Effect of Variability on Optimal Performance in Athletes

L. Martin

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Abstract

Purpose: This thesis details and critically evaluates a portfolio of published articles which describe and quantify the impact of biological variation on sports performance. Sports performance is influenced by performance-to-performance variation and within performance variation. Knowledge of performance variation enables athletes, coaches and sport scientists to manage expectations of performance at different times of day, seasonal progression with training and the anticipated impact of additional specific interventions.

Paper 1 identified variation in the relative contribution of selected kinematic and technical non-swimming elements to overall breaststroke performance with gender and event distance. Digital video playback measured start time (ST), turning time (TT), end time (ET), swimming velocity (SV), stroke rate (SR) and stroke length (SL) of finalists from 12 world, international and national 100 m and 200 m finals between 1992 and 1997. Multiple regression techniques generated a predictive equation to estimate finishing time (FT) for each event from the selected kinematic variables. Each equation was cross-validated using a separate group and limits of agreement were used to determine accuracy of predictive and actual FT. For all events SV was the primary determinant of FT, with TT being of secondary importance in the 200 m events and women's 100 m. In contrast, ST provided the second largest contribution to the men's 100 m event.

Paper 2 explored the impact of diurnal variation on physiological responses to sub-maximal swimming training in seven male collegiate swimmers. Swimmers completed morning and evening trials of 10 x 100 m paced intervals on three occasions. Oral temperature (T_o), heart rate (HR), minute ventilation (VE), oxygen uptake (VO_2), expiratory carbon dioxide (VCO_2), respiratory exchange ratio (RER), blood lactate (BLa) and blood glucose (BGl) were measured at rest and post exercise. Stroke rate, HR and RPE were measured during the first nine repetitions. Significant diurnal variation was found at rest for T_o, HR and VO_2 on all three occasions and for VE and VCO_2 on two days ($P<0.05$). During the training intervals only RPE showed diurnal variation ($P<0.05$), whilst post-exercise, significant diurnal variation was observed for T_o and BGl on two days ($P<0.05$). Therefore, although diurnal variation was evident at rest, there was no effect of time-of-day on physiological responses to paced sub-maximal swimming intervals.

Paper 3 determined whether critical swimming velocity (V*crit*) corresponded to the velocity at lactate threshold in eight elite triathletes since free swimming intervals and time trials are subject to variation from familiarisation, time-of-day, mood, motivation etc. V*crit* was expressed as the slope of a regression line between swimming distance and corresponding time from a series of 5 time trials over 100, 200, 400, 800 and 1500 m and all possible combinations. Lactate Threshold (LT) was determined as the first inflection point of the lactate-work rate curve following 5 x 300 m paced swims of increasing velocity. V*crit* was similar regardless of the combination or number of trials used in the linear regression. V*crit* was significantly faster than LT ($P<0.05$), and it was concluded that V*crit* could not be used as a non-invasive measure of LT in triathletes.

Paper 4 explored the effect of diurnal variation upon physiological responses to sub-maximal running. Nine male runners completed morning and evening trials of a 30 minute run at the speed of lactate threshold. Core body temperature (Tr), heart rate (HR), minute ventilation (VE), oxygen uptake (VO_2), carbon dioxide expired (VCO_2), respiratory exchange ratio (RER) and capillary blood lactate (BLa) were measured at

rest, post warm-up and at minutes 10, 20 and 30 of the sub-maximal run. In addition, RPE was reported every 10 minutes during the run. Significant diurnal variation was observed for Tr and RER at rest and post-warm-up (P<0.05), and for Tr this significant difference persisted during the exercise bout (P<0.05). RPE was significantly elevated during morning trials. Despite the diurnal variation in body temperature, other physiological responses to running at lactate threshold are largely unaffected, however coaches should prescribe a longer warm during morning training to minimise differences in physiological and psychological responses.

Paper 5 investigated the impact of temporal specificity of training upon diurnal variation in maximal swimming performance. Physiological and kinematic responses of two groups of youth swimmers routinely undertaking either morning and evening training (MEG) or evening only training (EOG) were compared during morning and evening trials of a 150 m race pace swim and a maximal 100 m time trial on two separate occasions. Oral temperature (T_o), heart rate (HR), and blood lactate (BLa) were assessed at rest, post warm-up, and after a 150 m race pace swim and a 100 m time trial. Stroke rate (SR), stroke count (SC), and time (T) were recorded for each length of the test swims. Results indicated that both groups recorded significantly slower 100 m performances (P<0.05) and a persistently lower oral temperature (P<0.05) during morning trials. No significant time-of-day effects were identified for any other variable. Results indicate that long term use of morning training does not appear to significantly reduce the diurnal variation in race pace swimming and body temperature.

Paper 6 examined variability in the pace profile of mountain bikers during a multiple-lap mountain bike race. A global-positioning system (GPS) recorded velocity (m/s), distance (m), elevation (m) and heart rate (b/min) at 1 Hz from 6 mountain bike riders. Lap-by-lap pacing was analysed using a 1-way ANOVA for mean time and mean velocity and indicated no significant difference in lap times (P = 0.99) or lap velocity (P= 0.65). Subsequently, velocity data were averaged every 100 m and plotted against race distance to observe the presence of intra-lap variation. A high degree of variation was observed which broadly reflected changes in terrain, however, high-resolution data demonstrated additional non-monotonic variation not related to terrain. Riders appeared to adopt an even pace strategy from lap-to-lap despite rapid adjustments in velocity within each lap which may be associated with dynamic regulation of self-paced exercise.

Critical Review section provides i) an autobiographical and chronological context of the development of the portfolio over a 13 year academic career, ii) reflections of the candidate’s development as a researcher and iii) details the contribution of the candidate to each paper. More importantly, a critical evaluation of how the papers have influenced and shaped future research and understanding is provided with reference to citations and wider literature.

Summary: Variation was observed in the contribution of non-swimming components to breaststroke swimming, the within-lap pace profile during a competitive mountain bike race and during maximal swimming performance in youth swimmers irrespective of the time-of-day at which training was undertaken. In contrast diurnal variation appeared to have no significant impact upon the metabolic responses to sub-maximal swimming or running. The body of work has been drawn upon in the literature to i) inform procedures for the assessment of critical swimming velocity, ii) apply critical swimming velocity in other techniques and populations, iii) further research exploring diurnal variation in sport, and exercise and health, and iv) explain research observations in the diurnal variation of performance.

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For believing in me through the ups and downs of my academic career, for listening to me over mountains of tea, for buying cake and for your endless encouragement and friendship a huge thank you to my colleagues from University of Wolverhampton and the University of Worcester, especially the Northwing crew…..Yay for Greatness!

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Introduction

Sports performance is influenced by biological variation and can be observed from performance-to-performance and within a single performance. Diurnal variation is reported when assessments are made only in the morning and evening, and therefore is particularly pertinent to sports such as swimming and athletics where qualifying heats are scheduled in the morning and finals are scheduled in the evening. Swimming studies have demonstrated that times for 100 m and 400 m performances improved by 1.9 – 3.6% from morning to evening (Baxter and Reilly 1983; Sinnerton and Reilly 1992), and mean and peak power output are highest in the evening when measured on a swim bench (Reilly and Marshall 1991). Reduced performance in the morning has been related to lowered body temperature (Reilly and Brooks 1986), reduced flexibility (Gifford 1987) and low alertness and vigour within a mood states profile (Trine and Morgan 1995).

The persistence of diurnal variations during sub-maximal exercise has implications for athletes' training yet little research has been conducted in this area. Reilly and Brooks (1982) and Reilly and Baxter (1983) observed no significant variation in metabolic variables during short bouts of sub-maximal exercise completed prior to a bout of maximal exercise. Whilst Reilly et al. (1984) reported a significant variation in heart rate during cycling at 150 W, their study included nocturnal trials which is less relevant to athletes. Reilly and Garrett (1998) investigated diurnal variation during exercise to exhaustion at 70% VO_2max. They reported no significant difference in time to exhaustion between morning and evening trials ($P>0.05$) despite a significantly lower body temperature in the morning ($P<0.05$). It appeared therefore, that further research was needed to identify the impact of diurnal variation upon responses to sustained exercise such as those completed during training since the presence of significant variation could have implications for the design of training schedules and timing of performance assessments.

