Research Ethics Committee approval from Health Science Faculty Ethics Committee in Trinity College Dublin.

12. Further information: All testing will take place in the Human Performance Laboratory in the Watts Building, Anatomy Department, Trinity College Dublin (see attached map for directions). You can get more information or answers to your questions about the study, your participation in the study, and your rights, from Eanna Mc Grath who can be telephoned at 0866075380. If the study team learns of important new information that might affect your desire to remain in the study, you will be informed at once. This study is in partial fulfilment of the qualification of PhD in the Discipline of Anatomy, School of Medicine by Eanna Mc Grath.

Names of Researchers:
Mr. Eanna Mc Grath
Mr. Bernard Donne.
Dr Neil Fleming.
Dr Nicholas Mahony

9.2: Consent form for study reported in Chapter 3

Consent Form

Project title: Assessment of the validity and reliability of the function threshold power (c-FTP) test as a measure of 60-min critical power.

Principal investigator: Eanna Mc Grath (Lead Investigator)

Additional investigators: Mr Bernard Donne (Supervisor), Dr Nicholas Mahony, Dr Neil Fleming.

Background

The primary purpose of this study is to determine whether the FTP test can accurately predict the highest possible power a cyclist can maintain for 60-min. The investigation is in partial fulfilment of a PhD by Eanna Mc Grath.

This study will assess performance during three different types of tests and four tests in total (one test protocol is repeated).
Test one: The 60-minute time-trial.
Test two and three: The FTP test.
Test four: A graded incremental test to volitional exhaustion.

A face mask will be placed over my nose and mouth, which is securely tightened to measure my ventilatory data. A heart rate strap will be placed around my chest to monitor my heart rate response. Small pinpricks at the fingertip will be used to assess the amount of blood lactate present in my circulation as I exercise.

Risks:

There are inherent risks associated with intense exercise and I will likely experience fatigue and discomfort. I understand I may experience some fingertip bruising from blood sampling.

Please mark "Y" to give consent or "N" to withhold consent in the boxes provided.

I give my consent to forward any contra-indications to exercise that are identified during the medical examination to my GP. ☐

I give permission for my anonymous information to be part of a research publication ☐

Declaration

I have read, or had read to me, the information leaflet for this project and I understand the contents. I have had the opportunity to ask questions and all my questions have been answered to my satisfaction. I freely and voluntarily agree to be part of this research study, though without prejudice to my legal and ethical rights. I understand that I may withdraw from the study at any time and I have received a copy of this agreement.

PARTICIPANT'S NAME: **……**
CONTACT DETAILS: ……

PARTICIPANT'S GP CONTACT DETAILS
Name……
Address……
……

PARTICIPANT'S SIGNATURE: ……
Date: ……..

Statement of investigator's responsibility:
I have explained the nature and purpose of this research study, the procedures to be undertaken and any risks that may be involved. I have offered to answer any questions and fully answered such questions. I believe that the participant understands my explanation and has freely given informed consent.

INVESTIGATOR'S SIGNATURE: ……
Date: ……..

9.2: Poster seeking volunteers for study reported in Chapter 4

9.2: Letter to gatekeepers for study reported in Chapter 4

Anatomy Department, Level 2 Watts Building,
Trinity College Dublin,
Dublin 2.
Phone: 0866075380
Email: eanna_mcgrath@hotmail.com

To .....

I am undertaking a PhD research project in Trinity College Dublin investigating "Critical Power", "Functional Threshold Power" and "Normalised Power" on a bicycle.

The title of my proposed study is "An assessment of mathematical models of human performance as proxies for physiological tests". I am looking for 20 to 30 volunteers, between the ages of 18 to 40 year to participate in this research. Study volunteers will partake in eight separate tests, the test details and benefits are outlined in the attached poster.

I would very much appreciate if you could pass this on, to any members of your club who you think may be interested in participating.

Many thanks.

Sincerely,

Eanna Mc Grath

9.2: Participant information leaflet for study reported in Chapter 4

Participant Information Leaflet

Title: An assessment of mathematical models of human performance as proxies for physiological tests.

Introduction:
The first goal of this investigation is to compare the "Critical Power" (CP) and "Functional Threshold Power" (c-FTP) tests. Critical power is the maximum cycling intensity that can be sustained for up to 20-min. Functional threshold power is the maximum cycling intensity that can be sustained for 1-hour. Thereafter, comparisons will be made on how each test is approached. In the first instance, the power output is constant. In the second test the power output changes frequently. The results of each test will be used to give you detailed feedback on your current fitness level. Prior to testing, you will undergo a medical screening to ensure you are in good health and that it is safe for you to exercise to exhaustion. There will be eight testing days that you will be required to attend the exercise-testing laboratory. You will have a mask placed over your nose and mouth during all of these tests, which will be securely tightened. A heart rate strap will be placed around your chest for all exercise tests. A very small pinprick in your fingertip will be used to collect and assess changes in blood lactate concentration at frequent intervals while you exercise.

Test outline

Test	Duration	No. of Tests	Composition of test
VO_2max	60-min	1	Progresses uniformly from easy to maximum effort
CP	40 to 60-min	4	Maximum effort trials at a fixed power output
c-FTP	60-min	1	A 5-min and a 20-min maximum effort self-paced trial
NP	40 to 90-min	2	A variable power output over 20 and 60-min

Procedures: Each participant is required to fulfil the following inclusion criteria:

- Aged between 18-40 years.
- Pass the medical screening provided by a medical doctor.
- Have consistently partaken in organised cycling or triathlon training and competitive events for at least one year prior to study commencement.

Benefits: The tests will give you information on your state of fitness. Using this information, you will be given feedback as to how to best orchestrate organise your training.

Risks: This study requires you to exercise maximally and therefore is a small risk of a heart coronary attack associated with such exercise. In a young healthy population these risks are markedly reduced and considered minimal. The lead investigator, whom is certified in AED/CPR and first aid, will supervise all of the study procedures. In addition, you will give a contact mobile phone number for usage at any time during your participation in the study, and you will be contacted 24 hour after each trial element by the lead investigator to enquire

if you have experienced any adverse effects. You may experience some minor bruising on your fingertip from blood sampling, however, all blood samples will be collected from the same site to minimise the need for additional finger pricks. Each trial requires repeated capillary blood samples throughout the test, which can be uncomfortable. The maximum number of capillary blood samples per test is twelve, the minimum number is four and the average number of blood samples is seven. If any contra-indications to exercise are identified during the medical examination, this information will be forwarded, with your consent, to your designated GP by the study team. There are small inherent risks associated with exercising at maximal, or near maximal, exercise intensities as in participation in most sporting activities. The estimated risk of a coronary attack is 1 in 5000 in a sedentary population. However, in a young healthy population these risks are markedly reduced and considered minimal.

Exclusion from participation: <u>You cannot participate in this study if any of the following are true:</u>

- You are outside the age range of 18 to 40 years old
- Are pregnant, or become pregnant during the time span of the proposed study.
- You have high or low blood pressure, or are found to have either during your pre-screening assessment
- You have a bleeding or clotting disorder
- You have ever been diagnosed with a heart condition or have had heart tests in the past identifying an abnormality, such as an ECG abnormality
- You have any breathing or respiratory difficulties (based on spirometry data) or symptoms of respiratory infection such as colds/influenza on the day of testing
- You have an a recent or long term musculoskeletal injury that could limit your ability to exercise
- You have any medical condition that would prevent you from participating in an exercise test
- You are deemed unfit to participate on completion of your medical questionnaire and medical examination due to an on-going illness or injury, or if you have any of the following; diabetes, hypertension, heart defects, metabolic disorders or other contraindications to exercise testing.

Confidentiality: Your identity will remain confidential. Your name will not be published and will not be disclosed to anyone outside the designated study group. All your data collected during the study will be stored on a computer in a secure location, which only the lead investigator will have access to. The computer will be password protected and only the investigator will have access to the password. All your hardcopy records will be kept in a secure storage place in the laboratory, which only the lead investigator will have access to. For additional security, your identity and data will be referenced under a study specific code number at all times. These security measures will stay in place during the study and after it has finished. Data will only be analysed in group format and no personal information or data relating to any participant will be disclosed. Your data will be kept for the duration of the study, and your data will then be kept in a locked cabinet for a further five years.

Compensation: This study is covered by standard institutional indemnity insurance. Nothing in this document restricts or curtails your rights.

Voluntary participation: If you decide to volunteer to participate in this study, you may withdraw at any time up to the point when you have completed all of the exercise trials. Thereafter, once your test results have been amalgamated with those of other athletes in this investigation, it will not be possible to withdraw your data. If you decide not to participate or, if you withdraw prior to this point, you will not be penalised and will not give up any benefits that you had before entering the study.

Stopping the study: You understand that the investigators may withdraw your participation in the study at any time without your consent.

Permission: This trial has Research Ethics Committee approval from Faculty of Health Sciences Research Ethics Committee in Trinity College Dublin.

Further information: Testing will take place in the Human Performance Laboratory in the Watts Building, Anatomy Department, Trinity College Dublin (see attached map for directions) or Base2Race, Dublin (see attached map for directions).

You can get more information or answers to your questions about the study, your participation in the study, and your rights, from Eanna Mc Grath who can be telephoned at 086-6075380. If the study team learns of important new information that might affect your desire to remain in the study, you will be informed at once. This study is in partial fulfilment of the qualification of PhD in Anatomy by Eanna Mc Grath.

Names of Researchers:
Mr. Eanna Mc Grath Dr Nicholas Mahony

9.2: Consent form for study reported in Chapter 4

Consent Form

Project title: An assessment of mathematical models of human performance as proxies for physiological tests.

Principal investigator: Eanna Mc Grath (Lead Investigator).

Additional investigators: Dr Nicholas Mahony.

Background

The primary purpose of this study is to determine whether the "Critical Power" and "Functional Threshold Power" are the same intensities, and whether "Normalised Power" algorithm can calculate the physical cost of exercise. The investigation is in partial fulfilment of a PhD by Eanna Mc Grath. This study will assess performance during eight different types of tests:

Test	Duration (Including warm-up and cool-down)	No. of Tests	Composition of test
VO_2max	60-min	1	Progresses uniformly from easy to maximum effort
CP	40 to 60-min	4	Maximum effort trials at a fixed power output
c-FTP	60-min	1	A 5-min and a 20-min maximum effort self-paced trial
NP	40 to 90-min	2	A variable power output over 20 and 60-min

Testing protocols

Please mark "Y" to give consent or "N" to withhold consent in the boxes provided.	**Tick box**
I understand that a face mask will be placed over my nose and mouth securely tightened to measure my ventilatory data.	
I understand that a heart rate strap will be placed around my chest to monitor my heart rate.	
I understand that pin-pricks will be made at my fingertip to assess the amount of blood lactate present in my circulation as I exercise	
I understand there are inherent risks associated with intense exercise and I will likely experience fatigue and discomfort.	

General

Please mark "Y" to give consent or "N" to withhold consent in the boxes provided.	**Tick box**
I have read, or had read to me, the information leaflet for this project and I understand the contents.	
I have had the opportunity to ask questions and all my questions have been answered to my satisfaction.	

