Performance and physiological consequences of roll dynamics during cross-country mountain bike racing.

A thesis presented in partial fulfilment of the requirements for

The Doctor of Philosophy *via publication*

in

Sport & Exercise Science

Massey University, Manawatu Campus, New Zealand

Paul William Macdermid

2015

STUDENT DECLARATION

I hereby declare that this thesis is my own work and does not, to the best of my knowledge, contain material from any other source unless due acknowledgement is made. The thesis was completed under the guidelines set out by Massey University's College of Health, for the degree of Doctorate of Philosophy and has not been submitted for a degree or diploma at any other academic institution.

Candidate: ……………………………………………………….

Date: ………………………………………………………………..

ABSTRACT

Background: Understanding the interaction between physical work done and subsequent physiological responses is key to the prescription of optimal training. Olympic format cross-country mountain bike racing presents unique challenges with regards to understanding the relationship between propulsive and non-propulsive work, the interaction with performance, and associated physiological responses.

Aims: The aims of this thesis were to: 1) Determine the nature of work demand during simulated cross-country mountain bike racing; 2) Quantify vibration exposure during cross-country mountain biking and the interaction of bike-body in the subsequent energy dissipation; 3) Establish additional work done and physiological responses to riding on surface-terrain variations; 4) Investigate technological interventions designed to reduce vibration exposure during cross-country mountain biking and the interaction with performance and cycling economy.

Methods & Results: To address these aims four original experimental investigations involving two descriptive elements and four experimental interventions were conducted.
Study 1: Participants (n=7) completed a submaximal treadmill test on bicycles in order to establish the power:oxygen uptake relationship, which when combined with an ergometer maximal ramp test, enabled the prediction of oxygen demand during the field and thus estimations of aerobic and anaerobic contributions to work done. Field work involved particpants riding at race pace on a cross-country mountain bike course whilst cadence, power output, oxygen consumption, heart rate, speed and geographical position were recorded. The data show power output and cadence to be highly variable with one power surge every 32 s and a supramaximal effort (greater than power associated with $\dot{V}O_{2\,max}$) every 106 s. The majority of time (20.7 ± 8.3 %) was spent pedalling at a low velocity-high force, whilst physiological

variables % $\dot{V}O_{2\,max}$ (77 ± 5 %) and % HR_{max} (93 ± 2 %) were consistantly elevated to a high level throughout the lap. Importantly, the results identified that terrain significantly affecteded power output (70.9 7.5 vs 41.0 ± 9.2 % W_{max}); % $\dot{V}O_{2\,max}$ (80 ± 2 vs 72 ± 4 %) but not % HR_{max} (94 ± 2 vs 91 ± 1 %) for uphill and downhill, respectively. Accordingly, it was hypothesised that there was an additional non-propulsive physical stress during downhill riding, affording less recovery compared to road cycling.

Study 2: Participant (n=8) completed one lap of a cross-country track at race pace under two conditions (26” vs 29” wheels) whilst tri-axial accelerometers located on the bicycle (handlebar and seatpost) and the rider (wrist, ankle, lower back, and forehead) recorded accelerations (128 Hz) to quantify vibrations over the whole lap and for terrain specific sections (uphill vs downhill). The result showed that significant vibration attenuation occurred from locations at the bike and bike-body interface compared to the lower back and forehead. The reduction of accelerations at the lower back and forehead implies additional non-propulsive, muscular challenges which may limit recovery during periods of non-propulsive load.

The hypothesis that 29” wheels would reduce vibration exposure was inconclusive as 29” wheels proved to be significantly quicker (p=0.0020) compared to 26” wheels even though no difference was found between power output (p=0.3062) and heart rate (p=0.8423). As such the greater velocity incurred by 29” wheels may have caused the greater vibration exposure seen in the 29” wheels.