An understanding of the diurnal variation in maximal performance is of real benefit to athletes who need to achieve times close to their best performances during morning heats in order to qualify for evening finals. Enhanced morning performance could occur by inducing a phase shift in the metabolic circadian rhythms by routinely waking and being active early (Edwards et al. 2002). Alternatively, there appears to be a temporal specificity of training effect since Hill et al. (1988) and Torii et al. (1992) observed improved performances in aerobic assessments which were undertaken at the same time of day at which training had been completed. Only Arnett (2002) had investigated the impact of routine morning training upon the diurnal variation of maximal performance. Although he observed a significant improvement in morning 100 m freestyle time following 16 weeks of morning training there were concerns with the accuracy of the data since a questionably high increase in mean morning oral temperature (34.7 ± 0.5°C to 35.8 ± 0.4°C) was reported. Further investigation of the potential benefits of early morning training upon race pace swimming was needed as a potential intervention to enhance morning performance.

Describing and quantifying variation within a single performance provides valuable information that can be used to enhance performance. Whilst research suggests that an even distribution of power during exercise is optimal (Atkinson et al. 2007a; Foster et al. 1993), the pace profile of athletes during competition is variable and has varying characteristics according to the duration of the event (Corbett 2009; Garland 2005; Tucker et al. 2006b). Additional high frequency measures (every 200 m) in the laboratory have identified a stochastic variation in power during self-paced 20 km cycling time trial and this was proposed to reflect the dynamic regulatory activity of pacing (Tucker et al. 2006a). In the field Abbiss et al. (2006) and Bernard et al. (2009) both observed a high variation in power output during each lap of the multiple lap bike stage of a triathlon. These findings have all been recorded in relatively stable environments indoors (Foster et al. 1993; Tucker et al. 2006b) or on a flat road course (Abbiss et al. 2006). Little is known, however, about either the overall or within-lap pacing strategy adopted during competition in an unstable environment and therefore warranted investigation.

Research has observed variation in the relationship between swimming velocity, stroke rate and stroke length during a swimming event (Craig et al. 1985). Arellano et al. (1994) and Thompson and Haljand (1997) also reported variation in swimmers' ability to undertake non-swimming technical elements (start, turn) and indicated these elements may have direct bearing on the outcome of a race. Despite access to a relatively large sample size, much of the research analysing swimming events had performed only simple correlation techniques (Kennedy et al. 1990; Chengular and Brown 1992; Arellano et al. 1994) which failed to account for the relationships which may exist between the variables. Research to present a more accurate and inclusive model of swimming performance was warranted.

Wakayoshi et al. (1992a,b,1993) were one of the first researchers to apply the concept of critical power to swimming. They defined critical swimming velocity (Vcrit) as 'the speed which can be theoretically maintained for a very long time without exhaustion' (Wakayoshi et al. 1992b p302) and reported significant correlations with v-OBLA and the maximal lactate steady state (Wakayoshi et al. 1992b, 1993). Toussaint et al. (1998) devised a systems model that related the mechanical and energetic demands of swimming with front crawl swimming performance to evaluate the application of critical swimming velocity. They concluded that Vcrit was indicative of the capacity of the aerobic energy system but not for anaerobic swimming performance. Whilst Swaine (1996) had reported a significant correlation (r = -0.89) between 1500 m swim performance and critical power assessed on an isokinetic swim bench, research had yet to consider its potential application to long distance swimmers or triathletes. Variation may also influence performance assessments in free swimming that are used by sport scientists. Assessment of critical swimming speed requires athletes to complete 2 – 5 maximal swim trials, whilst the assessment of lactate threshold requires accurate control of speed during each incremental stage. Variation associated with time-of-day and pacing will influence a swimmer's performance in these assessments and as such research comparing these two performance tests is appropriately placed in the portfolio.

Therefore, the aim of the research portfolio was to explore the impact of variability upon sports performance through the timely and precise measurement of selected physiological variables. More specifically, the research objectives were to:

i) Investigate the effect of variability on performance and pacing during training and competition through repeated measures research design

ii) Use new and developing technologies to support collection of valid and reliable data to examine variation in performance in the field by controlling speed or enabling high resolution data capture

PORTFOLIO OF EVIDENCE

Paper 1:

Thompson, K.G., Haljand, R., Cooper, S-M. and Martin, L. (2000) The relative importance of selected kinematic variables in relation to swimming performance in elite male and elite female 100m and 200m breaststroke swimmers. *Journal of Human Movement Studies*, 39, 015-032.

Paper 2:

Martin, L. and Thompson, K. (2000) Reproducibility of diurnal variation in sub-maximal swimming. *International Journal of Sports Medicine*, 21, 387-392.

Paper 3:

Martin, L. and Whyte, G.P. (2000) Comparison of critical swimming velocity and velocity at lactate threshold in elite triathletes. *International Journal of Sports Medicine*, 21, 366-368.

Paper 4:

Martin, L., Doggart, A.L. and Whyte, G.P. (2001) Comparison of physiological responses to morning and evening submaximal running. *Journal of Sports Sciences,* 19, 969 – 976.

Paper 5:

Martin, L., Nevill, A. M. and Thompson, K. G. (2007) Diurnal variation in swim performance remains, irrespective of training once or twice daily. *International Journal of Sports Physiology and Performance,* 2, 192-200.

Paper 6:

Martin, L., Lambeth-Mansell, A., Beretta-Azevedo, L., Holmes, L.A., Wright, R. and St Clair Gibson, A. (2012) Even between-lap pacing despite high within-lap variation during mountain biking. *International Journal of Sports Physiology and Performance,* 7 (4), 261 – 270.

CRITICAL OVERVIEW

a) *An autobiographical context and chronological description for the portfolio of evidence*

Having worked as sports science technician at University of Wales Institute Cardiff for three years, I commenced my academic career as a lecturer in sports studies (physiology) at the University of Wolverhampton in September 1998 under the guidance of Professor Greg Whyte. In that same month I submitted my dissertation completing my MSc Sport & Exercise Science which I passed with distinction. I joined a small but vibrant sports science team at the University of Wolverhampton who were engaged in research and sports science support consultancy. Consequently, I became actively involved in these areas and was encouraged by Professor Whyte and my MSc supervisor, Professor Kevin Thompson, to publish research of existing data in international peer reviewed journals (Papers 1 and 2). Accordingly, despite being a new lecturer, a key focus of my early career was research publication and with two early successes it was not long before I began new research projects.

During 1998-99, paper 3 was developed in response to a question from one of the triathlon coaches with whom I was working. He was keen to learn if he could accurately estimate lactate threshold intensity during swimming from a series of time trials as presented in the critical velocity literature. At the same time I was keen to research further the impact of diurnal variation on sporting performance in triathlon since these athletes also undertook repeat training at different times of the day, therefore maximising performance was critical to their success. I decided to investigate the physiological responses to running during morning and evening trials (Paper 4).

As a new researcher, Professor Whyte encouraged me to attend international conferences to disseminate my research and also for academic development and networking. I attended the annual conference of the European College of Sport Sciences (ECSS) and the British Association of Sport and Exercise Sciences (BASES) in both 1999 and 2000 and delivered several research presentations. Additionally, in 1999 I applied and was accepted to attend the ECSS pre-conference course in Rome. This 5 day course with other young European researchers provided unique opportunities to attend lectures, practical laboratory classes and undertake a group research project. Naturally, my continuing focus and engagement with research inevitably led, in December 1999, to the decision to register for a PhD on a part time basis at Wolverhampton with Professor Whyte, Professor Thompson and Professor Alan Nevill as my supervisory team.

I achieved BASES accreditation for scientific support in September 2000 as a result of the many hours of triathlete support work I had completed. During 2001, Professor Thompson invited me to assist him with sports science support work to the Wales national swimming squad as they made their final preparations for the 2002 Commonwealth Games. I embarked on a busy schedule of early morning trips to their training base in Somerset to undertake monitoring and assessment of the squad, and attended key competitions throughout the year to support warm-up and warm-down and collect post-race blood lactate data. I was also invited to speak to the swimmers about potential strategies to improve their morning performances, as it was going to be essential for the Welsh team to produce personal best times during morning qualifying rounds in order to make finals. Consequently my research in diurnal variation of swimming performance was able to inform and impact upon international performance and team preparations.

From September 2001 to February 2002 I undertook a research sabbatical to support my PhD work. During this time I completed two studies. The first was a qualitative questionnaire completed by swimming coaches across the UK to identify times of day of training and whether coaches undertook different training at different times of day. The second study investigated if the temporal specificity of training impacted upon their physiological responses to race pace and maximal swimming during morning and evening trials (Paper 5).