I freely and voluntarily agree to be part of this research study, though without prejudice to my legal and ethical rights.	
I understand that I may withdraw from the study at any ***during*** the testing period	
I understand that I ***cannot withdraw*** my personal data from the study findings after it has been pooled with other participant's data.	
I have received a copy of this agreement.	
I know I will not be paid for taking part in this study.	
I know how to contact the research team if I need to.	
I agree to being contacted by researchers by email / phone as part of the research study.	
I give permission for my coded information to be part of research publications	
I give my consent to forward any contra-indications to exercise that are identified; during the medical examination, apparent from my completed medical questionnaire, or adverse reactions to exercise, to my GP.	
I understand the study findings will be retained for 5-years. These findings will not be used in future unrelated studies without my permission being obtained	

PARTICIPANT'S NAME:**……**
CONTACT DETAILS: ……

PARTICIPANT'S GP CONTACT DETAILS
GP Name ……
GP Address ……

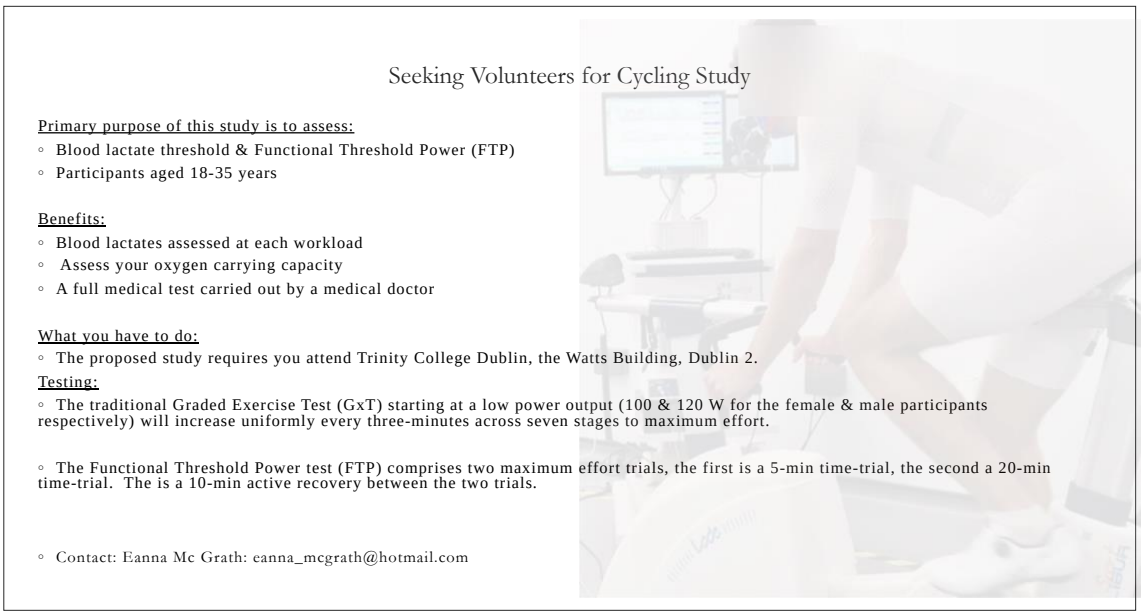
PARTICIPANT'S SIGNATURE: ……
Date: ……..

To be completed by the Principle Investigator:
Statement of investigator's responsibility
I, the undersigned, have taken the time to fully explain to the above participant the nature and purpose of this study in a way that they could understand and purpose of this study in a way they could understand. I have explained the risks and possible benefit involved. I have invited them to ask questions on any aspect of the study that concerned them.
I have given them a copy of the information leaflet and consent form to the participant with contacts of the study team.

SIGNATURE: ……

Date: …….

9.2: Poster seeking volunteers for study reported in Chapter 5



9.2: Letter to gatekeepers for study reported in Chapter 5

Eanna Mc Grath
Anatomy Department, Level 2 Watts Building,
Trinity College Dublin,
Dublin 2.
Phone: 0866075380
Email: eanna_mcgrath@hotmail.com

Date:
Dear (name of secretary) of Club

I am undertaking a PhD research project in Trinity College Dublin investigating the effectiveness of predictive equation for Functional Threshold Power derived from Graded Exercise Test data.

I am looking for 74 volunteers, between the ages of 18 and 35 year to participate in this research. Study volunteers will partake in two separate tests, the test details and benefits are outlined in the attached poster.

I would very much appreciate if you could pass this on, to any members of your club who you think may be interested in participating.
Many thanks,
Sincerely,

Eanna Mc Grath

9.2: Participant information leaflet for study reported in Chapter 5

Participant Information Leaflet

The prediction of Functional Threshold Power from a Graded Exercise Test data

Site	Human Performance Laboratory, Level 2 Watts Building, Trinity College Dublin.		
Research team	Principle Investigator	Mr Eanna Mc Grath	eamcgrat@tcd.ie
	Assistant Professor	Dr Nick Mahony	njmahony@tcd.ie
	Assistant Professor	Dr Neil Fleming	Neil.fleming@tcd.ie
Data Controllers Data Protection Officer	Trinity College Dublin Dr Neil Fleming Human Performance Laboratory, Level 2 Watts Building, Trinity College Dublin.		

You are being invited to take part in a research study that is being carried out by the School of Medicine, Anatomy Department, Trinity College Dublin by Eanna Mc Grath, in partial fulfilment of a PhD qualification. This prospective study has been submitted to the Trinity College Research Ethics Committee for approval and will not proceed without approval. Before you decide whether or not you wish to take part, please read this information sheet carefully. Ask the principle investigator Eanna Mc Grath any questions. Do not feel rushed or under pressure to make a quick decision. You should understand the risks and benefits of taking part in this study so that you can make a decision that is right for you. You may wish to discuss it with your family, friends or GP.

Our study aims to collect data from a "Graded Exercise Test" (GxT) and compare it with a bicycling test called the "Functional Threshold Power Test". The c-FTP test may provide the athlete with information relating to their fitness that is not provided by the GxT alone.

<u>You would be required to fulfil the following conditions to participate in this study:</u>

- Aged between 18 and 35 years.
- Pass the medical screening provided by a medical doctor.
- Have consistently partaken in organised running training and competitive events for at least one year prior to study commencement.

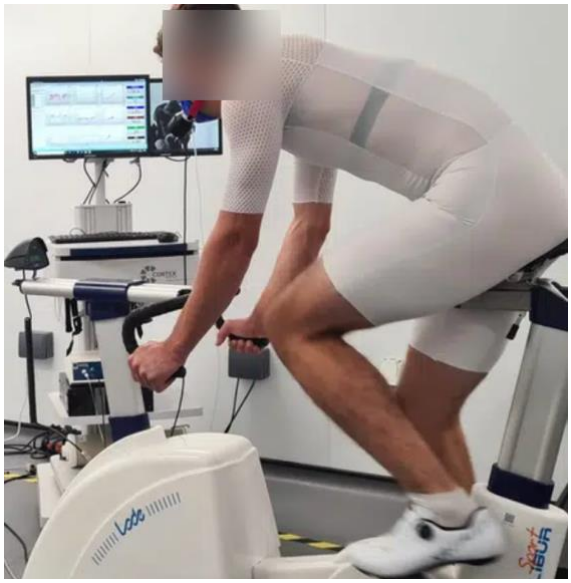
Unfortunately, you cannot participate in this study if any of the following are true:

- You are pregnant, or become pregnant during the time span of the proposed study.
- You have high or low blood pressure, or are found to have either during your pre-screening assessment
- You have a bleeding or clotting disorder
- You have ever been diagnosed with a heart condition or have had heart tests in the past identifying cardiac abnormalities, such as ECG abnormality
- You have any breathing or respiratory difficulties (based on spirometry data) or symptoms of respiratory infection such as colds/influenza on the day of testing
- You have a recent or long term musculoskeletal injury that could limit your ability to exercise
- You have any medical condition that would prevent you from participating in an exercise test
- You are deemed unfit to participate on completion of your medical questionnaire and medical examination due to an on-going illness or injury, or if you have any of the following; diabetes, hypertension, heart defects, metabolic disorders or other contraindications to exercise testing.

Voluntary participation: There are two tests, which should be completed within a 10-day period. There are no further tests required thereafter. If you decide to volunteer to participate in this study, you may withdraw at any time up to the point when you have completed all the exercise trials. Thereafter, once your test results have been amalgamated with those of other athletes in this investigation, it will not be possible to withdraw your data. If you decide not to participate or, if you withdraw prior to this point, contact Eanna Mc Grath (eanna_mcgrath @hotmail.com). In this circumstance, you will not be penalised and will not give up any benefits that you had before entering the study.

There will be seventy athletes partaking in this investigation. The testing will take place in Human Performance Laboratory, Level 2, Watts Building in Trinity College Dublin. Prior to testing, you will undergo a medical screening to ensure you are in good health and that it is safe for you to exercise to exhaustion. There will be two testing days that you will be required to attend the exercise-testing laboratory. You will have a mask placed over your nose and mouth during each test, which will be securely tightened. A heart rate strap will be placed around your chest for all exercise tests. A very small pinprick in your earlobe will be used to collect and assess changes in blood lactate concentration at frequent intervals while you exercise.

The GxT duration, including your warm-up and cool-down is approximately 60-min. The test starts at a very low intensity (starting at 100-W and 120-W for the female and male athletes, respectively) and will increase uniformly every three-minutes across seven stages to maximum effort. The c-FTP test requires the athlete to complete a 5-min and 20-min time-trial at the highest sustainable power that can be tolerated. There is a 10-min active recovery phase between the two time-trials. The results of each test will be used to give insight as to your current fitness level.



Test outline

Test	Duration	No. of Tests	Composition of test
GxT	60-min	1	Progresses uniformly from easy to maximum effort
FTP	60-min	1	A 5-min and a 20-min maximum effort self-paced time-trial

During both test, there will be two support personnel in attendance, both certified in first aid, AED and CPR. Eanna Mc Grath, the primary investigator, will be present for both tests. In the event of cardiac event, standard CPR procedures are implemented. In the case of non-cardiac event, the Medical Officer is notified of adverse event and will appraise whether an ambulance is required. In all cases, an incident report form is completed and submitted to School of Medicine and the Faculty Research Ethics Team.

What will happen to my samples and data?

Enlisted participants will be assigned a study number and data for that participant will be only referenced according to their study number, therefore making the data confidential and pseudo-anonymised. For the duration of the study all participants will be referenced under their specific number. This security measure will also stay in place after the study has finished. Data will only be analysed in group format and no personal information or data for any participant will be disclosed. This code number will be stored in a single password encrypted excel file stored on a designated TEAMS folder. Only the code number will be entered on the pre-trial health screening forms. This identification allows matching codes across data sets.

All hardcopies of written consent will be stored in the supervisor's office in a locked filing cabinet. Only the lead investigator will have direct access to the data collected. The study

supervisor will have secondary access to the data via consultation with the lead investigator. Names and codes will all be stored separately. This is the legal basis for processing data. The data will only be presented under the participants study number, therefore allowing the identity of the participants to remain pseudo-anonymous. No data will be disclosed to individuals outside of the designated study team. Your pseudo-anonymised data will be securely retained for 7 years as this is accepted best practice.