Study 3: Participants (n=7) ascended a tar-sealed road climb and a singletrack off-road climb of identical length and gradient at the same speed. Tri-axial accelerometers (128 Hz) located at the handlebar, wrist, ankle, seat post, lower back, and forehead were used to quantify vibration exposure while power output , cadence, heart rate and oxygen consumption were used to determine work done and physiological cost. Accelerations signified (P<0.0001) greater vibration exposure for off-road compared to tar-sealed riding and post-hoc analysis identified differences at the bike and bike-body interface but not the lower back and forehead. This indicates a greater non-propulsive component in the form of vibration damping to off-road cycling compared to road cycling, reflected by significant increases in work done (280 ± 69 vs 312 ± 74 W; $p=0.0003$). This was associated with a greater rate of oxygen consumption (48.5 ± 7.5 vs 51.4 ± 7.3 $ml \cdot kg^{-1} \cdot min^{-1}$; $p=0.0033$) and a higher heart rate (161 ± 10 vs 170 ± 10 bpm; $p=0.0001$) for tar-sealed road and off-road conditions, respectively. These findings advocate that technological interventions aimed at decreasing vibration exposure could increase cycling economy and therefore improve performance.

Study 4: Participants (n=8) completed a lap of a cross-country mountain bike circuit under two conditions (hardtail and full suspension) incorporating the same downhill section twice and separated by a forestry road climb. The particpants were asked to complete the downhill sections at race pace while the climb was performed at a power output associated with respiratory compensation point. The aim of this was to control physiological variables at the start of the second downhill. Tri-axial accelerometers (located at the handlebar, wrist, ankle, seat post, lower back, and forehead) were used to quantify vibration exposure while simultaneous power output , cadence, heart rate and oxygen consumption measurements enabled assessment of work done and physiological response. Performance was determined by time to complete the overall lap and specific sections.

Physiological demand of loaded downhill riding (2nd descent) was greater than unloaded (1st descent) ($p<0.0001$). Full suspension decreased total vibration exposure ($p<0.01$) but had no effect on performance times ($p=0.9697$) or power outputs ($p=0.8600$) whilst post-hoc analysis identified trial differences (downhill 1 vs downhill 2) in power output ($p<0.0001$) but not for time ($p>0.05$). Interestingly, the reduction of non-propulsive work did not affect oxygen consumption ($p=0.9840$), heart rate ($p=0.9779$) or cycling economy ($p=0.9240$).

Conclusions: This thesis demonstrates that surface-terrain negatively affectss cycling economy, presenting greater physiological responses as a consequence of increased non-propulsive work. This is likely due to vibration damping throughout the soft tissue of the limbs in order to protect the central nervous system. Reductions in vibration exposure diminished work done and physiological response for surface controlled interventions, yet mechanical system modifications capable of reducing exposure were unable to alter physiological response to work done.

ACKNOWLEDGEMENTS

I would like to express my thanks to all those that have helped in the completion of this thesis:

To Steve and Phil, the consummate cycling enthusiasts who embraced the sport of cross-country mountain biking and guided me through the course of study and became good friends in the process. Phil – for all those hours you spent with me in front of the computer exploring the possibilities of Matlab and Math in relation to sports analysis. I certainly look at things from a different perspective now. Steve, for keeping me on the straight and narrow, avoiding all the tangents, adding your experience and expertise to the papers and even getting on the bike and participating at busy times.

To all those that participated and perservered with their participation in my studies. Thanks for your time and cameraderie in the enjoyment of exploring your sport. Hopefully, you all learnt something in the process.

Fiona, who was always there to bounce ideas off, trial protocols, read through proposals and manuscripts to make sure they made sense. I can't thank you enough.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

ANOVA:	Analysis of Variance
AT:	Anaerobic Threshold
BM:	Body Mass
BMI:	Body Mass Index
BPM:	Beats per minute
CV:	Coefficient of Variation
DH:	Downhill
H:	Hill
HR:	Heart Rate
IAT:	Individual Anaerobic Threshold
ISO:	International Standard Organisation
MTB:	Mountain Bike
O_2:	Oxygen
OBLA:	Onset of Blood Lactate Accumulation
Off-Rd:	Non-smooth (tar-sealed) surface
RCP:	Respiratory Compensation Point
Rd:	Road (tar-sealed)
RMS:	Root Mean Squared
rpm:	revolutions per minute
SD:	Standard Deviation
UCI:	Union Cycliste Internationale
$\dot{V}O_2$:	Volume of Oxygen utilised per minute in time
W_{max}:	The maximal power output obtained over a 60 s epoch durng a cycle ergometry ramp test
XCO-MTB:	Olympic Format Cross-Country Mountain Biking