During October 2002, I moved to the University of Worcester as Senior Lecturer in Sports Science. Immediately it was evident that the focus and strength of the department was in teaching and learning and I identified early on that I needed to further develop my practice in this area. This led to a shift in my academic focus occurred and learning and teaching was placed higher on my academic agenda. As with all academic moves, time was needed to become familiar with new systems, new colleagues and a new portfolio of modules to teach. Whilst I successfully continued my sports science support consultancy and quickly developed a client base for regional triathletes and rowers, it was research time that was lacking and progress on my PhD slowed significantly and ultimately I withdrew from my programme of studies in June 2004. Nevertheless, I continued to work with Professors Nevill and Thompson and after repeated drafts and submissions the temporal specificity of training study was published in 2007 (Paper 5).

In September 2004, as part of my self-development and enthusiasm for learning and teaching, I made my first application for research funding to the Higher Education Academy (HEA) for a small pedagogical research project on Problem Based Learning (PBL). The £3,500 application was successful and the completed research was published in Journal of Hospitality Leisure Sport and Tourism Education during 2008. Two years later, the same research team made a second successful application to the HEA to investigate research ethics processes in undergraduate dissertations and this work was duly published in Research Ethics Review during 2010. My growing interest in learning and teaching pedagogy and research enabled me to successfully apply for a University of Worcester Teaching Fellowship in 2006. As I developed a strong reputation for learning and teaching, my interest continued and I attended a range of learning and teaching development events and workshops. I presented my PBL research at the HEA annual conference in 2006 and completed a number of on-line courses with Oxford Brookes University developing skills in e-learning and on-line tutoring. When the University of Worcester announced part time secondment posts in the Academic Development and Practice Unit the opportunity to work cross-institutionally to develop learning and teaching was an attractive prospect for my career development. Following a successful application I began an eighteen month 0.5 secondment with the remit to develop e-learning and establish University wide special interest groups in PBL, reflective practice and research informed teaching, as well as develop and lead an on-line version of the first module of the PG Certificate in Learning & Teaching. As part of the secondment, I also completed the Staff and Educational Development Association's (SEDA) supporting educational change course, and wrote a number of University good practice guides including research informed teaching, and I wrote the University's new policy on peer observation to outline a substantial shift from peer observation to peer learning.

Within the Institute of Sport & Exercise Science (ISES), I continued to play key roles in the on-going development of curriculum and research. In 2006 I published a paper that detailed the nutritional practices of international women footballers. This was a collaborative project with a former colleague who was the England Women's Football squad sports scientist and had requested support to analyse the players' nutritional practices. In 2005/6 there was a significant shift in relation to the organisation and co-ordination of research in ISES. Research Interest Groups were set up and I was appointed research coordinator alongside Professor Derek Peters. This important role within the Institute reflected my experience as a researcher, publication record and positive working relationships with colleagues. During the first physiology group meeting I proposed a project to investigate the physiological demands of cross-country mountain biking which ultimately led me to be the principal researcher of a substantive project that collected field data at 4 regional events between April and September 2006 and laboratory assessments before and after these races. This led to conference presentations at both ECSS and BASES during 2007. With the arrival of Professor St Clair Gibson as Visiting Professor a new insight of the data was identified (see below). My role as research coordinator for ISES led me to become Chair of Research Committee and to represent ISES at the University Research and Knowledge Transfer Committee and the Research Focus working group.

During June 2009 as the secondment to Academic Development & Practice Unit was almost complete, and having made a substantive contribution to ISES for a number of years I made a successful application to Principal Lecturer, an important career step which would not have been successful had I not been able to demonstrate excellence in areas of learning and teaching, research, and leadership and management.

I began a period of maternity leave in July 2009 and returned to full time work at the end of January 2010. On return to work, I was immediately required to focus on the new pacing angle of the mountain bike project data which my colleague Annie Lambeth-Mansell and new Visiting Professor Alan St Clair Gibson had been discussing using some preliminary data from the existing data set whilst I was on maternity leave. In March 2010, I presented the findings of this preliminary data at the University of Worcester Research Focus day and wrote a full manuscript which was ultimately accepted in November 2011 by the International Journal of Sports Physiology and Performance (Paper 6). This new work under the expert guidance of Professor St Clair Gibson represented a return to sports performance based research. I joined the new ISES Regulation of Performance research group which has been a dynamic and successful research team. Membership of this group has enabled me to return to research focusing on sports performance. I co-authored a case study on pacing in rowing which was also accepted for publication in December 2011 in International Journal of Sports Physiology and Performance and was presented at the 2012 European College of Sports Science conference.

Having been a co-opted member on the ISES senior management team from January 2009, I was appointed as a full member from January 2011 until December 2012. In this role, I raised, discussed and identified strategic developments for research within the Institute. I continue to attend these meetings as research co-ordinator when required. I am also a member of the University's Research Excellence Framework (REF) working group to prepare the REF submission in our subject area.

Table 1: Gantt chart illustrating chronological development of the research portfolio

	Paper 1	Paper 2	Paper 3	Paper 4	Paper 5	Paper 6
1998						
1999						
2000						
2001						
2002						
2003						
2004						
2005						
2006						
2007						
2008						
2009						
2010						
2011						

Now in 2012/13, I have come full circle and research is once again a primary focus on my academic agenda. As part of a dynamic and highly motivated research team, I am in the process of completing a paper on pacing during endurance mountain bike events, and a co-author on an original and unique review paper regarding decision making theory during self-paced endurance events. In the future I hope to lead on other projects relating to pacing and the regulation of performance in a range of populations.

b) *An evaluative description of the originality of each output*

Phillips and Pugh (2010) identify fifteen statements to define originality of research and these will be referred to in the evaluations of each article (Appendix 1).

Paper 1 integrated two existing areas of swimming performance literature a) the relationship between stroke length and stroke rate to achieve swimming velocity and b) the contribution of non-swimming components e.g. turning time and start time to overall swimming performance to develop predictive equations in elite male and female breaststroke swimming. Prior to our study, the existing literature (Kennedy et al. 1990; Chengular and Brown 1992; Arellano et al. 1994) had analysed data from large sample sizes using simple correlation techniques which failed to account for the relationships which may exist between the different variables and consequently may have exaggerated their influence on performance. To this end, paper 1 undertook multivariate analysis to reduce such errors and provide a more accurate and inclusive model of performance that considered both swimming and non-swimming components. With reference to Phillips and Pugh (2010) originality is demonstrated in that the work used already known material but with a new interpretation (statement 9), took a particular technique and applied it to a new area (statement 11) and adding to knowledge in a way that has not previously been done before (statement 15).

A key feature of paper 2 is that it used new innovative technology (Aquapacer™) to pace the swimmers during their trials. Unlike running and cycling, it is more difficult to control swimming speed during testing. The study required swimming speed to be consistent between trials to ensure that any measured differences in the physiological and kinematic responses to the swimming could be attributed to time of day and not swimming speed. A programmable unit that emitted an audible beep through a small unit that was placed behind the swimmer's ear was used. This was a new, yet to be patented technology at the time of use and was subsequently shown to accurately pace swimming (Thompson et al. 2002). Previous papers had relied on poolside audible cues (Lavoie and Montpetit 1986) or an underwater lighting system that required the swimmer to reach each light as it illuminated (Keskinen 1998). Therefore, according to Phillips and Pugh (2010) this research is original as it utilised a novel original technique (statement 4). Additionally, the research considered an area that researchers have not looked at before (statement 14) since only Hill et al. (1989a) had previously investigated time-of-day variations during sub-maximal exercise. The primary focus of circadian rhythm research focused on the variation in maximal swimming performance (Baxter and Reilly 1983; Reilly and Marshall 1991) and had not considered the sub-maximal training intensities that athletes spend the majority of their time undertaking. Furthermore, no previous study had considered the reproducibility of diurnal or circadian variation. Reproducibility was important to consider in this paper, because of the focus on sub-maximal training intensities.

As with paper 2, paper 3 also utilised the new pacing technology to enable accurate pacing during the pool based lactate threshold (LT) assessment. The inability to accurately control swimming speed during free swimming had previously been identified as a limitation of the assessment of LT during swimming (Wakayoshi et al. 1993). Consequently this paper meets originality criteria through the achievement of statement 4 "providing a single original technique, observation or result in an otherwise unoriginal but competent piece of research" of Phillips and Pugh's (2010, p69) originality statements. Additionally, the study extended previous critical swimming velocity (Vcrit) research whose protocols utilised time trials from 50 m to 400 m (Wakayoshi et al. 1992a and 1993). This study included two additional longer time trials over 800 m and 1500 m into the Vcrit protocol to improve applicability to the triathlete population.