- The right to access to your data and receive a copy of it
- The right to restrict or object to processing of your data
- The right to object to any further processing of the information we hold about you (except where it is de-identified)
- The right to have inaccurate information about you corrected or deleted
- The right to receive your data in a portable format and to have it transferred to another data controller
- The right to request deletion of your data

By law you can exercise the following rights in relation to your personal data, unless the request would make it impossible or very difficult to conduct the research. You can exercise these rights by contacting your Eanna Mc Grath or the Trinity College Data Protection Officer, Secretary's Office, Trinity College Dublin, Dublin 2, Ireland. Email: dataprotection@tcd.ie. Website: www.tcd.ie/privacy. Pseudo-anonymised data retained after the study is completed will not be used in future unrelated studies without further specific permission being obtained.

Are there any benefits to taking part in this research?

Participants will gain a measure of their trained state and they may choose to use this information to improve their training. Participants will be provided with training advice based on data collected during their exercise tests.

Are there any risks to me or others if I take part?

This study requires you to exercise maximally and therefore is a small risk of a heart coronary attack associated with such exercise. In a young healthy population these risks are markedly reduced and considered minimal. The lead investigator, whom is certified in AED/CPR and first aid, will supervise all of the study procedures. In addition, you will give a contact email for usage at any time during your participation in the study, and you will be contacted 24 hour after each trial element by the lead investigator to enquire if you have experienced any adverse effects. You may experience some minor bruising on your earlobe from blood sampling, however, all blood samples will be collected from the same site to minimise the need for additional earlobe pricks. Each trial requires repeated capillary blood samples throughout the test, which can be uncomfortable. The maximum number of capillary

blood samples per test is twelve, the minimum number is four and the average number of blood samples is seven. If any contra-indications to exercise are identified during the medical examination, this information will be forwarded, with your consent, to your designated GP by the study team. There are small inherent risks associated with exercising at maximal, or near maximal, exercise intensities as in participation in most sporting activities. The estimated risk of a cardiac arrest is 1 in 5000 in a sedentary population. However, in a young healthy population these risks are markedly reduced and considered minimal.

Once you have completed the two tests, you will be given your test results immediately. The results of the study will be reported in medical/scientific journals and disclosed at medical/scientific conferences. No information which reveals your identity will be disclosed. By law, we can use your personal information for scientific research (in the public interest). We will also ask for your explicit consent to use your data as a requirement of the Irish Health Research Regulations.

The medical examination will be performed by a registered medical practitioner, including; spirometry, blood pressure, full blood count and any other tests deemed necessary. If any medical abnormalities are identified on examination the potential participant will be excluded from the trial and pertinent details relating to the diagnosed abnormalities will be forwarded to your doctor. All enlisted participants will also be requested to complete a detailed medical questionnaire (attached) prior to the medical examination; which will be reviewed by the medical practitioner to ensure you are safe to exercise.

Who should I contact for information or complaints?

If you have any concerns or questions, you can contact:

- Eanna Mc Grath: email: eanna_mcgrath@hotmail.com
- Neil Fleming: email neil.fleming@tcd.ie
- Data Protection Officer, Trinity College Dublin: Data Protection Officer, Secretary's Office, Trinity College Dublin, Dublin 2, Ireland. Email: dataprotection@tcd.ie. Website: www.tcd.ie/privacy.

Under GDPR, if you are not satisfied with how your data is being processed, you have the right to lodge a complaint with the Office of the Data Protection Commission, 21 Fitzwilliam Square South, Dublin 2, Ireland. Website: www.dataprotection.ie.

If you would like to take part in this study, you will be asked to sign the Consent Form on the next page. You will be given a copy of this information leaflet and the signed Consent Form to keep.

9.2: Consent form for study reported in Chapter 5

Consent Form

Project title: The prediction of Functional Threshold Power from a Graded Exercise Test
Principal investigator: Eanna Mc Grath (Lead Investigator).
Additional investigators: Dr Nick Mahony and Dr Neil Fleming.

Background

The purpose of this investigation is to predict "Functional Threshold Power" (FTP) using the data derived from a Graded Exercise Test (GxT). The investigation is in partial fulfilment of a PhD by Eanna Mc Grath. This study will assess performance during two tests:

Test	Duration (Including warm-up and cool-down)	No. of Tests	Composition of test
GxT	60-min	1	Progresses in steps from easy to maximum effort
FTP	60-min	1	A 5-min and a 20-min maximum effort self-paced time-trial

Testing protocols

Please mark "Y" to give consent or "N" to withhold consent in the boxes provided.	Tick box
I understand that a face mask will be placed over my nose and mouth securely tightened to measure my ventilatory data.	
I understand that a heart rate strap will be placed around my chest to monitor my heart rate.	
I understand that pin-pricks will be made at my earlobe to assess the amount of blood lactate present in my circulation as I exercise, which may cause very minor and temporary pain.	
I understand there are inherent risks associated with intense exercise and I will likely experience fatigue and discomfort.	
I understand that my blood lactate samples will be disposed of in a lawful and respectful way.	

General

Please mark "Y" to give consent or "N" to withhold consent in the boxes provided.	**Tick box**
I have read, or had read to me, the information leaflet for this project and I understand the contents.	
I have had the opportunity to ask questions and all my questions have been answered to my satisfaction.	
I freely and voluntarily agree to be part of this research study, though without prejudice to my legal and ethical rights.	
I understand that I may withdraw from the study at any ***during*** the testing period	
I understand that I ***cannot withdraw*** my personal data from the study findings after it has been pooled with other participants data.	
I have received a copy of this agreement.	
I know I will not be paid for taking part in this study.	
I know how to contact the research team if I need to.	
I agree to being contacted by researchers by email / phone as part of the research study.	

Data processing

I give permission for my coded information to be part of research publications	
I give my consent to forward any contra-indications to exercise that are identified; during the medical examination, apparent from my completed medical questionnaire, or adverse reactions to exercise, to my GP.	
I understand the study findings will be retained for 7-years. These findings will not be used in future unrelated studies without my permission being obtained.	

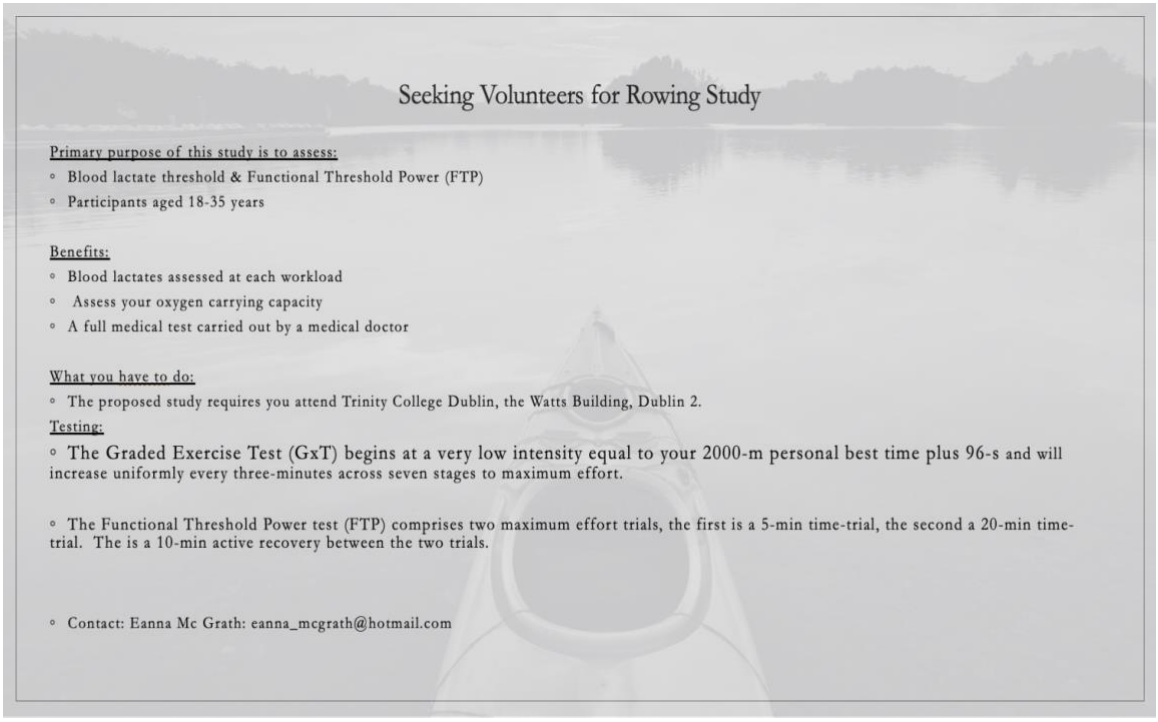
PARTICIPANT'S NAME: ……..…….……
CONTACT DETAILS: ……...……

PARTICIPANT'S GP CONTACT DETAILS
GP Name……..……
GP Address……..

PARTICIPANT'S SIGNATURE: ……Date: ……..
To be completed by the Principle Investigator: Statement of investigator's responsibility
I, the undersigned, have taken the time to fully explain to the above participant the nature and purpose of this study in a way that they could understand and purpose of this study in a way they could understand. I have explained the risks and possible benefit involved. I have invited them to ask questions on any aspect of the study that concerned them.
I have given them a copy of the information leaflet and consent form to the participant with contacts of the study team.

SIGNATURE:……
Date: ……..
BSc (Hons), MSc.

9.2: Poster seeking volunteers



9.2: Letter to gatekeepers for study reported in Chapter 6

Eanna Mc Grath
Anatomy Department, Level 2 Watts Building,
Trinity College Dublin,
Dublin 2.
Phone: 0866075380
Email: eanna_mcgrath@hotmail.com

Date:
Dear (name of secretary) of Rowing Club

I am undertaking a PhD research project in Trinity College Dublin investigating alternative measures of blood lactate threshold and "Functional Threshold Power" on a rowing ergometer.

The title of my proposed study is "An assessment of mathematical models of human performance as proxies for physiological tests". I am looking for 20 to 30 volunteers, between the ages of 18 and 35 year to participate in this research. Study volunteers will partake in two separate tests, the test details and benefits are outlined in the attached poster.

I would very much appreciate if you could pass this on, to any members of your club who you think may be interested in participating.
Many thanks,
Sincerely,

Eanna Mc Grath

9.2: Participant information leaflet for study reported in Chapter 6

Participant Information Leaflet

An assessment of mathematical models of human performance as proxies for physiological tests

You are being invited to take part in a research study that is being carried out by the School of Medicine, Anatomy Department, Trinity College Dublin by Eanna Mc Grath, in partial fulfilment of a PhD qualification. This prospective study has been submitted to the Trinity College Research Ethics Committee for approval and will not proceed without approval. Before you decide whether or not you wish to take part, please read this information sheet carefully. Ask the principle investigator Eanna Mc Grath any questions. Do not feel rushed or under pressure to make a quick decision. You should understand the risks and benefits of taking part in this study so that you can make a decision that is right for you. You may wish to discuss it with your family, friends or GP.