SUBMISSIONS AND PUBLICATIONS

Publications

Macdermid, P.W., & Stannard, S. (2012). Mechanical work and physiological responses to simulated cross-country mountain bike racing. *Journal of Sports Sciences,* 30(14), 1491-1501. Doi: 10.1080/02640414.2012.711487 (Appendix 1)

Macdermid, P.W., Fink, P.W., & Stannard, S. (2014a). The influence of tyre characteristics on measures of rolling performance during cross-country mountain biking. *Journal of Sports Sciences,* 1-9, Doi: 10.1080/02640414.2014.942682 (Appendix 2)

Macdermid, P.W., Fink, P.W., & Stannard, S. (2014b). Transferance of 3D accelerations during cross-country mountain bike racing. *Journal of Biomechanics,* 47(8), 1829-1837. Doi: http://dx.doi.org/10.1016/j.jbiomech.2014.03.024 (Appendix 3)

Macdermid, P.W., Fink, P.W., & Stannard, S.R. (2015). The effects of vibrations experienced during road vs off-road cycling. *International Journal of Sports Medicine.* In Press. (Appendix 4)

Macdermid, P.W., Fink, P.W., Miller, M & Stannard, S.R. (2015). The impact of uphill cycling and bicycle suspension on downhill performance during cross-country mountain biking. *Journal of Sports Sciences.* Currently Under Review. (Appendix 5)

Macdermid PW (2015) Ergonomic Interventions, Health and Injury Prevention during Off-Road Mountain Biking. J Ergonomics 5: e130.doi:10.4172/2165-7556.1000e130 (Appendix 9)

Conference Presentations

Macdermid, P., Fink, P., Stannard, S. Quantification of vibrations during mountain biking. *Journal of Science and Cycling*, North America, 3, jul. 2014. Available at: <http://www.jsc-journal.com/ojs/index.php?journal=JSC&page=article&op=view&path%5B%5D=99
(Appendix 5)

Industry Media

Macdermid, P., Fink, P., Stannard, S. (2013, Dec-Jan) Weight: Does it matter? *New Zealand Mountain Biker Magazine,* Issue 56 pg 84-87. (Appendix 6)

Macdermid, P., Fink, P., Stannard, S. (2013, Oct-Nov) Wheel Weight: Does it really matter? We test to find out. *New Zealand Mountain Biker Magazine,* Issue 61. (Appendix 7)

Beran, R. (Director). (2014, January 30). Our Changing World: Vibrations on Mountain Bikes (Radio Broadcast & Podcast). Radio New Zealand. Available at:
http://www.radionz.co.nz/national/programmes/ourchangingworld/2014

CHAPTER ONE: INTRODUCTION

In order to prescribe optimal training guidelines for specific sports, a thorough understanding of the interaction between physical work done during competition and subsequent physiological responses is required. Traditional classification of sport has been based on duration, intensity and activity characteristics. As such the majority of cycling based research does not, unwisely, differentiate between cycling disciplines lasting greater than 90 minutes with regards to performance analysis and training recommendations.

Olympic format cross-country mountain bike racing (MTB-XCO) presents unique challenges compared to road cycling races. Union Cycliste International (UCI) rules dictate that the sport is a mass-start, single day event consisting of several laps of a circuit ranging from 4-9 km in length over diverse terrain, where approximtely 40% of race distance is uphill and the surface terrain is typically dirt, gravel or grass in the form of single track trails, forestry roads and open fields (Lee, Martin, Anson, Grundy, & Hahn, 2002; Stapelfeldt, Schwirtz, Schumacher, & Hillebrecht, 2004). Course schematics from the 2013 World XCO-MTB championships (Figure 1.1) highlight the non-uniform trajectory with many changes in direction travelled, ascent or descent and technical demands dictated by the surface characteristics, all causing potential discontinuous patterns of accelerations and thus work done in a forward propulsive and non-propulsive manner. In this respect propulsive work is defined as muscular work transferred to the pedals and drive chain in order to propel the bicycle in a forwards direction. Conversley, non-propulsive work is work done by the rider that does not contribute directly to forwards momentum through the drive chain. Additionally, the mass start component means athletes are required to sprint from the start in order to obtain positional advantage over competitors in parts of the track restrictive in dimensions (Macdermid & Morton, 2012). Such supramaximal efforts early and continuously throughout an endurance race of this length are unusual and are more akin to dynamics of team sports such as football or rugby. These external demands distinguish XCO-MTB from other cycle disciplines with regards to training methodologies and technological advances required to enhance performance.