Phillips and Pugh (2010) suggested that research is original if it is continuing a previously original piece of work (statement 2) and as such paper 4 is original since it further considers the concept of diurnal variation during sub-maximal exercise. This is also an area with limited previous research particularly in running. Faria and Drummond (1982) reported no significant diurnal variation during incremental workloads to maximum. Although some previous literature in cycling exists these papers utilise a fixed exercise intensity (Reilly et al. 1984; Hill et al. 1989a; Reilly and Brooks 1990) or have included nocturnal trials (Cohen and Muehl 1977; Reilly et al. 1984; Reilly and Brooks 1986) which have limited practical application to athletes and coaches as training is unlikely to occur during the night. Consequently, statements 7 and 14 of Phillips and Pugh (2010) can also be cited for originality of this paper.

Despite research observing that the time-of-day of daily training impacted upon the extent of performance improvements in ventilatory threshold (Hill et al. 1988) and leg strength (Gutenbrunner 1992) at the time of publication of paper 5 only Arnett (2002) had attempted to investigate if regular morning training can reduce the observed diurnal variation in sports performance. Therefore, paper 5 can be considered original in that it carried out empirical work that had not been done before and looked at areas that researchers in the discipline had not looked at before (Phillips and Pugh (2010) statements 7 and 14). Additionally, during the peer review process for publication a reviewer from the Canadian Journal of Applied Physiology identified that "the potential of the findings by research in this area could be far reaching for those engaged in the planning, sequencing and periodisation of training for any sport group". As with papers 2 and 3 the relatively novel pacing technology that is utilised throughout this portfolio to enable accurate pacing during the pool based assessments was used to provide robust control of swimming speed.

The final paper in the portfolio (Paper 6), is the first paper to explore pacing during off-road cycling competition. This is confirmed by the independent expert reviewers who wrote in their comments "No study has yet examined the pacing strategies adopted during such events and therefore the findings of this study are novel" (reviewer 2) whilst expert reviewer 1 stated "the authors can be commended for embarking on a novel methodology in their research study". Consequently, paper 6 can be considered original in that it carried out empirical work that had not been done before and looked at areas that researchers in the discipline had not looked at before (Phillips and Pugh (2010) statements 7 and 14). Additionally, the accepted paper was selected by the editor of International Journal of Sports Physiology and Performance to be highlighted on the journal's home page as a forthcoming article and indicated that the paper is of particular interest to readers. The paper is also original with regard to high resolution data capture (1Hz) during real competition since most previous pacing studies during competition have limited data points due to being able to only access official split times (Garland 2005; Lambert et al. 2004; Tucker et al. 2006b), consequently the study is able to provide a unique insight into the microoscillations in velocity that are masked when data sampling occurs over longer time periods (Kay et al. 2001). Therefore, according to Phillips and Pugh (2010) this research is original as it utilised a novel original technique (statement 4).

c) An evaluative review of the contribution made by the portfolio of evidence to the subject or discipline area and any subsequent developments since the work was completed including published reviews of any of the submitted works and/or evidence of citation frequency of any of the submitted works (where practicable and available)

Table 2 identifies that of the six papers included in the portfolio all have been cited in a range of published peer-reviewed articles, professional outputs and other scholarly work. This section will evaluate how these works have drawn upon the findings of the research portfolio to develop knowledge and understanding in relation to variation and sports performance.

Table 2: Citations of each journal article (source: Google Scholar February 2012) alongside 2011 Impact factor (source: Sports Science 2011 Volume 15 www.sportsci.org)

Journal Article	2011 Impact Factor	Citations
1	not rated	0
2	2.43	12
3	2.43	34
4	1.93	14
5	1.79	4
6	1.79	0

Diurnal variation of sub-maximal exercise was the focus of two papers in the portfolio. Martin and Thompson (2000) and Martin et al. (2001) investigated the impact of diurnal variation upon sub-maximal swimming and running. Using a similar research design, each study measured selected physiological variables at rest, during and immediately after completion of a sustained bout of aerobic exercise at a standardised relative exercise intensity during morning and evening trials. Whilst both studies observed significant diurnal variation in body temperature at rest and during the exercise bout ($P<0.05$), there was no time-of-day effect in ventilation or pulmonary gas exchange variables ($P>0.05$). Rating of perceived exertion was significantly higher during the morning trials in both studies even though exercise was completed at same exercise intensity as evening trials ($P<0.05$). Both papers concluded that time-of-day had no significant impact upon the physiological responses to sub-maximal swimming or running. Prior to their publication, the diurnal variation of sub-maximal exercise had been considered only as short stages of incremental exercise protocols where the primary focus of the research was to investigate circadian variation of maximal sports performance (Reilly and Brooks, 1982; Reilly and Baxter 1983; Hill et al. 1989a). Whilst Reilly and Garrett (1998) had investigated the effect of diurnal variation upon exercise to exhaustion at 70% VO_2max in seven college soccer players, their focus was the impact of a reduced morning body temperature upon heat tolerance during exercise to volitional exhaustion. They reported no significant difference in mean time to exhaustion between morning (62.14 ± 7.88 min) and evening (60.86 ± 6.64 min) trials, and at the termination of exercise elevated rectal temperature in evening trials (38.6 ± 0.2 and 39.2 ± 0.5 °C) and a similar heart rate (182 ± 14 and 183 ± 9 $b.min^{-1}$). Therefore, research with a primary focus upon sub-maximal exercise intensity undertaken for a sustained period of time similar to aerobic training sessions was warranted.

Examination of the citations for Martin and Thompson (2000) and Martin et al. (2001) indicates that many of these are in review papers where the research design or reported findings are included alongside other scientific studies to provide a comprehensive report of the knowledge of circadian variation in sports performance (Drust et al. 2005; Minati et al. 2006; Reilly and Waterhouse

2009; Teo et al. 2011b; Forbes-Robertson et al. 2012). It is apparent, however, from these review papers that since the publication of Martin and Thompson (2000) and Martin et al (2001) there has been limited further examination of the impact of time-of-day upon sub-maximal exercise. Refinetti and Laney (2003) provided further confirmation of our research findings of no time-of-day effect during exercise despite significant diurnal variation in body temperature when completed in a real world setting. They evaluated daily variation of body temperature, physical vigour and performance in an attention/memory test at 5 different times of day over a 2 week period. Refinetti and Laney (2003) observed a significant time-of-day effect in aural temperature which was lowest immediately after waking and peaked 9 hours later ($P<0.05$), and in the performance of the attention/ memory test which was lowest when completed 3 – 6 hours after waking and best 12 – 15 hours after waking ($P<0.05$). In contrast, there was no significant time of day effect for physical vigour as measured by the number of repetitions completed on an exercise machine of the participants' choice. Refinetti and Laney (2003) suggested that in a real world situation cognitive and motivational aspects in addition to physical endurance can fully mask any potential time-of-day effects.

Brisswalter et al. (2007) referred to and further developed our research by suggesting that VO_2 kinetics could provide a more accurate reflection of the metabolic demands of activity rather than steady state exercise. As such they asked 14 male participants to complete 10 minutes of moderate exercise (80% power output at ventilatory threshold) at 0700 – 0830 h and 1900 – 2030 h after a 5 minute warm up at 45 W. In agreement with Martin et al. (2001), Brisswalter et al. (2007) also observed no significant time-of-day effects in VO_2, VE and VCO_2 at rest or during the low intensity warm-up. However, during the sub-maximal cycling exercise Brisswalter et al. (2007) reported slower VO_2 kinetics during morning trials as a result of a significantly slower time constant and a significantly larger VO_2 amplitude ($P<0.05$). Furthermore an enhanced net efficiency was observed during the evening trials and this was thought to be linked to the significantly lower variation in cadence that was also observed in the evening trial ($P<0.05$). This observation is inconsistent with the papers in this portfolio (Martin and Thompson 2000; Martin et al. 2001) and other similar studies (Carter et al. 2002; Deschenes et al. 1998; Hobson et al. 2008; Reilly and Brooks 1990; Reilly and Garrett 1998). Indeed Carter et al. (2002) observed no effect of diurnal variation upon VO_2 kinetics at the same moderate exercise intensity (80% ventilatory threshold) during treadmill running despite reporting a significantly lower body temperature at rest and after exercise. Brisswalter et al. (2007) did not measure body temperature during their investigation which would have provided important additional information to confirm that the timings of trials, and controls were appropriate to measure the presence of diurnal variation in a primary variable.