Our study aims to collect data from the well-know rowing "Graded Exercise Test" (GxT) and compare it with a bicycling test called the "Functional Threshold Power Test". The FTP test may provide rowers with information relating to their fitness that is not provided by the more traditional rowing GxT.

Site	Human Performance Laboratory, Level 2 Watts Building, Trinity College Dublin.		
Research team	Principle Investigator	Mr Eanna Mc Grath	eamcgrat@tcd.ie
	Assistant Professor	Dr Nick Mahony	njmahony@tcd.ie
	Assistant Professor	Dr Neil Fleming	Neil.fleming@tcd.ie
Data Controllers Data Protection Officer	Trinity College Dublin Dr Neil Fleming Human Performance Laboratory, Level 2 Watts Building, Trinity College Dublin.		

<u>You would be required to fulfil the following conditions to participate in this study:</u>

- Aged between 18 and 35 years.
- Pass the medical screening provided by a medical doctor.
- Have consistently partaken in organised rowing training and competitive events for at least one year prior to study commencement.

<u>Unfortunately, you cannot participate in this study if any of the following are true:</u>

- You are pregnant, or become pregnant during the time span of the proposed study.
- You have high or low blood pressure, or are found to have either during your pre-screening assessment
- You have a bleeding or clotting disorder

- You have ever been diagnosed with a heart condition or have had heart tests in the past identifying cardiac abnormalities, such as ECG abnormality
- You have any breathing or respiratory difficulties (based on spirometry data) or symptoms of respiratory infection such as colds/influenza on the day of testing
- You have a recent or long term musculoskeletal injury that could limit your ability to exercise
- You have any medical condition that would prevent you from participating in an exercise test
- You are deemed unfit to participate on completion of your medical questionnaire and medical examination due to an on-going illness or injury, or if you have any of the following; diabetes, hypertension, heart defects, metabolic disorders or other contraindications to exercise testing.

Voluntary participation: The initial testing of rowers will commence in December 2021. There are two tests, which should be completed within a 10-day period. There are no further tests required thereafter. If you decide to volunteer to participate in this study, you may withdraw at any time up to the point when you have completed all the exercise trials. Thereafter, once your test results have been amalgamated with those of other athletes in this investigation, it will not be possible to withdraw your data. If you decide not to participate or, if you withdraw prior to this point, contact Eanna Mc Grath (eanna_mcgrath @hotmail.com). In this circumstance, you will not be penalized and will not give up any benefits that you had before entering the study.

There will be twenty rowers partaking in this investigation. The testing will take place in Human Performance Laboratory, Level 2, Watts Building, Trinity College Dublin, and an option of testing in the Human Performance Laboratory, Base2Race, Unit 46, Ballymount Road Upper, Dublin will also be given. Prior to testing, you will undergo a medical screening to ensure you are in good health and that it is safe for you to exercise to exhaustion. There will be two testing days that you will be required to attend the exercise-testing laboratory. You will have a mask placed over your nose and mouth during each test, which will be securely tightened. A heart rate strap will be placed around your chest for all exercise tests. A very small pinprick in your earlobe will be used to collect and assess changes in blood lactate concentration at frequent intervals while you exercise.

The GxT duration, including your warm-up and cool-down is approximately 60-min. The test starts at a very low intensity (your two-kilometre personal best time plus 96-s) and will increase uniformly every three-minutes across seven stages to maximum effort. The r-FTP test requires the rower to complete a 5-min and 20-min time-trial at the highest sustainable power the athlete can tolerate. There is a 10-min active recovery between the two time-trials. The results of each test will be used to give insight as to your current fitness level.

Test outline

Test	Duration	No. of Tests	Composition of test
GxT	60-min	1	Progresses uniformly from easy to maximum effort
FTP	60-min	1	A 5-min and a 20-min maximum effort self-paced time-trial

During both test, there will be two support personnel in attendance, both certified in first aid, AED and CPR. Eanna Mc Grath, the primary investigator, will be present for both tests. In the event of cardiac event, standard CPR procedures are implemented. In the case of non-cardiac event, the Medical Officer is notified of adverse event and will appraise whether an ambulance is required. In all cases, an incident report form is completed and submitted to School of Medicine and the Faculty Research Ethics Team.

What will happen to my samples and data?

Enlisted participants will be assigned a study number and data for that participant will be only referenced according to their study number, therefore making the data confidential and pseudo-anonymised. For the duration of the study all participants will be referenced under their specific number. This security measure will also stay in place after the study has finished. Data will only be analysed in group format and no personal information or data for any participant will be disclosed. This code number will be stored in a single password encrypted excel file stored on a designated TEAMS folder. Only the code number will be entered on the pre-trial health screening forms. This identification allows matching codes across data sets.

All hardcopies of written consent will be stored in the supervisor's office in a locked filing cabinet. Only the lead investigator will have direct access to the data collected. The study supervisor will have secondary access to the data via consultation with the lead investigator. Names and codes will all be stored separately. This is the legal basis for

processing data. The data will only be presented under the participants study number, therefore allowing the identity of the participants to remain pseudo-anonymous. No data will be disclosed to individuals outside of the designated study team. Your pseudo-anonymised data will be securely retained for 7 years as this is accepted best practice.

- The right to access to your data and receive a copy of it
- The right to restrict or object to processing of your data
- The right to object to any further processing of the information we hold about you (except where it is de-identified)
- The right to have inaccurate information about you corrected or deleted
- The right to receive your data in a portable format and to have it transferred to another data controller
- The right to request deletion of your data

By law you can exercise the following rights in relation to your personal data, unless the request would make it impossible or very difficult to conduct the research. You can exercise these rights by contacting your Eanna Mc Grath or the Trinity College Data Protection Officer, Secretary's Office, Trinity College Dublin, Dublin 2, Ireland. Email: dataprotection@tcd.ie. Website: www.tcd.ie/privacy. Pseudo-anonymised data retained after the study is completed will not be used in future unrelated studies without further specific permission being obtained.

Are there any benefits to taking part in this research?

Participants will gain a measure of their trained state and they may choose to use this information to improve their training. Participants will be provided with training advice based on data collected during their exercise tests.

Are there any risks to me or others if I take part?

This study requires you to exercise maximally and therefore is a small risk of a heart coronary attack associated with such exercise. In a young healthy population these risks are markedly reduced and considered minimal. The lead investigator, whom is certified in AED/CPR and first aid, will supervise all of the study procedures. In addition, you will give a contact email for usage at any time during your participation in the study, and you will be contacted 24 hour after each trial element by the lead investigator to enquire if you have experienced any adverse effects. You may experience some minor bruising on your earlobe from blood sampling, however, all blood samples will be collected from the same site to minimise the need for additional earlobe pricks. Each trial requires repeated capillary blood samples throughout the test, which can be uncomfortable. The maximum number of capillary blood samples per test is twelve, the minimum number is four and the average number of blood samples is seven. If any contra-indications to exercise are identified during the medical examination, this information will be forwarded, with your consent, to your designated GP by the study team. There are small inherent risks associated with exercising at

maximal, or near maximal, exercise intensities as in participation in most sporting activities. The estimated risk of a cardiac arrest is 1 in 5000 in a sedentary population. However, in a young healthy population these risks are markedly reduced and considered minimal.

Once you have completed the two tests, you will be given your test results immediately. The results of the study will be reported in medical/scientific journals and disclosed at medical/scientific conferences. No information which reveals your identity will be disclosed. By law, we can use your personal information for scientific research (in the public interest). We will also ask for your explicit consent to use your data as a requirement of the Irish Health Research Regulations.

The medical examination will be performed by a registered medical practitioner, including spirometry, blood pressure, full blood count and any other tests deemed necessary. If any medical abnormalities are identified on examination the potential participant will be excluded from the trial and pertinent details relating to the diagnosed abnormalities will be forwarded to your doctor. All enlisted participants will also be requested to complete a detailed medical questionnaire (attached) prior to the medical examination; which will be reviewed by the medical practitioner to ensure you are safe to exercise.

Who should I contact for information or complaints?

If you have any concerns or questions, you can contact:

- Eanna Mc Grath: email: eanna_mcgrath@hotmail.com
- Neil Fleming: email neil.fleming@tcd.ie
- Data Protection Officer, Trinity College Dublin: Data Protection Officer, Secretary's Office, Trinity College Dublin, Dublin 2, Ireland. Email: dataprotection@tcd.ie. Website: www.tcd.ie/privacy.

Under GDPR, if you are not satisfied with how your data is being processed, you have the right to lodge a complaint with the Office of the Data Protection Commission, 21 Fitzwilliam Square South, Dublin 2, Ireland. Website: www.dataprotection.ie.

If you would like to take part in this study, you will be asked to sign the Consent Form on the next page. You will be given a copy of this information leaflet and the signed Consent Form to keep.

9.2: Consent form for study reported in Chapter 6

Consent Form

Project title: An assessment of mathematical models of human performance as proxies for physiological tests.
Principal investigator: Eanna Mc Grath (Lead Investigator).
Additional investigators: Dr Nick Mahony and Dr Neil Fleming.

Background

The purpose of this investigation is to compare a variety of blood lactate derived threshold markers calculated from a Graded Exercise Test (GxT) with the power output from a "Functional Threshold Power" (FTP) test. The investigation is in partial fulfilment of a PhD by Eanna Mc Grath. This study will assess performance during two tests:

Test	Duration (Including warm-up and cool-down)	No. of Tests	Composition of test
GxT	60-min	1	Progresses in steps from easy to maximum effort
FTP	60-min	1	A 5-min and a 20-min maximum effort self-paced time-trial

Testing protocols

Please mark "Y" to give consent or "N" to withhold consent in the boxes provided.	**Tick box**
I understand that a face mask will be placed over my nose and mouth securely tightened to measure my ventilatory data.	
I understand that a heart rate strap will be placed around my chest to monitor my heart rate.	
I understand that pin-pricks will be made at my earlobe to assess the amount of blood lactate present in my circulation as I exercise, which may cause very minor and temporary pain.	
I understand there are inherent risks associated with intense exercise and I will likely experience fatigue and discomfort.	
I understand that my blood lactate samples will be disposed of in a lawful and respectful way.	

General

Please mark "Y" to give consent or "N" to withhold consent in the boxes provided.	**Tick box**
I have read, or had read to me, the information leaflet for this project and I understand the contents.	
I have had the opportunity to ask questions and all my questions have been answered to my satisfaction.	

I freely and voluntarily agree to be part of this research study, though without prejudice to my legal and ethical rights.	
I understand that I may withdraw from the study at any ***during*** the testing period	
I understand that I ***cannot withdraw*** my personal data from the study findings after it has been pooled with other participants data.	
I have received a copy of this agreement.	
I know I will not be paid for taking part in this study.	
I know how to contact the research team if I need to.	
I agree to being contacted by researchers by email / phone as part of the research study.	

Data processing

I give permission for my coded information to be part of research publications	
I give my consent to forward any contra-indications to exercise that are identified; during the medical examination, apparent from my completed medical questionnaire, or adverse reactions to exercise, to my GP.	
I understand the study findings will be retained for 7-years. These findings will not be used in future unrelated studies without my permission being obtained.	