Presently, advances in technology have meant both propulsive and non-propulsive work done along with the metabolic consequences can now be logged in the field, providing considerable insight into XCO-MTB previously un-reported in peer reviewed literature.

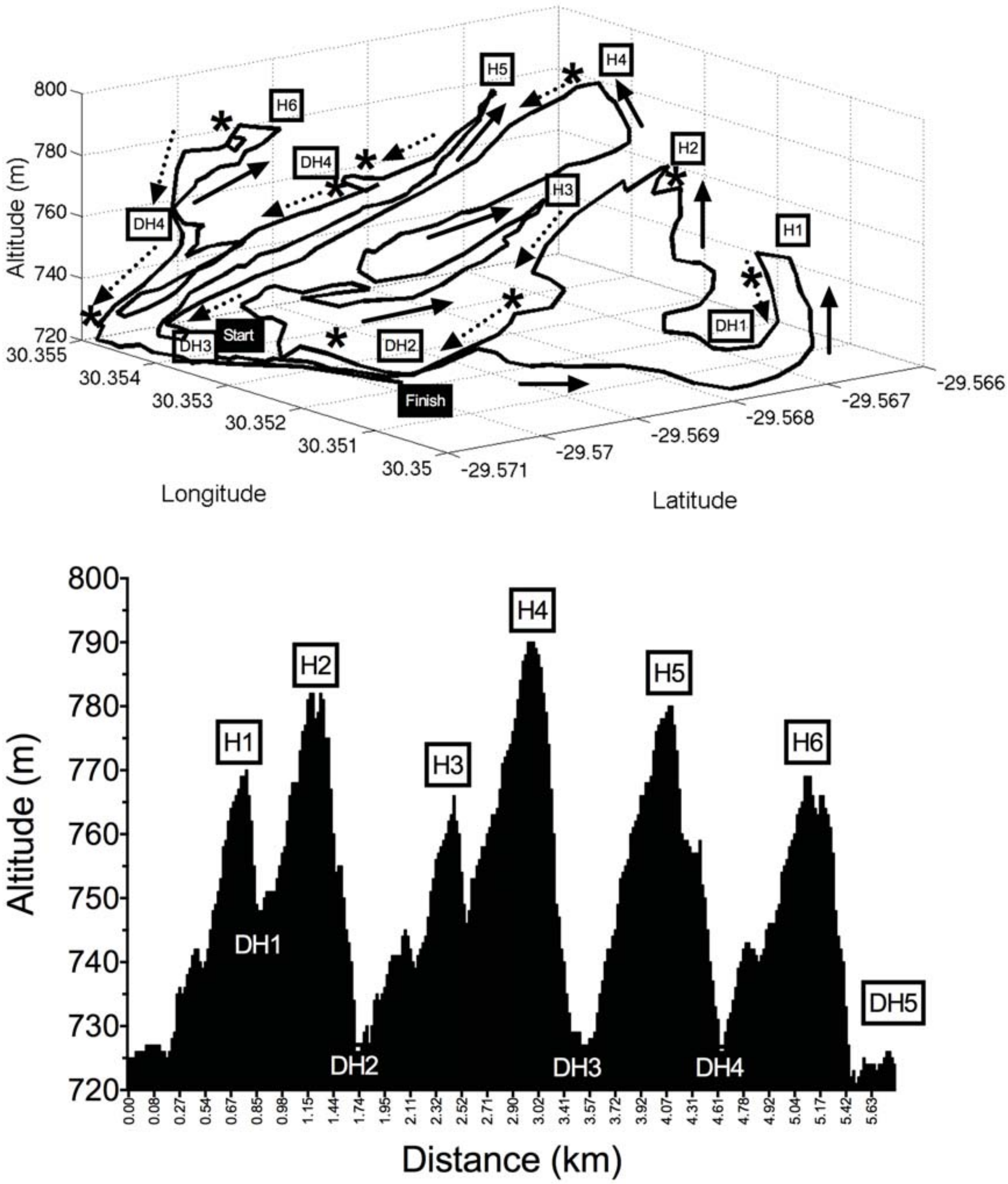


Figure 1.1: 2013 UCI Pietermaritzburg XCO-MTB World Championship course schematic and profile. Where, * signifies techical section; → uphill with hills numbered (H1…); --> downhill with downhills numbered (DH1…)

The programme of research described within this thesis utilizes this technology to describe, quantify and test interventions during XCO-MTB. The specific aims linking the body of work presented in this thesis initially focused on the overall mechanical work demand in relation to physiological responses while negotiating XCO-MTB trails equivalent to ~30 % race duration. From the descriptive metrics analysed from this race simulation study (Ch.4) it was then hypothesized that a non-propulsive (physical work) element to XCO-MTB could be identified via a differentiation between (measured) propulsive work and calculated work as indicated by physiological measures (VO2). As such, the greater extent of the information then presented here in this thesis involved: a) quantifying this non-propulsive element through the use of earth referenced tri-axial accelerometers and the transference of accelerations imparted by the surface-terrain, and subsequently dissipated by the bicycle and soft-tissue prior to reach the central nervous system (CNS) (Ch.5); b) the additional physiological response to such damping; and c) the potential of ergonomic design features (Ch.5 and Ch.7) to enhancing rider efficiency and ultimately performance. While certainly not exhaustive of the research required to fully understand the necessary role of non-propulsive work in XCO-MTB, it is envisaged that these studies will add to the currently small body of knowledge concerning of the sport of XCO-MTB, both from a mechanical and a physiological perspective.

CHAPTER TWO: REVIEW OF THE LITERATURE

Descriptive Characteristics of Elite XCO-MTB Athletes.