Similar to Reilly and Garrett (1998), Hobson et al. (2008) investigated the impact of diurnal variation upon exercise tolerance in the heat. In contrast to Reilly and Garrett (1998) they reported that exercise capacity was 5.3 ± 4.7 minutes longer during morning trials with a mean exercise duration time of 45.8 vs 40.5 minutes and this was linked to a 0.5 °C lower body temperature at the outset of exercise in the morning although there was no significant difference at the termination of exercise. Additionally, Hobson et al. (2008) observed no time-of-day effect upon heart rate, VE, VO_2, VCO_2, RER, and energy expenditure during exercise at 65% VO_2peak. They suggested that the combined stress of exercise and the additional stress of the heat and humidity (35.1 °C; 60% RH) resulted in a greater overall exercise stress closer to that undertaken in Martin et al. (2001) and therefore a non-significant time-of-day effect was in agreement with our findings.

My research pertaining to diurnal variation of sub-maximal exercise has also been cited and developed in the area of exercise and health. Maraki et al. (2005) investigated if the time of day of an exercise class affected appetite, energy intake and mood in 12 healthy non-routine exercisers. In agreement with Martin and Thompson (2000) and Martin et al. (2001) they reported significantly higher ratings of perceived exertion during the morning exercise class even though the reported intensity of the class was similar. Furthermore, Maraki et al. (2005) reported that exercise had the same effect upon appetite sensations and energy intake irrespective of time of day that the class was completed. Similarly, Ahmadizad and Bassain (2010) observed that all changes in haemodynamic parameters in response to 45 minutes running at 60% VO_2max occurred similarly in morning and evening trials. However, given that they did not observe a significant time of day effect in body temperature at rest as is commonly reported in the literature (Baxter and Reilly 1983; Reilly et al. 2007; Martin and Thompson 2000; Martin et al. 2001) questions the sensitivity of instrumentation used and/or the appropriateness of controls in place for extraneous variables.

It appears, therefore, that my research investigating the impact of diurnal variation upon sub-maximal exercise has contributed to an on-going development of knowledge in this area. There has been a consistent observation both in sports performance and exercise and health research that time-of-day has no significant effect upon the physiological responses to sub-maximal exercise despite the significantly lower morning body temperature. Additionally, rating of perceived exertion has also been reported to be significantly higher during morning trials. Coaches and health practitioners need to be aware of the elevated RPE and lower body temperature during morning exercise, and they may wish to promote longer warm ups and provide additional encouragement to ensure exercise is completed at the required intensity. The consistency of observations reported may also explain the apparently limited number of studies in this area since my publications in 2000 and 2001 which suggest that the scientific community have no need to further investigate this area, or that publication of other studies which have also identified non-significant time-of-day effects are less likely to be accepted for publication.

A third paper in the portfolio also investigated the diurnal variation in sports performance. Martin et al. (2007) investigated if regular morning training could be used as a specific intervention to enhance swimmers' maximal swimming performance in the morning. A direct comparison of swimmers routinely undertaking training in the morning and the evening (MEG) and swimmers who routinely trained in the evening (EOG) showed that significant time-of-day effects were observed in oral temperature at rest, post warm-up and post 100 m time trial ($P<0.05$) and in 100 m time trial performance ($P<0.05$) for both MEG and EOG groups. Unexpectedly, the intra-daily variation for the 100 m time trial was higher for the MEG (2.5%) than for the EOG (2.0%). Additionally, despite the use of a pacing device the MEG swam the 150 m race pace swim significantly faster during the evening trial ($P<0.05$). We concluded that the use of combined morning and evening training did not reduce intra-daily variation in race-pace and maximal swimming or oral temperature.

This paper has been cited on just 2 occasions in the literature. In a review article Teo et al. (2011b) simply identified the work in a summary table of previous literature, whilst Zarrouk et al. (2012) have drawn upon our research as they explored whether water temperature helps to reduce diurnal variation of short maximal swimming performance. Whereas we reported no benefit of undertaking routine training in the morning to reduce time-of-day effects, Zarrouck et al. (2012) observed that increasing the water temperature to 30°C removed time-of-day effects in swimming propulsion, 10 m and 25 m swimming performance ($P>0.05$). More recently Mora-Rodriguez et al. (2012) and Edwards et al. (2013), although not citing my work, have also examined strategies to reduce the diurnal variation observed in maximal sports performance. Edwards et al. (2013) observed that undertaking either a passive or active warm up to increase morning body temperature to equivalent evening values failed to increase morning muscle strength to evening performance values. Conversely, Mora-Rodriguez et al. (2012) were able to successfully remove the time-of-day effect observed in neuromuscular performance by morning caffeine ingestion of 3mg/kg 1 hour prior to performance despite morning temperature being 0.7°C lower than in evening trials. It appears, therefore, that despite the consistent observation of the parallels between daily variation of sports performance and body temperature, strategies to enable morning performance to match evening performance may be more successful if they enhance alertness, affect or mood rather than increasing body temperature. There appears to be scope for further investigation in this area.

From a temporal specificity of training viewpoint, the Martin et al. (2007) paper had developed the original work of Arnett (2002) who had observed a reduction in the diurnal variation of maximal swimming performance when college swimmers began to undertake morning training during early season training. Despite the contrasting findings of these two studies, there appears to have been no further development of research in this area. In a recent review paper Chtourou and Souissi (2012c) reported only three papers that had investigated the temporal specificity of aerobic training (Hill et al. 1989b; 1998; Torii et al. 1992) all of which were completed prior to the research in this portfolio. One explanation for my research not being included in the review paper is that it utilised a cross-sectional research design comparing the two contrasting training groups at the same point which is in contrast to the longitudinal designs adopted by Hill et al. 1989b and 1998; Torii et al. 1992 who observed changes following up to 6 weeks of training at a specified time of day. Furthermore, the aerobic training studies included by Chtourou and Souissi (2012c) also utilised a research design where each training group completed training at a single time-of-day, whereas in Martin et al.'s (2007) study one group completed both morning and evening training (MEG) and the comparative group completed evening training only (EOG). Completing both morning and evening training may have negated any potential advantage of inducing a phase shift via routinely waking early and being physically active (Edwards et al. 2002). For these reasons, Chtourou and Souissi (2012c) may have excluded Martin et al. (2007) from their review. Nevertheless, the Martin et al. (2007) study provides important knowledge of the real world situation of swimmers involved in long term established training routines. It would seem, from our data, that for those athletes training more than once a day, alternative strategies such as those presented by Mora-Rodriguez et al. (2012) need to be considered to enhance morning performance. Further research to confirm the observation that when morning training combined with evening training offers no benefit to enhancing morning performance compared to morning training only, and research to investigate interventions to improve affect, mood and alertness in the morning is needed.

Martin and Whyte (2000) is the most cited paper of those included in the portfolio and this may reflect the equivocal findings of the literature regarding the application of the critical power concept in swimming as identified by Garatachea et al. (2006). Bosquet et al.'s (2002) review paper on methods to determine aerobic endurance performance included Martin and Whyte (2000) within their summary table of 33 studies that have determined critical power in a range of sports. The procedure used by Martin and Whyte (2000) to determine critical velocity (Vcrit) compared favourably with the other studies presented with the use of 4 – 5 trials and 24 hour recovery between each maximal time trial. Interestingly, within the summary table only one other swimming study is included (Wakayoshi et al. 1993) despite the reasonably high numbers of studies in this area. In our study, Martin and Whyte (2000) included additional longer distance 800 m and 1500 m trials during the assessment of critical swimming velocity to ensure specificity to the triathlete population being investigated. The inclusion of these longer trials has led to further citations by Dekerle (2006) and Dekerle et al. (2006) as evidence for the distances time trials that should be used for the assessment of critical swimming velocity. Indeed, Suzuki et al. (2007) cited Martin and Whyte (2000) in their procedure to justify their selection of trials for the determination of critical swimming velocity. Suzuki et al. (2007) subsequently completed 200 m swimming intervals at the 95% and 110% of the calculated Vcrit to explore the impact of 20s and 40 s rest periods upon the rating of perceived exertion. They observed that the duration of the rest period only affected the RPE during the 110% Vcrit trials.