PARTICIPANT'S NAME: **…….**
CONTACT DETAILS: ……...……

PARTICIPANT'S GP CONTACT DETAILS
GP Name……...
GP Address……

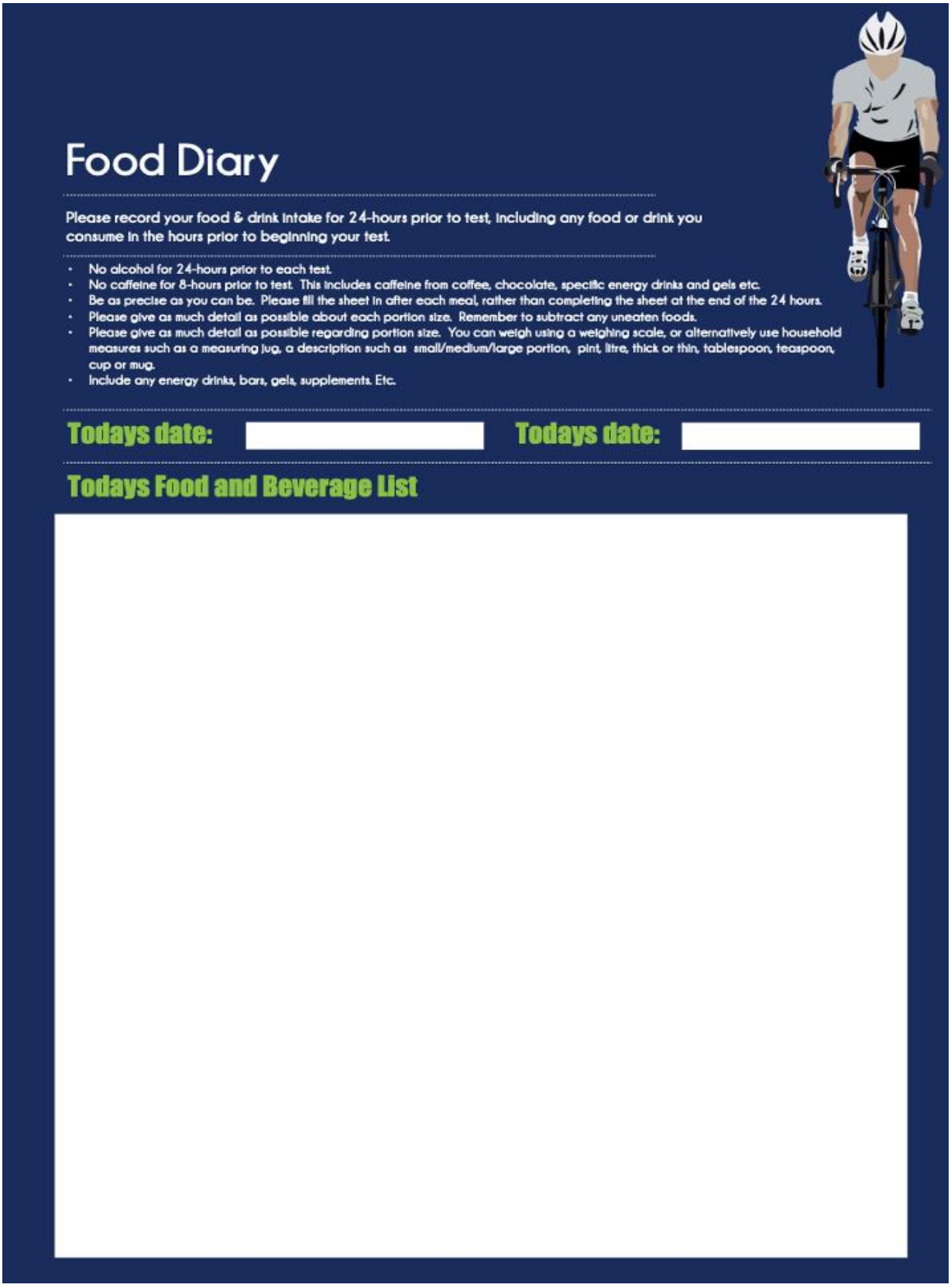
PARTICIPANT'S SIGNATURE:
……...…
Date: ……..

To be completed by the Principle Investigator:

Statement of investigator's responsibility
I, the undersigned, have taken the time to fully explain to the above participant the nature and purpose of this study in a way that they could understand and purpose of this study in a way they could understand. I have explained the risks and possible benefit involved. I have invited them to ask questions on any aspect of the study that concerned them.
I have given them a copy of the information leaflet and consent form to the participant with contacts of the study team.

SIGNATURE:……
Date: ……..
BSc (Hons), MSc.

9.2: Food diary



Appendix 9.3: Power Profile Chart (Allen & Coggan, 2010).

	maximal power output (W/kg)							
	MEN				WOMAN			
	5 sec.	1 min.	5 min.	FTP	5 sec.	1 min.	5 min.	FTP
	25.18	11.50	7.60	6.40	19.42	9.29	6.74	5.69
	24.88	11.39	7.50	6.31	19.20	9.20	6.64	5.61
	24.59	11.27	7.39	6.22	18.99	9.11	6.55	5.53
	24.29	11.16	7.29	6.13	18.77	9.02	6.45	5.44
world class pro, international	24.00	11.04	7.19	6.04	18.56	8.93	6.36	5.36
	23.70	10.93	7.08	5.96	18.34	8.84	6.26	5.28
	23.40	10.81	6.98	5.87	18.13	8.75	6.17	5.20
	23.11	10.70	6.88	5.78	17.91	8.66	6.07	5.12
	22.81	10.58	6.77	5.69	17.70	8.56	5.98	5.03
	22.51	10.47	6.67	5.60	17.48	8.47	5.88	4.95
Exceptional domestic pro	22.22	10.35	6.57	5.51	17.26	8.38	5.79	4.87
	21.92	10.24	6.46	5.42	17.05	8.29	5.69	4.79
	21.63	10.12	6.36	5.33	16.83	8.20	5.60	4.70
	21.33	10.01	6.26	5.24	16.62	8.11	5.50	4.62
	21.03	9.89	6.15	5.15	16.40	8.02	5.41	4.54
Excellent category I	20.74	9.78	6.05	5.07	16.19	7.93	5.31	4.46
	20.44	9.66	5.95	4.98	15.97	7.84	5.21	4.38
	20.15	9.55	5.84	4.89	15.76	7.75	5.12	4.29
	19.85	9.43	5.74	4.80	15.54	7.66	5.02	4.21
	19.55	9.32	5.64	4.71	15.32	7.57	4.93	4.13
	19.26	9.20	5.53	4.62	15.11	7.48	4.83	4.05
	18.96	9.09	5.43	4.53	14.89	7.39	4.74	3.97
Very good category II	18.66	8.97	5.33	4.44	14.68	7.30	4.64	3.88
	18.37	8.86	5.22	4.35	14.46	7.21	4.55	3.80
	18.07	8.74	5.12	4.27	14.25	7.11	4.45	3.72
	17.78	8.63	5.01	4.18	14.03	7.02	4.36	3.64
	17.48	8.51	4.91	4.09	13.82	6.93	4.26	3.55
	17.18	8.40	4.81	4.00	13.60	6.84	4.17	3.47
	16.89	8.28	4.70	3.91	13.39	6.75	4.07	3.39
Good category III	16.59	8.17	4.60	3.82	13.17	6.66	3.98	3.31
	16.29	8.05	4.50	3.73	12.95	6.57	3.88	3.23
	16.00	7.94	4.39	3.64	12.74	6.48	3.79	3.14
	15.70	7.82	4.29	3.55	12.52	6.39	3.69	3.06
	15.41	7.71	4.19	3.47	12.31	6.30	3.59	2.98
	15.11	7.59	4.08	3.38	12.09	6.21	3.50	2.90
Moderate category IV	14.81	7.48	3.98	3.29	11.88	6.12	3.40	2.82
	14.52	7.36	3.88	3.20	11.66	6.03	3.31	2.73
	14.22	7.25	3.77	3.11	11.45	5.94	3.21	2.65
	13.93	7.13	3.67	3.02	11.23	5.85	3.12	2.57
	13.63	7.02	3.57	2.93	11.01	5.76	3.02	2.49
	13.33	6.90	3.46	2.84	10.80	5.66	2.93	2.40
Fair category V	13.04	6.79	3.36	2.75	10.58	5.57	2.83	2.32
	12.74	6.67	3.26	2.66	10.37	5.48	2.74	2.24
	12.44	6.56	3.15	2.58	10.15	5.39	2.64	2.16
	12.15	6.44	3.05	2.49	9.94	5.30	2.55	2.08
	11.85	6.33	2.95	2.40	9.72	5.21	2.45	1.99
	11.56	6.21	2.84	2.31	9.51	5.12	2.36	1.91
Untrainend non racer	11.26	6.10	2.74	2.22	9.29	5.03	2.26	1.83
	10.96	5.99	2.64	2.13	9.07	4.94	2.16	1.75
	10.67	5.87	2.53	2.04	8.86	4.85	2.07	1.67
	10.37	5.76	2.43	1.95	8.64	4.76	1.97	1.58
	10.08	5.64	2.33	1.86	8.43	4.67	1.88	1.50

Appendix 9.3: Participant's VO_2peak, body mass, body mass index (BMI) and % body fat.

Participant code	VO_2peak GxT test ($mL.kg^{-1}.min^{-1}$)	VO_2peak c-FTP test ($mL.kg^{-1}.min^{-1}$)	Mass (kg)	BMI ($kg.m^{-2}$)	Age (yr)	Body fat (%)
1 (M)	67.0	65.0	61.0	21.9	35	9
2 (M)	61.5	58.0	63.0	19.2	30	9
3 (M)	64.6	61.0	71.4	22.0	32	11
4 (M)	70.3	-	72.8	23.5	22	9
5 (M)	72.3	69.5	64.4	20.3	25	9
6 (M)	56.6	53.5	66.0	20.4	29	12
7 (M)	61.0	58.0	76.5	24.7	35	10
8 (M)	68.1	64.4	70.1	23.2	32	10
9 (M)	71.2	66.0	68.0	23.0	25	10
10 (M)	61.0	61.4	63.0	19.9	23	13
11 (M)	64.6	62.3	73.3	22.4	28	14
12 (M)	72.5	72.9	73.4	19.9	18	11
13 (F)	51.7	53.5	75.5	27.4	35	13
14 (F)	60.1	60.0	52.0	18.6	26	18
15 (F)	60.0	54.6	59.0	22.8	29	15
16 (F)	58.2	58.4	60.6	22.0	34	16
17 (F)	57.5	-	62.8	21.5	33	15
18 (F)	62.1	59.7	59.5	19.2	26	16
19 (F)	51.8	53.3	61.0	20.4	19	18
Mean	62.7	60.7	66.0	21.7	28	12
SD	6.3	5.6	6.7	2.2	5	3

- Metabolic cart fault during data collection

Appendix 9.3: Participant's BLa (mmol.L^{-1}) response to bicycling at c-FTP.