Descriptive physiological and anthropometric characteristics of elite athletes can provide a useful insight into the physical requirement for success in a sport. Early work (Impellizzeri, Marcora, Rampinini, Mognoni, & Sassi, 2005; Lee et al., 2002; Wilber, Zawadzki, Kearney, Shannon, & Disalvo, 1997) investigating descriptives of XCO-MTB athletes identified anthropometric values similar to those categorised as climbers and possibly overall contenders in the major tours within professional road cycling (Lucía, Hoyos, & Chicharro, 2001; Padilla, Mujika, Cuesta, & Goiriena, 1999). Research conducted within the Australian Institute of Sport into the comparisons of male XCO-MTB and Road cycling athletes (Lee et al., 2002) identified elite Olympic standard Australian XCO-MTB athletes, including the world No.1 (who incidently went on to win the Tour de France in 2011), were lighter and leaner than the equivalent professional Australian road cyclists. XCO-MTB athletes had mean ± SD values for height 1.78 ± 0.07 m with body mass 65.3 ± 6.3 kg and estimated body fat 6.1 ± 1.0 %. Differences between disciplines equated to -9.4 kg for body mass, -10.6 mm for sum of seven skinfolds and -1.8 % body fat when comparing XCO-MTB athletes with road cyclists. Similar variables in elite (A grade Australian male XCO-MTB athletes) but not world class athletes (Gregory, Johns, & Walls, 2007a) included height 1.80 ± 0.04 m, body mas 71.6 ± 6.3 kg and estimated body fat 9.2 ± 2.8 %. Comparable studies on female athletes of a world class standard (Impellizzeri et al., 2008; Wilber et al., 1997) have reported variables for height 1.62 ± 0.05 m and 1.64 m; body mass 57.5 ± 4.7 and 53.1 ± 3.4 kg, respectively. Only one study (Wilber et al., 1997) reported lean body mass (49.9 ± 3.8 kg) equating to a percentage body fat of 13.2 ± 2.0 %. While such data is useful, it must be recognised that the sport of XCO-MTB has undergone significant changes since 2008, with much shorter (≤ 3 minutes) and more technically demanding climbs with considerably more challenging downhill sections, man made for spectator purposes. Such sections now incorporate very steep sections with rock gardens, drop jumps and gap jumps (Figure 2.2) compared to pre-2008 were such features were rarely seen. As such