Thanopoulos et al. (2008) investigated the effect of swimming pool length (25 or 50 m) upon the calculation of Vcrit in young swimmers. Citing Martin and Whyte (2000) with regard to the use of linear regression to calculate Vcrit, they observed a significant difference in critical swimming speed with pool length when the calculation included 100 m and 200 m trials. This is to be anticipated given that the additional turns completed in a 25m pool would result in a faster time due to the higher speed attained underwater, and as such it is unclear why Thanopoulos et al. (2008) selected to utilise distances of 15, 25, 50, 100 and 200 m to determine Vcrit. The selection of short distance trials is likely to result in an inaccurate estimate of the critical swim speed due to the non-attainment of steady state in trials lasting under 2 minutes (Dekerle et al. 2006) and that these short trials would be entirely unaffected by pool length due to not including a turn and therefore the faster underwater element.

Abe et al. (2006) cited Martin and Whyte (2000) and a number of other studies suggesting that previous research in the field of critical swimming velocity has focussed on middle and long distance freestyle swimming and consequently extended the research base by investigating its application to breaststroke swimming. Possibly to reflect that competitive breaststroke events occur over 50, 100 and 200 m distances, Abe et al. (2006) calculated critical swimming speed (Vcrit) from three short trials (75, 100 and 150 m) which would have been too short (< 2 minutes) for the achievement of steady state and attainment of VO_2max which Dekerle et al. (2006) identified to be essential for the accurate estimation of Vcrit as an indicator of aerobic performance. Despite this Abe et al. (2006) observed that, in their participants, the Vcrit calculated from 3 short trials was the primary determinant of success in short distance breaststroke swimming. Very short trials of 10, 15, 20 and 25 m were also undertaken in Marinho et al.'s (2011) research to determine the 'anaerobic' critical swimming velocity (AnVcrit). Citing Martin and Whyte (2000) as one of a number of studies who had evaluated the use of Vcrit in swimming against a second measure of aerobic ability, Marinho et al. (2011) observed a significant relationship between AnVcrit and swimming performance in 50 m and 100 m backstroke, breaststroke and front crawl and also for the 200 m breaststroke and front crawl events. They suggested that AnCV could be an important parameter for monitoring and prescribing anaerobic training in swimmers.

Garatachea et al. (2006) also drew upon our research and extended the application of critical swimming velocity literature by investigating its application in disabled backstroke swimmers. Participants completed 50, 100, 200 and 400 m trials followed by a confirmation test of 3 x 10 minute swims at 95, 100 and 105% of calculated Vcrit. Use of shorter time trials was not problematic in this study since the time to complete these distances in physically disabled swimmers is slower than able-bodied. In contrast to the cited findings of Martin and Whyte (2000) they observed that Vcrit corresponded to a steady state lactate value of 4.03 $mmol.l^{-1}$ and concluded that Vcrit could be a useful assessment to support planning training schedule in disabled swimmers. In contrast, Campos-Mello and Franchini (2005) observed that blood lactate did not achieve steady state during their confirmatory 30 minute test at calculated Vcrit in rowers. Drawing upon the findings of Martin and Whyte (2000) to support, they concluded that Vcrit is not sustainable for an indefinite period of time. Whilst calculating Vcrit from 500, 1000, 1500 and 2000 m rowing ergometer trials it is surprising that the authors chose to utilise time to complete each trial to calculate Vcrit rather than recording power to calculate critical power.

Silva et al. (2005) explored the application of critical velocity in recreationally active rather than athletic population. Drawing on the research of Martin and Whyte (2000) to evidence the use of critical velocity as a non-invasive measure of aerobic function in athletes, they compared results from 5 direct and indirect running based procedures for determining aerobic fitness. Silva et al. (2005) observed that the speed of Vcrit was significantly slower than V_{max} and the mean speed to complete 3km ($P<0.05$) and was significantly faster than speed of individual anaerobic and glucose thresholds ($P<0.05$). The significantly higher speed of Vcrit to individual anaerobic threshold is in agreement with Martin and Whyte (2000). Ribeiro et al. (2004) also compared a range of protocols to determine anaerobic threshold in swimming, however they did not include Vcrit as one of their assessments. As anticipated, they reported significant correlations between each of the protocols undertaken (MLSS, Lac_{min}, $Gluc_{min}$, LT and GT). Ribeiro et al. (2004) made direct comparison of their lactate threshold data with those of Martin and Whyte (2000) explaining the higher speed at LT in their participants could be attributed to different population (swimmers vs triathletes) and different protocol (200m vs 300m intervals) which would be expected given the differing physiological demands of the two populations.

There is evidence, therefore, that the findings of Martin and Whyte (2000) have shaped the on-going advancement of research relating to critical swimming velocity. Our research has informed the selection of time trial distances used for the assessment of Vcrit (Dekerle 2006; Dekerle et al. 2006; Suzuki et al. 2007), and has also contributed to the application of Vcrit in other recognised swimming techniques in both able-bodied and disabled populations (Abe et al. 2006; Garatachea et al. 2006). Finally, our research has been cited in support of the consistent observation that Vcrit overestimates the speed of the anaerobic or lactate threshold and is not sustainable for an indefinite period of time (Campos-Mello and Franchini 2005; Silva et al. 2005; Ribeiro et al. 2004).

Within performance variation has also been investigated within this research portfolio. Thompson et al. (2000) investigated the relative contribution of swimming and no-swimming technical components to 100 m and 200 m breaststroke swimming. During our analysis, we excluded stoke length (SL) from the regression analysis due to its relationship with stroke rate (SR) had resulted in the presence of multicollinearity. Stroke length was removed from the analysis as this parameter was less easy for a coach to accurately measure from the pool side. Conceicao et al. (2013) recently reported a high negative relationships of -0.78 between Δ SR and Δ SL during 200 m breaststroke swimming, confirming the strength of this relationship and citing our research in support. With the additional measurement of surface EMG activity of pectoralis major, biceps brachii, triceps brachii and anterior deltoid they also observed a significant correlation between changes in kinematic variables and neuromuscular activation. This additional information, along with the findings from our research enables swimming coaches to undertake detailed analysis of breaststroke swimming performance and detail specific interventions to enhance performance.

Martin et al. (2012) were the first to report pace profiles during off-road competitive mountain biking and observed that cyclists utilised an even pace profile from lap-to-lap, but during a single lap a dynamic variable pace profile was adopted that was often independent to changes in terrain. Abbiss et al. (2013) have recently published speed data collected during a world cup cross-country mountain bike event, although disappointingly they chose not to make any reference to our earlier similar study. In contrast to our data, they reported a variable pace profile from lap-to-lap characterised by a fast second lap followed by a gradual decrease in speed for subsequent laps in elite senior and junior riders. Such a linear decrease is also reported to have been observed in power output during an unpublished simulated 4-lap mountain bike race by Ferreira et al. (2013). It is possible, that a decrease in speed during the final lap of our research was masked by the inclusion of a female rider who raced over only 4 laps, rather than 5 laps in the men's race. Therefore, the final 5th lap speed is potentially elevated as it includes only male riders and not the female rider. Nevertheless, in partial agreement of our data, Abbiss et al. (2013) observed that the top placed riders were able to maintain a more even pace profile than lower placed riders, suggesting that adoption of an even pace profile is preferable. Abbiss et al. (2013) suggested that their observed slower paced first lap in comparison to the second lap is a reflection of the mass start and narrow tracks which forces riders to ride at a slower speed. Ferreira et al. (2013) also indicated that lap-to-lap pace profiles in x-country mountain bike races would be influenced by an individual rider's start position on the grid. Referring to our work (Martin et al. 2013), they suggested that our observation of even pacing could be related to poor positioning on the start grid, however a starting grid was not utilised in the regional event where data was collected. Instead riders self-selected their start position and this is likely to have reflected their confidence and expectation of their ability therefore ultimately enabling them to choose an optimal placement on the start line resulting in the achievement of an even pace profile.

This review has evidenced that the research included in this portfolio has stimulated and shaped further research investigation into the variability of sport performance. Specifically my research has i) informed procedures for the assessment of critical swimming velocity, ii) contributed to the application of critical swimming velocity in other swimming techniques and swimming populations, iii) contributed to the development of research exploring diurnal variation in sports performance and also in exercise and health, and iv) explained research observations investigating diurnal variation of exercise.

d) A description, synthesis and evaluation of any links between the outputs and the development of the portfolio of evidence

The research outputs are linked in that each paper assesses the impact of biological variation on sports performance and utilises applied research techniques and equipment in order to assess variation.