Participant Code	10m	20m	30m	40m	50m	60m
1 (M)	2.5	2.6	2.8	2.8	3.2	3.2
2 (M)	4.0	4.1	4.1	3.4	Exhaustion	3.9
3 (M)	3.9	3.9	3.6	4.1	4.5	5.1
4 (M)	2.9	2.6	2.9	3.7	4.0	4.2
5 (M)	2.8	2.4	3.0	3.4	3.3	3.9
6 (M)	3.9	5.2	3.8	4.8	3.2	3.6
7 (M)	4.1	4.8	5.0	4.8	Exhaustion	4.7
8 (M)	3.1	4.1	4.9	4.7	4.4	4.4
9 (M)	7.0	7.2	6.5	6.9	5.8	6.8
10 (M)	4.1	4.3	4.5	4.5	4.2	4.2
11 (M)	3.8	4.8	4.0	4.0	3.8	3.5
12 (M)	4.1	3.9	3.0	3.5	3.5	3.6
13 (F)	3.8	3.2	2.6	3.2	2.8	2.1
14 (F)	2.3	1.8	2.0	1.6	NA	1.2
15 (F)	2.0	1.3	1.3	2.4	2.0	2.6
16 (F)	3.2	3.4	3.5	3.3	3.4	3.5
17 (F)	3.7	4.7	4.4	5.3	5.5	5.4
18 (F)	3.7	3.8	3.0	3.1	3.3	2.5
19 (F)	3.8	3.8	3.9	3.8	3.8	3.2
Mean	3.6	3.8	3.6	3.9	3.8	3.8
SD	1.1	1.3	1.2	1.2	1.0	1.3

Appendix 9.3: Participant's Dmax, c-FTP, T_{Lac} and T_{vent}, all data are expressed in W.

Participant code	Dmax (W)	c-FTP (W)	T_{Lac} (W)	T_{vent} (W)
1 (M)	246	256	257	231
2 (M)	253	267	248	215
3 (M)	318	326	337	315
4 (M)	247	257	283	214
5 (M)	280	316	313	275
6 (M)	278	290	261	232
7 (M)	236	237	230	184
8 (M)	265	276	257	184
9 (M)	275	300	234	204
10 (M)	272	285	308	178
11 (M)	190	209	178	161
12 (M)	193	209	181	147
13 (F)	206	218	191	170
14 (F)	220	232	200	169
15 (F)	200	218	200	177
16 (F)	218	231	221	179
17 (F)	277	285	261	170
18 (F)	295	304	280	186
19 (F)	189	195	178	146
Mean	245	259	243	197
SD	39	40	48	43

Appendix 9.3: Participant's Dmax, c-FTP, T_{Lac} and GxT Pmax.

Participant code	Dmax $W.kg^{-1}$	FTP $W.kg^{-1}$	T_{Lac} $W.kg^{-1}$	GxT $W.kg^{-1}$
1 (M)	4.0	4.2	4.2	6.1
2 (M)	4.0	4.2	3.9	5.1
3 (M)	4.5	4.6	4.7	4.8
4 (M)	3.4	3.5	3.9	5.1
5 (M)	4.3	4.9	4.9	5.4
6 (M)	4.2	4.4	4.0	6.0
7 (M)	3.1	3.1	3.0	4.5
8 (M)	3.8	3.9	3.7	4.4
9 (M)	4.0	4.4	3.4	5.1
10 (M)	4.4	4.5	4.1	5.1
11 (M)	4.0	4.1	3.8	4.7
12 (M)	3.7	3.9	4.2	4.7
13 (F)	2.5	2.8	2.4	3.0
14 (F)	3.7	4.0	3.5	4.8
15 (F)	3.5	3.7	3.2	4.6
16 (F)	3.6	3.8	3.3	4.5
17 (F)	3.2	3.5	3.2	4.0
18 (F)	3.7	3.9	3.7	4.5
19 (F)	3.1	3.2	2.9	4.1
Mean	3.7	3.9	3.7	4.8
SD	0.5	0.5	0.6	0.7

Appendix 9.4: Participant's gender, body mass, height, body mass index (BMI), weekly training hours (h), number of years in structured training (yr), VO_2max ($mL.min^{-1}.kg^{-1}$) and age (yr).

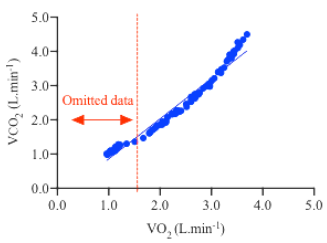
Participant code	Mass (kg)	Height (m)	BMI ($kg \cdot m^{-2}$)	Weekly volume (h)	Training (yr)	VO_2max ($mL.min^{-1}.kg^{-1}$)	Age (yr)
1F	71.5	1.80	22.1	26.0	7.0	70.0	20
2F	48.4	1.56	19.9	19.0	6.0	58.0	31
3F	58.6	1.70	20.3	15.0	6.5	64.5	35
4F	56.0	1.66	20.3	19.0	7.0	58.1	35
5F	60.1	1.70	20.8	19.0	6.0	78.2	19
6F	55.5	1.74	18.3	16.0	4.0	70.9	33
7F	61.9	1.73	20.7	20.0	6.0	63.0	34
8F	52.1	1.63	19.6	19.0	5.0	68.2	30
9M	72.3	1.77	23.1	21.0	3.0	58.0	27
10M	70.7	1.75	23.1	22.0	7.5	57.6	22
11M	83.0	1.79	25.9	17.0	4.5	72.2	24
12M	79.3	1.81	24.2	14.0	4.0	55.0	29
13M	64.8	1.89	18.1	17.0	6.0	60.9	29
14M	78.1	1.78	24.6	20.0	7.5	61.1	22
15M	76.2	1.82	23.0	17.0	6.0	56.7	29
Mean	65.9	1.7	21.6	18.7	5.7	63.5	28
SD	10.8	0.1	2.3	3.0	1.4	6.9	5

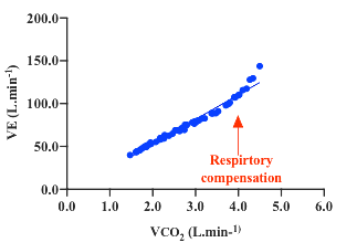
Appendix 9.4: Participants measured power output (W) on the Lode Cycle Ergometer and Garmin power pedal at FTP.

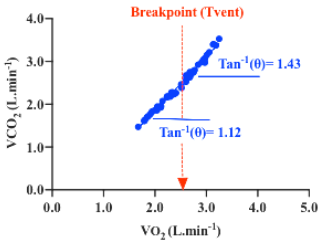
Participant code	Lode (W)	Garmin (W)	Δ power (W)
1F	252	260	2
2F	197	201	-3
3F	205	209	-4
4F	206	215	1
5F	250	254	-4
6F	256	264	4
7F	200	202	-2
8F	228	236	-4
9M	295	293	2
10M	312	313	-1
11M	269	278	0
12M	315	311	4
13M	355	350	5
14M	294	293	1
15M	350	344	6
Mean	266	268	0
SD	53	49	3

Appendix 9.4: Sequential methodology used to determine participant's T_{vent} ($L.min^{-1}$).

1







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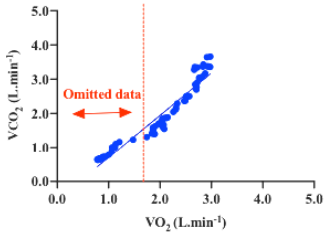

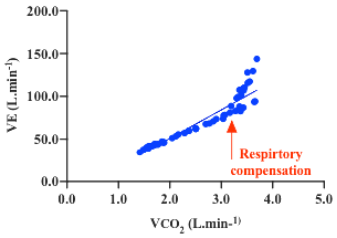

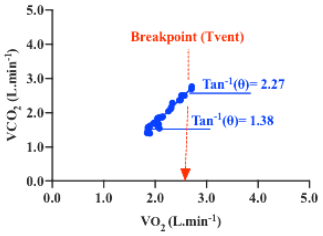

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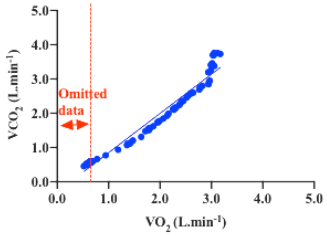

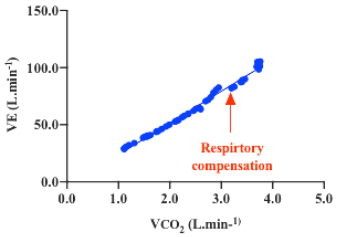

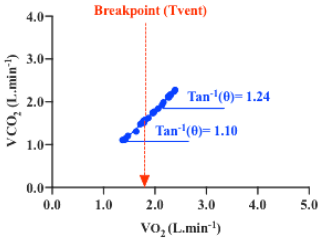

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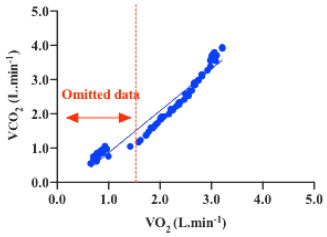

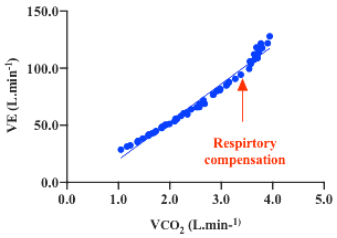

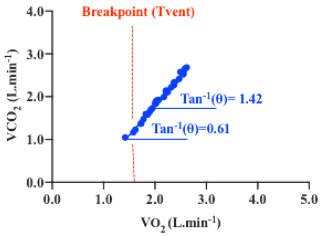

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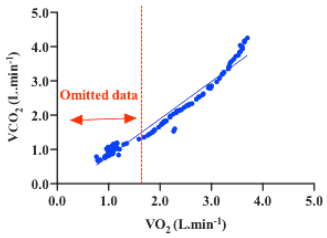

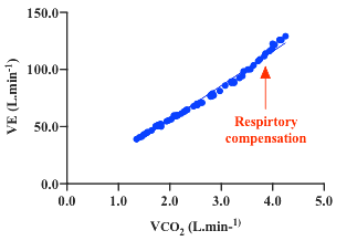

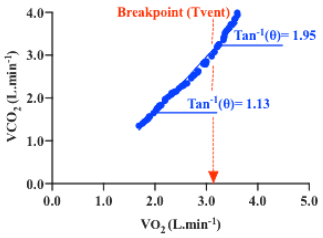

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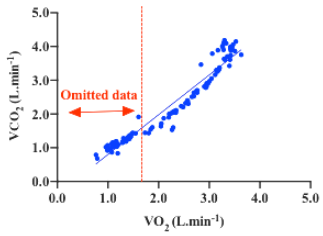
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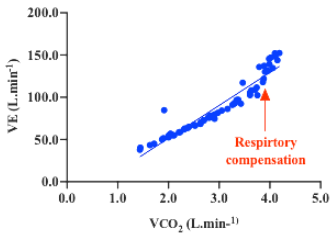
VO2 (L.min-1)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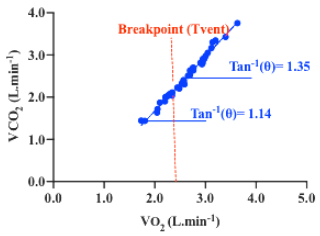
VCO2 (L.min-1)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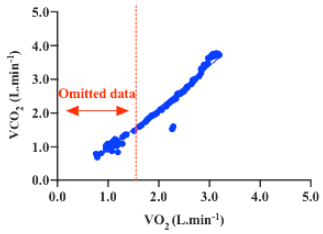
VCO2 (L.min-1)
VO2 (L.min-1)