anthropometric characteristics previously reported (Impellizzeri, Sassi, Rodriguez-Alonso, Mognoni, & Marcora, 2002; Lee et al., 2002; Wilber et al., 1997) amongst elite XCO-MTB athletes has led to numerous world class XCO-MTB athletes making the transition to overall contenders in events like the Tour de France (Michael Rasmussen; Floyd Landis; Cadel Evans; and Jean-Christophe Peraud). This may change because greater absolute muscle mass is likely required by modern day course designs (Figure 1.1 & 2.2). For example, unreported analysis of male athletes who medalled at the Olympic Games since 2000 (Figure 2.1) shows a gradual increase in body mass index (BMI) as a result of changes to body mass rather than height (http://www.olympic.org/ioc). This is further supported by unpublished data on 11 athletes (8 males and 3 females) from the 2013 Swiss national team who had a mean BMI of 22.01 kg·m^2. In the latter study, athletes were typically shorter and proportionally heavier than the aforementioned studies. While unsubstantiated, it is likely that the increased non-propulsive physical demand of the XCO-MTB courses requires greater upper body muscle mass to deal with increased shock attenuation resulting from negotiation of man made obstacles at numerous locations throughout the course (Figure 1.1 and 2.2). It is now more likely that modern day successful XCO-MTB athletes will be more comparable to those winning one day classic races and shorter stage races that typically involve shorter more powerful climbs. An example would include professional road cyclist Peter Sagan who won the Junior XCO-MTB championships in 2008 and has gone on to win a number of classic one day events, smaller week long tours and numerous sprint stages in the grand tours as a professional road cyclist. Interestingly, his BMI is 21.6 kg·m^2 which is more akin to medal winners at the 2012 Olympics XCO-MTB rather than those reported in earlier descriptive research into XCO-MTB (Lee et al., 2002).

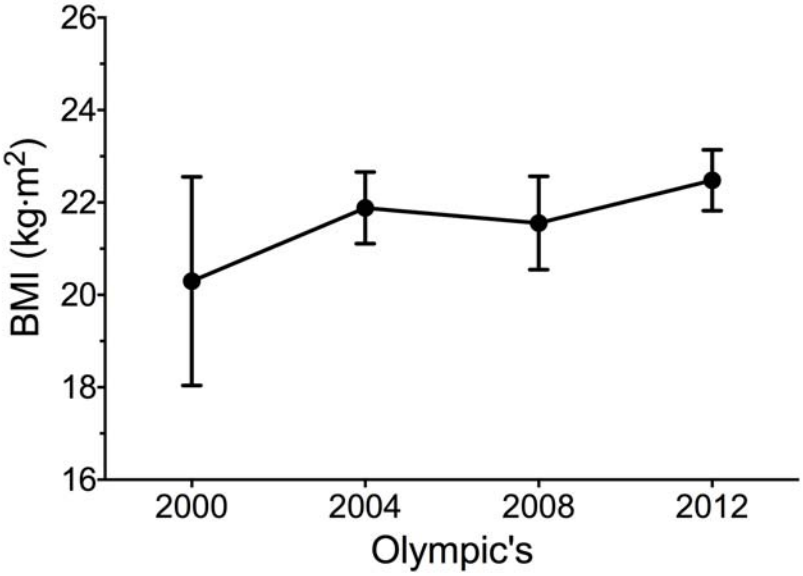


Figure 2.1: Mean ± SD body mass index for the male medal winners from the last four Olympic games.

Figure 2.2: Images showing the technical nature of modern day XCO-MTB events during study 4 of this thesis and inserts at the 2012 Summer Olympic Games.