Paton and Hopkins (2006) identified that intra-individual performance variation of elite cyclists competing in Olympic, National and World Cup series ranged from 0.4 – 2.9% across three different cycling events. Whilst the authors focussed on identifying reasons for different levels of variation across the events e.g. pack riding/drafting, technical demands the data indicate that variation in sports performance is expected. Calculation of the typical variation in individual performance is important since it identifies the smallest worthwhile change in performance that training and other interventions need to induce to improve/enhance performance (Hopkins et al. 1999).

Performance-to-performance variation is not only observed over a competitive season, but also occurs from day-to-day and between performances completed within a single day. Regular rhythmic variation of biological variables reflects the body's internal 'body-clock' which regulates activity in accordance with the solar day (Reilly and Waterhouse 2009). Chronobiology investigates the degree of variation in biological variables and the endogenous and exogenous mechanisms which regulate the fluctuations (Drust et al. 2005). The internal 'body clock' is located in the suprachiasmatic nuclei at the base of the hypothalamus producing regular feedback loops which result in rhythmic variation (Reilly and Waterhouse 2009). Environmental influences from the light-dark cycle of the solar day and the sleep-wake cycle assist in entraining the endogenous rhythm to the 24-hour day (Gronfier et al. 2007; Roenneberg et al. 2007). Research measuring maximal sports performance every 4 – 6 h over a 24-hour period has identified significant variation of performance, with performance in the late afternoon/evening being significantly better than performance completed early in the morning (Kline et al. 2007; Reilly et al. 2007; Souissi et al. 2010; Racinais et al. 2010). The variation in performance typically parallels the body temperature rhythm (Reilly et al. 2007) with similar rhythms evident in heart rate (Carandente et al. 2006), flexibility (Reilly et al. 2007), and grip strength (Reilly et al. 2007). When only morning and evening assessments are taken diurnal variation of performance or its component parts can be reported. The diurnal variation of performance is particularly important in sports such as swimming and athletics where qualifying heats are scheduled in the morning whilst finals are scheduled for the evening. Therefore, the ability to produce a fast time in the morning is impaired by the circadian rhythm of performance. Investigation of diurnal variation and interventions which may enhance morning performance is valuable to coaches and athletes.

Variation within a single performance is also evident. Frequent assessment of power/velocity data during a single bout of exercise has been shown to provide information on variation in pacing profiles (Garland 2005; Lambert et al. 2004; Tucker et al. 2006b; Angus and Waterhouse 2011). These studies have identified that a common variation profile characterised by a fast start, a slower middle portion and a fast end is typically observed in events lasting ~120 s and longer (Garland 2005; Tucker et al. 2006b). Atkinson et al. (2007b) indicate that a successful pacing strategy enables the optimal allocation of physiological resources for an exercise task of known duration. It has been proposed that the sub-conscious brain controls and regulates workload throughout self-paced exercise in an oscillatory manner ensuring that a 'reserve' is maintained to protect the body from catastrophic physiological or metabolic failure (St Clair Gibson and Noakes 2004). The observed 'end-spurt' during the final stages of maximal self-paced exercise and deterministic variations in performance throughout the exercise bout indirectly supports the notion of the reserve capacity (Tucker et al. 2006a, 2006b) and the continuous regulation of workload by the brain (Tucker et al. 2006a; Billat et al. 2009; Abbiss et al. 2010).

Measurement of variation requires appropriate tools and techniques to be used by the researcher to ensure reliability and validity within a field-setting. The identification of variation requires measurements to be made at timely intervals. If measurements are made too infrequently then variation might be missed. Within-race variation requires measurements to be made at high frequency intervals to provide moving image data rather than infrequent snapshots (Kay et al. 2001). Similarly intra-daily variation needs to be measured at regular intervals throughout the day beginning and ending at the same time in order to clearly evidence the full cyclical variation in performance (Drust et al. 2005).

From the discussion above it is evident that extensive variation exists both within a single bout of exercise or between performances. Research utilising appropriate techniques and instrumentation to assess the amount of variation in performance is crucial to understand the dynamic regulation principles underpinning the variation in performance.

e) *A critical reflection using an appropriate methodology, model or theory on the candidate's development as a research practitioner*

The Vitae Researcher Development Framework identifies four domains that encompass the knowledge, skills and personal qualities of excellent researchers (Careers Research and Advisory Centre 2010). This section will critically reflect upon my development as a researcher with reference to each of the four domains.

Domain A: Knowledge and intellectual abilities

Discussion, applied practice and teaching have been the three prominent drivers of my knowledge and intellectual development. Building upon the strong foundations of subject knowledge on completion of my MSc, discussions whilst providing sport science support with two early mentors Professor Greg Whyte and Dr Kevin Thompson were instrumental to developing detailed knowledge and understanding of sports physiology and linking theory to actual sports performance. At the University of Worcester, I initiated a research discussion forum where staff were invited to discuss papers which stimulated discussion of research design, assessment protocols and theory. More recently, monthly meetings of the Regulation of Performance research interest group has promoted engagement with literature from physiology and psychology disciplines to develop a multi-disciplinary understanding of the diverse factors thought to impact upon pacing and performance regulation. These meetings have led to stimulating debate with creative thinking, and research ideas as well as evaluating proposed methods of our group's research projects which have all contributed to my on-going development in this area.

Engaging in applied practice with local and regional endurance athletes has cultivated an interest in improving performance. Talking with and observing athletes during training and performance, together with answering their questions has stimulated me to undertake further reading, attend BASES workshops and critique assessment protocols. I have supervised 2 candidates through BASES supervised experience route and this was challenging and further encouraged debate of theory of performance assessment techniques, data interpretation and strategies to enhance training and performance.

As a University Teaching Fellow, I have been recognised for excellence in learning and teaching, and my innovative work in the use of problem-based learning has been highly influential in the development of our current Sport and Exercise Science programmes. This approach to learning promotes research informed teaching in an applied real-world framework and enables students to develop a range of key skills in research, reading, interpretation, problem-solving and application of theory to practice. Teaching research methods enhances my own knowledge and capabilities through revisiting fundamental techniques, promoting critical evaluation skills and advancing students capacities in new techniques. Teaching has also ensured I am familiar with information and digital technology capabilities enabling me to communicate effectively with a range of audiences. I have attended workshops led by the Graduate Research School and the University's Information and Learning Services centre in the use of database and bibliographic referencing software. Due to sporadic use I have not yet mastered these aspects and this is a key area for my development both as a researcher but also as a mentor, teacher and future supervisor.

Domain B: Personal effectiveness

Early publication success and excellent mentorship developed a deep enthusiasm for research and instilled self-confidence in my abilities as a researcher. I am able to defend my work in public and through the peer review process for publication, and I have always taken responsibility for the development and planning of my own research projects effectively seeking support as needed. Whilst still a relatively new researcher, I moved into a role where I provided support, encouragement and opportunity to other staff to engage and develop their own research interests and confidently took on the role of principal investigator for internal and external research projects. In this role, I am skilled at involving all staff, setting clear actions and expectations of individuals whilst accepting overall responsibility for the project. At the University of Worcester, my research experience alongside good inter-personal skills and objective and strategic viewpoints enabled me to be influential in the strategic development of departmental research. My appointment as Institute research co-ordinator has given me responsibility for developing our research vision, research strategy, writing annual research reports, research seminar programmes, advise on planning, resources and workloads to develop our research culture. As a member of the University's Research and Knowledge Transfer committee I also contribute to the University's strategy and policy.

Domain C: Research governance and organisation

As Laboratory Director I have responsibility for determining health and safety policy for students, staff and external clients, budget control and resource management and ensuring quality control and practice. I ensure that research students undertake competency training in all equipment and procedures prior to data collection, and lead staff development workshops in these areas. As

Laboratory Director I was asked to join the research ethics committee at the University of Wolverhampton and I also serve on the equivalent committee at Worcester University. My practice and belief is to lead by example in all areas of my work and therefore ensure that I am thorough in the completion of all ethics documentation and review ethics applications with an objective viewpoint. In 2007, I was part of a research team that conducted a Higher Education Academy (HEA) funded project “Transparency and comparability of research ethical interpretation and the research ethics decision making process in sport and exercise science”. Published in Research Ethics Review this project identified typical ethical review processes and practice in HE institutions and indicated the minimum level of information required by committees to enable decisions to be made. This research influenced the development of ethics procedures and staff development in my Institute. This extensive experience enables me to confidently provide advice pertaining to ethics, copyright, confidentiality and authorship to students and staff. A key area for my development is research funding through grant applications and company sponsorship. Without a PhD qualification, I have not considered myself to be in a position to apply for funding although I have successfully been awarded two small (£3,500) research grants from the HEA to undertake pedagogical projects.