7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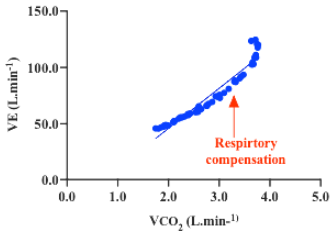
Respirtory compensation
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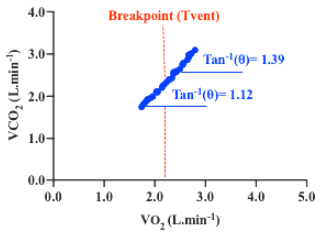
VCO2 (L.min-1)


Breakpoint (Tvent)
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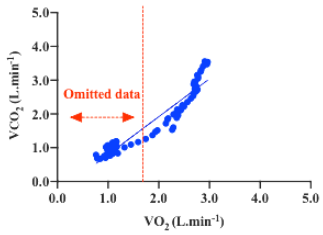
Tan-1(θ)= 1.12
VCO2 (L.min-1)
VO2 (L.min-1)

8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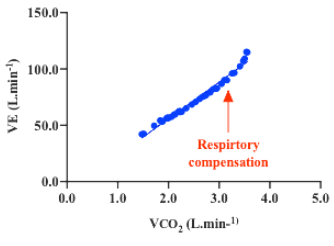
VCO2 (L.min-1)
VO2 (L.min-1)


Respirtory compensation
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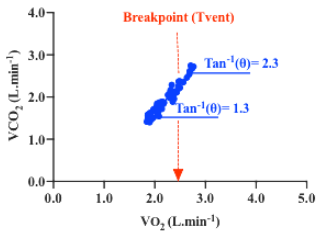
VCO2 (L.min-1)


Breakpoint (Tvent)
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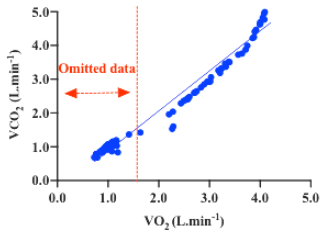
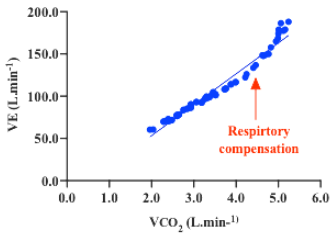
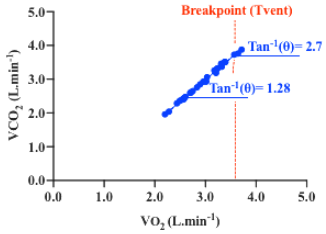
Tan-1(θ)= 1.3
VCO2 (L.min-1)
VO2 (L.min-1)

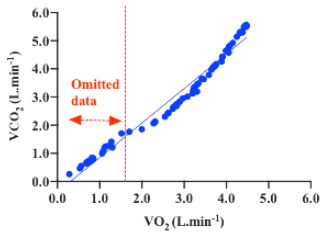
10

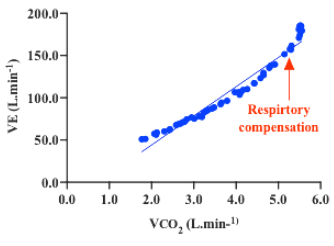

Omitted data
VCO2 (L.min-1)
VO2 (L.min-1)

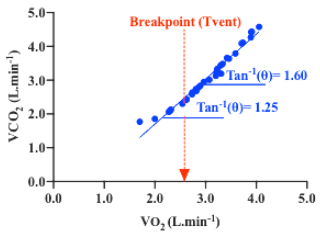

Respirtory compensation
VE (L.min-1)
VCO2 (L.min-1)


Breakpoint (Tvent)
Tan-1(θ)= 2.7
Tan-1(θ)= 1.28
VCO2 (L.min-1)
VO2 (L.min-1)

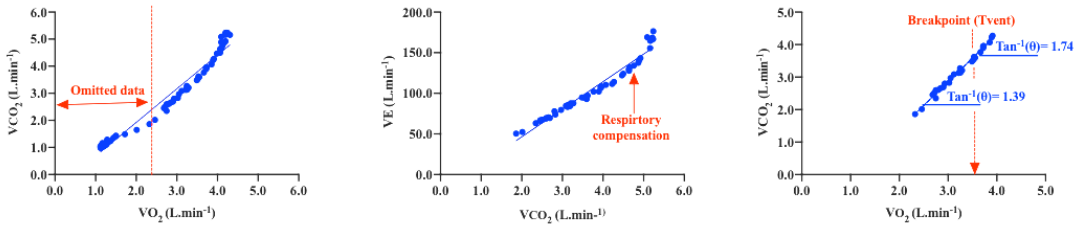
11


Omitted data
VCO2 (L.min-1)
VO2 (L.min-1)

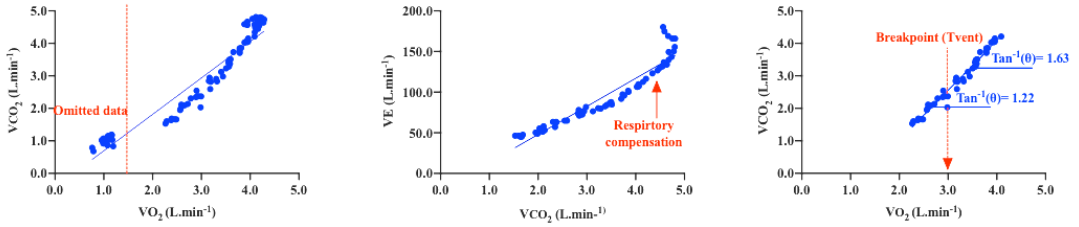

Respirtory compensation
VE (L.min-1)
VCO2 (L.min-1)


Breakpoint (Tvent)
Tan-1(θ)= 1.60
Tan-1(θ)= 1.25
VCO2 (L.min-1)
VO2 (L.min-1)

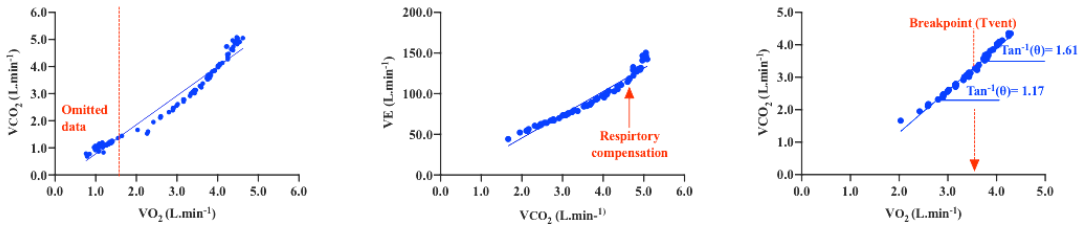
12



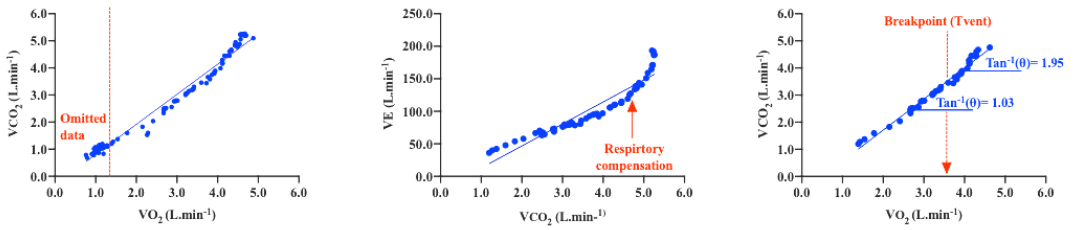
13



14



15



a. Prior to applying the segmented linear regression, the three minutes unloaded at 20-W and the first minute of the ramp were excluded, facilitating an initial adjustment in CO_2 stores (Beaver *et al*., 1986).
b. Respiratory compensation data, or "hyperventilation" data were excluded. Respiratory compensation was identified using a scatter plot of VCO_2 and VE, with a double linear regression applied with a constraint of > 15 % change in the slope prior to the second line being fitted (Beaver *et al*., 1986).
c. T_{vent} was then identified by plotting the remaining VO_2 and VCO_2 data. A change in the expected slope of > 10 % was used to demark a transition T_{vent} (Beaver *et al*., 1986).

Appendix 9.4: Participant's gender, body mass, height, body mass index (BMI), weekly training hours (h), number of years in structured training (yr), VO_2max ($mL.min^{-1}.kg^{-1}$) and age (yr).

Participant code	Mass (kg)	Height (m)	BMI ($kg.m^{-2}$)	Weekly volume (h)	Training (yr)	VO_2max ($mL.min^{-1}.kg^{-1}$)	Age (yr)
1F	71.5	1.80	22.1	26	7	70.1	20
2F	48.4	1.56	19.9	19	6	58.0	31
3F	58.6	1.70	20.3	15	6	64.5	35
4F	56.0	1.66	20.3	19	7	58.1	35
5F	60.1	1.70	20.8	19	6	78.2	19
6F	55.5	1.74	18.3	16	4	70.9	33
7F	61.9	1.73	20.7	20	6	63.0	34
8F	52.1	1.63	19.6	19	5	68.2	30
9M	72.3	1.77	23.1	21	3	58.2	27
10M	70.7	1.75	23.1	22	7	57.6	22
11M	83.0	1.79	25.9	17	4	72.2	24
12M	79.3	1.81	24.2	14	4	55.1	29
13M	64.8	1.89	18.1	17	6	60.9	29
14M	78.1	1.78	24.6	20	7	61.1	22
15M	76.2	1.82	23.0	17	6	56.7	29
Mean	65.9	1.70	21.6	19	6	63.5	28
SD	10.8	0.10	2.3	3	1	6.9	5

Appendix 9.4: Participant scores for FTP (W); three CP models in W: CP H_{model}; CP J_{model} and CP I_{model}, and three W′ models in J: CP H_{model}; CP J_{model} and CP I_{model}.

Participant code	c-FTP (W)	CP H_{model} (W)	CP J_{model} (W)	CP I_{model} (W)	W′ H_{model} (J)	W′ J_{model} (J)	W′ I_{model} (J)
1F	254	275	274	280	14341	15960	13900
2F	194	241	214	256	17596	17890	4900
3F	201	218	240	217	7231	7610	17000
4F	207	227	230	238	24804	22860	19400
5F	355	365	370	403	24767	22220	12800
6F	297	302	298	309	19098	19950	16500
7F	251	275	271	284	15242	17310	12600
8F	311	306	313	325	28565	23000	12600
9M	269	296	289	298	17762	19080	18300
10M	319	341	344	347	20566	18540	17000
11M	260	270	263	262	13811	16890	17500
12M	360	371	378	392	14677	11810	17500
13M	224	220	231	228	20348	15140	7400
14M	295	306	304	315	30728	30410	16100
15M	198	219	215	213	9262	10960	11600
Mean	266	282	282	291	18587	17975	14340
SD	55	51	53	59	6633	5578	4111

Appendix 9.4: Participant's power output (W) at cessation of the VO_{2max} test (Pmax at VO_{2max}), GET and Δ Pmax at VO_{2max} versus GET minus $^2/_3$ of ramp rate.