Physiological Correlates of performance in XCO-MTB.

The previous section identified XCO-MTB athletes to be similar anthropometrically to professional road cyclists classified as climbers and/or overall contenders for major tours (Impellizzeri & Marcora, 2007). However, it should not be assumed that all components of fitness and physiological indices amongst these groups correspond. Investigating and describing such characteristics within a range of performance capabilities provides coaches, athletes and those involved in high performance sport valuable information for talent identification and athlete development. Not suprisingly, the majority of research into XCO-MTB thus far has focussed on descriptive physiological values measured in a laboratory and their specific relationship to XCO-MTB performance including such measures as maximal oxygen uptake ($\dot{V}O_{2\,max}$) and the accompanying submaximal thresholds that traditionally offer a more critical determinant of endurance performance in continuous sports such as road cycling and marathon running (Davis, Frank, Whipp, & Wasserman, 1979). The latter have variously been referred to as anaerobic threshold (AT) (Macdougall, 1977), onset of blood lactate (OBLA) (Sjödin & Jacobs, 1981), ventilatory threshold (VT) and respiratory compensation point (RCP) (Beaver, Wasserman, & Whipp, 1986). Pre-requisites for elite level performance have been recommended based on descriptors/variables relative to body mass (Gregory et al., 2007a; Impellizzeri & Marcora, 2007; Impellizzeri, Marcora, et al., 2005). To this end it is expected that elite male competitors have $\dot{V}O_{2\,max}$ values >70 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ (Impellizzeri & Marcora, 2007) while elite female competitors criterion are expected to be >60 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ (Impellizzeri et al., 2008; Macdermid & Edwards, 2010; Wilber et al., 1997). However, differences in performance levels even in the elite classification can be quite heterogeneous and a more homogenous look at those ranked amongst the top 15 in the world would indicate $\dot{V}O_{2\,max}$ values >75 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ for males equating to a maximal power output (W_{max}) of 413 ± 36 W or 6.3 ± 0.5 $W{\cdot}kg^{-1}$ (Lee et al., 2002). World class female athletes (top 15 finishers at world cups, world championships, and Olympics) to have $\dot{V}O_{2\,max}$ values of 62.3 ± 5.9 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ (Impellizzeri et al., 2008) equating to W_{max} values 320.4 ± 14.7 W or 6.1 ± 0.6 $W \cdot kg^{-1}$. Submaximal determinants related to OBLA, RCP, IAT or AT occur between 290-310 W or 78-84 % of W_{max}, 79 % $\dot{V}O_{2\,max}$, and 86 % HR_{max} (Gregory et al., 2007a; Prins, Terblanche, & Myburgh, 2007) for elite male XCO-MTB athletes and similarly reported in world class male XCO-MTB athletes (340 W or 5.2 $W \cdot kg^{-1}$) and greater than relative values for professional male road cyclists (Lee et al., 2002). Likewise, values for elite females range considerably for power outputs between 204-250 W or 65-78 % W_{max}, 84-88 % $\dot{V}O_{2\,max}$, and 87 % HR_{max} (Impellizzeri et al., 2008; Wilber et al., 1997) with relative values being non-significantly different to professional female road cyclists.

When these indices of aerobic fitness have been related to XCO-MTB performance it becomes difficult to attain detailed information regarding specific athletic capability. Indeed it has been suggested that laboratory testing is probably not applicable when trying to predict athletic performance in XCO-MTB, especially when compared to the sport of road cycling (Prins et al., 2007). However, initial work (Impellizzeri, Marcora, et al., 2005) investigating the relationship between race times and laboratory measures (W_{max}, $\dot{V}O_{2\,max}$, and power output associated with VT and RCP) in a hetrogeneity sample of a 6 min range in performance only produced a significant correlation with W_{max} when expressed as a relative value. Further work by the same author (Impellizzeri, Rampinini, Sassi, Mognoni, & Marcora, 2005) found significant relationships between W_{max}, $\dot{V}O_{2\,max}$, and power output associated with OBLA and performance when scaled to body mass. Likewise, later research (Gregory et al., 2007a) supported the findings that relative values were more valuable than absolute values at predicting XCO-MTB performance ($\dot{V}O_2$ $r=0.8$, $p<0.05$ vs $r=0.66$, $p<0.05$; OBLA $r=0.78$, $p<0.05$ vs $r=0.5$, $p<0.05$), respectively. In suggesting laboratory testing might not be the best option for predicting XCO-MTB performance, Prins *et al. (2007)* combined traditional laboratory testing with cycle ergometry, using fixed variable efforts aimed at simulating a XCO-MTB lap followed by all out 1 km time trials in addition to a field time trial over 1 lap of a XCO-MTB course (Prins et al., 2007). Interestingly, the relationship between a 1 lap time trial and race performance ($r=0.79$, $p<0.05$)