Domain D: Engagement, influence and impact

My inter-personal skills and objective, inclusive views were instrumental in being appointed as research co-ordinator. In particular, I have promoted the importance of staff working collegially to develop their research enabling individuals to contribute in the areas of their strength and receive support and guidance from others in research aspects they are still to develop. Technical, support staff and research students are all encouraged to engage with research teams. Recently, I led a small team to develop an Institute research mentoring scheme to further nurture and support staff in research and scholarly activity. I co-ordinate a peer review system for applications to University funded PhD studentships and other research schemes and this has led to increased success through higher quality submissions. I meet regularly with the Senior Management Team to inform and guide policy and practice to encourage on-going research development. Recent examples of this impact include the development of an MRes in Sociology of Sport and negotiated reduced workloads for staff with particularly high research demands or those in the final stages of their PhD. I regularly present to staff data on research activity and publications to promote and encourage effective use of research time, and this has been particularly important leading up to REF. I am co-lead for the Institute's REF submission and contribute to the University's REF working group in this capacity. I am an eloquent presenter, making effective use of multi-media as required, and have only received positive feedback on my academic writing style resulting in an acceptable publication profile. I need to further develop my networking skills and have the confidence to actively seek external collaboration on future research projects.

f) Full statements on the extent of the contributions of all other persons where some or all of the outputs submitted are collaborative

Paper 1: Professor Thompson proposed the study based upon his professional practice with Professor Haljand who undertook the videoing of all the events used and generated the split times and performance data. My contribution was the research design and selection of statistical analyses and to undertake the data analysis and generate the predictive equations, and finally compiled an early draft. Working with myself, Professor Thompson assisted in producing the final submission and Dr Cooper undertook some final data analysis when one equation was revised following removal of an additional element.

Paper 2: As principal investigator my contributions were extensive throughout the process proposing the research question, research design, all data collection and analysis and writing of the paper. Professor Thompson contributed in a supervisory role, advising throughout the process and editing drafts of the manuscript as it developed.

Paper 3: As principal investigator my contributions were extensive throughout the process establishing the research design and procedures, undertaking all data collection and analysis and writing of the paper. Professor Whyte contributed in a supervisory role, advising throughout the process and editing drafts of the manuscript as it developed.

Paper 4: As principal investigator my contributions were extensive throughout the process identifying the research question, establishing the research design and procedures, undertaking all data collection and analysis and writing of the paper. Professor Whyte contributed in a supervisory role, advising throughout the process and editing drafts of the manuscript as it developed. Dr Doggart assisted in some aspects of data analysis.

Paper 5: As principal investigator my contributions were extensive throughout the process identifying the research question, establishing the research design and procedures, undertaking all data collection and analysis and writing of the paper. Professors Thompson and Nevill contributed in a supervisory role, advising throughout the process and editing drafts of the manuscript as it developed.

Paper 6: As principal investigator, I undertook liaison with the race organisers and communication with participants, co-ordinated and undertook field data collection, undertook all laboratory tests, assisted in data analysis and wrote up the manuscript for publication. Annie Lambeth-Mansell undertook field data collection, data analysis and contributed to writing of manuscript. Co-authors Wright, Azevedo and Holmes participated in data collection either in field or laboratory and reviewed final drafts of the manuscript. Professor St Clair Gibson advised with the research idea, assisted with data analysis and edited drafts of manuscript as it developed.

g) Conclusions and suggestions for future work

Conclusion

The aim of the research portfolio was to explore the impact of variability upon sports performance through the timely and precise measurement of selected physiological variables. To investigate the effect of variability on performance and pacing during training and competition (objective 1) was met by undertaking six studies. Key findings from these investigations indicated that diurnal variation had no significant effect upon the metabolic responses to sub-maximal swimming or running (Martin and Thompson, 2000; Martin et al. 2001) and that early morning training when combined with evening training did not help to reduce the diurnal variation in race pace and maximal swimming performance (Martin et al. 2007). Importantly, however, it was recommended that coaches use longer warm ups prior to morning training in order to help alleviate the observed differences in body temperature and rating of perceived exertion (Martin et al. 2001). Research findings also indicated that critical swimming velocity could not be used as an indirect assessment of the speed of lactate threshold in triathletes (Martin and Whyte 2000), and identified that the relative contribution of technical non-swimming components (turning time and end time) varied with race distance and also with gender in breaststroke swimming (Thompson et al. 2000). Finally, in competitive mountain bike racing Martin et al. (2012) reported that cyclists adopted an even pace strategy across the 5 laps despite rapid adjustments in speed during each lap. Whilst changes in terrain accounted for some of this variation in speed, the additional dynamic changes were thought to reflect the dynamic regulation of self-paced exercise.

Valid and reliable data were collected using new and developing technologies (objective 2) such as the Aquapacer ™ (Martin and Thompson 2000; Martin and

Whyte 2000; Martin et al. 2007) and Global Positioning System (Martin et al. 2012) to meet objective 2. Measurements were taken using valid time points to enable identification of diurnal variation and at high resolution to measure dynamic regulation of pacing.

Future work

I have a co-authored paper on pacing during rowing published in International Journal of Sports Physiology and Performance in September 2012. This paper identified that whilst the overall power profile for the boat is consistent with previously reported profiles in both on-water and ergometer rowing, individual oarsmen demonstrate different profiles and remarkably produce different profiles. The co-author and I are planning to work with Worcester Rowing Club to see if these preliminary findings are replicated in other boat crews and to monitor potential changes in pacing and power profiles over the training year. This research will utilise relatively new technology (powerline system) to measure force at the oar of individual rowers for each stroke during on-water rowing. Following presentation of the rowing study and other related pacing research by co-author Andrew Renfree at the 2012 European Colleges of Sport Science annual conference, German researchers have invited us to collaborate with them to investigate pacing profiles during pool and open-water swimming.

I have a number of on-going research projects which further explore pacing and the factors influencing pacing during competition. A manuscript is currently being prepared which explores the pacing profile of cross-country mountain bike riders during a 6 hour race. Within this area future projects are likely to include investigation of year-on-year changes in pacing profiles of cross-country mountain bikers during 6 or 24 hour events. Additionally I am a co-author with colleagues Andy Renfree, Professor Alan St Clair Gibson and Dr Dominic Micklewright of a review paper on decision making during self-paced athletic competition. This work is the first to apply decision making theory to the regulation of self-paced activity and is currently under review in Sports Medicine.

There is potential collaboration with external colleagues in this area. I have recently communicated with Dr Simon Angus, a complexity science specialist in Australia who can provide advanced data analysis e.g. power spectrum analysis to help discover pacing and variability in velocity and heart rate data. I have extensive heart rate data sets from the mountain bike data that lend themselves well to analysis in this way.

I am part of the Regulation of Performance Research Interest Group and as part of this multi-disciplinary team of researchers have aspirations to attract external funding and research students to understand the integrated mechanisms that underpin pacing of self-paced exercise.

Whilst a successful publication record indicates proven capabilities to undertake research, the award of PhD is critical to enhance my confidence to further my research profile, apply for research funding and collaborate with national and international researchers.

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Appendix 1

Phillips and Pugh (2010; p69/70) fifteen statements of originality:

1. setting down a major piece of new information in writing for the first time.
2. continuing a previously original piece of work.
3. carrying out original work designed by your supervisor.
4. providing a single original technique, observation, or result in an otherwise unoriginal but competent piece of research.
5. having many original ideas, methods and interpretations all performed by others under the direction of the postgraduate.
6. showing originality in testing somebody else's idea.
7. carrying out empirical work that hasn't yet been done before.
8. making a synthesis that hasn't been made before.
9. using already known material but with a new interpretation.
10. trying out something in this country that has previously only been done in other countries.
11. taking a particular techniques and applying it to a new area.
12. bringing new evidence to bear on an old issue.
13. being cross-disciplinary and using different methodologies.
14. looking at areas that people in the discipline haven't looked at before.
15. adding to knowledge in a way that hasn't previously been done before.