Participant code	Pmax at VO_{2max}	GET	Δ Pmax at VO_{2max} versus GET minus $^2/_3$ of ramp rate
	(W)	(W)	(W)
1F	372	228	144
2F	325	193	132
3F	313	174	139
4F	342	142	200
5F	400	298	102
6F	364	209	155
7F	340	211	129
8F	288	200	88
9M	-	-	-
10M	415	336	79
11M	432	270	162
12M	430	305	125
13M	455	266	189
14M	477	297	180
15M	465	325	140
Mean	387	247	140
SD	61	61	36

- Metabolic cart fault during data collection

Appendix 9.4: Predicted power output derived from 65, 75, 85 and 90% of Δ Pmax at VO_2max versus GET minus $^2/_3$ of ramp rate and the actual power output of riders during the four trials to predict CP and W′.

Participant code	Predicted power Trial 1 (W)	Predicted power Trial 2 (W)	Predicted power Trial 3 (W)	Predicted power Trial 4 (W)	Actual power Trial 1 (W)	Actual power Trial 2 (W)	Actual power Trial 3 (W)	Actual power Trial 4 (W)
1F	309	323	337	345	290	323	337	353
2F	266	279	292	299	240	262	299	316
3F	251	265	279	286	251	270	279	293
4F	259	279	299	309	259	279	299	309
5F	351	362	372	377	290	342	372	382
6F	297	312	328	336	285	297	327	343
7F	282	295	308	314	255	268	311	330
8F	244	253	262	266	230	241	269	290
9M	-	-	-	-	-	-	-	-
10M	367	375	383	387	330	340	390	391
11M	355	372	388	396	335	363	390	418
12M	366	379	391	398	320	366	404	424
13M	369	388	407	416	369	388	426	440
14M	394	412	430	439	394	412	430	448
15M	396	410	424	431	350	370	396	426
Mean	322	366	350	357	300	323	352	369
SD	55	56	56	57	51	54	55	56

- Metabolic cart fault during data collection

Appendix 9.4: Participant's power output (W) associated with Trials 1, 2, 3 and 4; and corresponding limits of tolerance (LoT).

Participant code	Fixed Trial 1 (W)	Fixed Trial 2 (W)	Fixed Trial 3 (W)	Fixed Trial 4 (W)	LoT Trial 1 (s)	LoT Trial 2 (s)	LoT Trial 3 (s)	LoT Trial 4 (s)
1F	290	323	337	353	940	400	220	195
2F	240	262	299	316	660	420	194	180
3F	251	270	279	293	660	255	240	141
4F	259	279	299	309	675	543	355	230
5F	290	342	372	382	840	270	159	118
6F	285	297	327	343	814	420	304	210
7F	255	268	311	330	515	446	198	158
8F	230	241	269	290	750	375	220	150
9M	400	450	475	500	625	339	265	120
10M	330	340	390	391	602	460	258	140
11M	335	363	390	418	857	605	314	187
12M	320	366	404	424	610	260	180	127
13M	369	388	426	440	660	495	217	189
14M	394	412	430	448	595	365	310	125
15M	350	370	396	426	610	498	370	228
Mean	307	331	360	378	694	410	254	167
SD	55	61	62	64	119	103	64	39

Appendix 9.4: Participant's Dmax (W), GxT Pmax (W), ΔPmax vs. Dmax and predicted fixed load trials (W).

Participant code	Dmax (W)	GxT Pmax (W)	ΔPmax vs. Dmax (W)	Predicted load 1 (W)	Predicted load 2 (W)	Predicted load 3 (W)	Predicted load 4 (W)
1F	252	320	68	290	306	323	340
2F	197	250	53	226	239	253	266
3F	207	260	53	236	249	263	276
4F	182	280	98	236	260	285	309
5F	264	340	76	306	325	344	363
6F	255	320	65	291	307	323	340
7F	202	250	48	228	240	252	264
8F	182	230	48	208	220	232	245
9M	310	420	110	371	398	426	453
10M	270	360	90	320	342	364	387
11M	290	390	100	345	370	395	420
12M	281	360	79	324	344	364	384
13M	303	400	97	356	381	405	429
14M	331	420	89	380	402	424	447
15M	263	360	97	316	341	365	389
Mean	254	331	78	296	315	335	354
SD	48	64	21	57	61	65	70

Appendix 9.5: Individual c-FTP, Dmax, FBLC-4, Pmax and body mass.

Participant code	c-FTP (W)	Dmax (W)	FBLC-4 (W)	Pmax (W)	Body mass (kg)
1	201	182	185	230	53.1
2	200	181	186	230	56.2
3	204	171	198	230	61.1
4	229	203	205	250	64.7
5	206	209	212	250	65.2
6	191	208	212	260	55.6
7	196	198	216	250	50.0
8	190	172	218	250	50.9
9	202	198	217	260	53.1
10	211	186	233	250	43.5
11	224	186	239	270	61.1
12	225	234	240	280	61.2
13	206	230	242	300	51.5
14	230	208	239	270	77.2
15	256	237	244	300	58.2
16	236	233	245	310	81.9
17	189	202	256	250	47.6
18	219	202	254	270	70.6
19	245	225	257	280	60.0
20	255	234	257	320	75.5
21	237	234	261	310	63.3
22	269	282	265	360	85.9
23	248	248	270	320	71.0
24	260	255	270	330	72.5
25	295	*271*	277	390	81.9
26	202	207	277	270	48.8
27	295	277	285	375	58.8
28	293	270	285	360	69.9
29	251	264	286	340	60.0
30	249	243	287	320	63.5
31	290	253	292	330	76.0
32	303	242	293	360	83.2
33	277	287	297	290	73.0
34	254	267	297	345	85.0
35	317	279	299	375	108.7
36	278	233	301	345	71.9
37	256	273	300	360	85.9
38	274	278	302	370	80.3
39	299	242	303	320	63.0
40	276	284	305	360	67.1
41	290	294	305	390	88.1
42	270	244	306	345	69.4

Participant code	c-FTP	Dmax	FBLC-4	Pmax (GxT)	Body mass
43	286	241	306	345	68.0
44	284	256	308	345	86.6
45	304	289	311	390	67.0
46	292	261	312	360	89.0
47	290	293	312	420	68.1
48	361	302	313	420	93.4
49	301	295	316	390	71.6
50	319	321	321	390	73.6
51	309	251	324	345	97.0
52	296	289	324	390	79.9
53	316	265	327	360	79.3
54	322	270	329	390	77.0
55	324	306	327	410	60.9
56	263	270	329	345	69.4
57	281	284	336	375	82.0
58	295	262	336	360	78.2
59	349	308	337	435	84.8
60	303	281	339	390	77.4
61	325	290	341	370	67.9
62	316	300	345	400	64.8
63	315	303	346	400	64.5
64	361	366	359	450	67.8
65	324	307	369	420	90.1
66	355	333	370	420	83.0
67	365	315	376	420	80.6
68	323	311	376	395	72.1
69	354	320	382	420	72.0
70	355	338	387	450	70.5
Mean	274	258	291	341	70.9
SD	49	44	50	60	12.8

Appendix 9.6: Participant's VO_2peak, body mass index (BMI), age (yr) and % body fat.

Participant code	VO_2peak GxT tes ($mL.kg^{-1}.min^{-1}$)	Mass (kg)	BMI ($kg.m^{-2}$)	Age (yr)	Body fat (%)
1 (F)	50.0	65.6	22.7	24	25.0
2 (F)	57.2	68.2	21.3	23	24.3
3 (F)	50.3	60.0	22.0	20	27.4
4 (F)	47.9	72.5	23.1	22	24.5
5 (F)	66.0	71.9	22.9	23	19.6
6 (F)	53.9	60.0	21.3	29	18.7
7 (F)	51.9	75.3	22.2	18	25.5
9 (M)	49.1	75.1	22.9	18	15.5
10 (M)	55.7	90.0	23.4	20	8.0
11 (M)	63.7	79.5	25.4	22	8.0
12 (M)	54.2	73.0	23.3	20	11.5
13 (M)	67.4	90.4	24.8	28	11.1
14 (M)	64.5	79.5	22.3	28	6.6
15 (M)	42.1	88.4	26.1	18	17.7
16 (M)	70.6	73.5	21.5	24	11.0
17 (M)	43.1	113.0	30.3	32	24.8
18 (M)	47.0	92.5	25.1	35	20.6
19 (M)	54.0	87.2	24.9	35	17.5
Mean	54.9	78.6	23.6	24	17.6
SD	8.4	13.2	2.2	6	6.9

Appendix 9.6: Individual BLa (mmol.L^{-1}) and HR (beats.min^{-1}) on cessation of the GxT and c-FTP test.

Participant code	GxT mmol.L^{-1}	c-FTP test mmol.L^{-1}	GxT beats.min^{-1}	c-FTP beats.min^{-1}
1 (F)	13.4	14.2	183	189
2 (F)	9.1	9.8	180	187
3 (F)	13.4	7.4	183	195
4 (F)	11.3	12.4	181	193
5 (F)	13.3	11.8	190	204
6 (F)	11.5	9.0	181	177
7 (F)	10.6	5.3	193	188
9 (M)	14.5	13.2	180	193
10 (M)	13.8	14.7	174	196
11 (M)	10.6	6.0	180	185
12 (M)	9.0	9.6	189	204
13 (M)	10.2	10.4	-	-
14 (M)	16.7	19.7	172	172
15 (M)	12.9	13.7	189	194
16 (M)	17.1	12.0	195	195
17 (M)	14.4	16.0	177	179
18 (M)	7.1	8.0	198	197
19 (M)	15.0	13.3	180	-
Mean	12.4	11.5	184	191
SD	2.7	3.7	7	9

- Indicates an erroneous reading

Appendix 9.6: Individual participant's r-FTP (W), m-FTP (W), body mass (kg), FBLC-4 (W), and Pmax (W).

	r-FTP (W)	m-FTP (W)	Body mass (kg)	FBLC-4 (W)	Pmax (W)
1 (F)	168	171	65.6	168	210
2 (F)	219	221	68.2	233	270
3 (F)	140	149	60.0	142	180
4 (F)	176	174	72.5	170	220
5 (F)	174	188	71.9	170	240
6 (F)	175	165	60.0	157	210
7 (F)	193	200	75.3	202	240
9 (M)	173	168	75.1	132	220
10 (M)	311	305	90.0	294	390
11 (M)	295	305	79.5	324	380
12 (M)	204	212	73.0	214	260
13 (M)	342	338	90.4	353	422
14 (M)	285	271	79.5	266	345
15 (M)	180	188	88.4	161	230
16 (M)	315	304	73.5	300	400
17 (M)	235	251	113.0	234	295
18 (M)	289	295	92.5	304	360
19 (M)	281	274	87.2	274	340
Mean	231	232	78.6	228	290
SD	64	61	13.1	69	78