only accounted for 70 % variance, which was no better than relative W_{max} values ($r=-0.83$, $p<0.05$). The extra 30 % could be explained due to strategies used during a race to overcome issues surrounding start position, overtaking possibilities (Macdermid & Morton, 2012) and negotiating technical sections in a competitive environment where there is close interaction with other athletes. Comparable to previous studies, a better relationship with relative rather than absolute measures of aerobic performance and in particular W_{max} and OBLA ($r=-0.74$, $p<0.05$) was found. However, aerobic fitness variables taken from laboratory testing such as described above have only accounted for ~40 % of variance in performance (Impellizzeri & Marcora, 2007). Only two studies (Baron, 2001; Macdermid & Edwards, 2010) have investigated anaerobic measures of performance with no reference to correlations with performance. The first study identified that peak powers in male athletes were >14 $W \cdot kg^{-1}$ and is supported by unpublished data (Impellizzeri & Marcora, 2007). The latter looked in more detail at rate of power development along with isokinetic strength at a fixed cadence of 50 rpm (Maximum power: 504 ± 35 W and average power: 426 ± 51 W, over a 10 s epoch) in female athletes. As such, further research into the effects of surface terrain on riding economy along with measures of sport specific measures of strength, anaerobic power, upper body strength , skill capability and risk tolerance need investigating. This could be performed under laboratory and field conditions in order to expand our understanding of the sport.

Complexities of measuring XCO-MTB performance

The basic difference between XCO-MTB riding/racing and road riding/racing is simple; the former is performed on a relatively smooth service, and the latter is performed over often very tough terrain. Indeed the XCO-MTB has evolved more recently to include a variety of surfaces and terrains to showcase the riders various skills in overcoming what are essentially obstacles. Road riding, performed almost exclusively on bitumen, is fairly easy to replicate in the laboratory through the use of stationary cycling ergometers as surface vibration on a good bitumen road is minimal, and physical work done is almost entirely propulsive in nature. The difficulty then in studying XCO-MTB is replicating the terrain in the lab; this is impossible. Thus, studying XCO-MTB must be done in the field. This then brings about the difficulty of taking accurate and reliable physiological measurements in a field setting where there is often severe mechanical stresses, dirt, water, and other environmental issues. Such research would require portable devices such as standalone powermeters, portable telemetrics, and data capture (and storage) appliances that can simultaneously collected information from a number of devices. It is possible therefore, that one of the reasons that the published literature is sparse in relation to XCO-MTB is that these devices are either just new to the market, or have not been fully developed. Currently available tools include a number of crank and hub-based powermeters, telemetric-based HR monitors, portable expired respiratory gas analysers, and portable accelerometers. It is not within the scope of this Literature Review to discuss the advantages and disadvantages, accuracy and reliability of all these pieces of equipment; such information can be found elsewhere (Coza, Nigg, & Fliri, 2010; Duffield, Dawson, Pinnington, & Wong, 2004; Matthew C Miller, InPress; Stannard & Thompson, 1998) .

Work done and the physiological consequences during XCO-MTB

Common knowledge of a range of sports identifies the occurrence of changes in exercise intensity at irregular and frequent intervals and as such are referred to as intermittent. Typically, these sports are classified as 'games' and their intermittent nature is determined through chosen strategy of play used to gain ascendancy over an opponent(s). Movement analysis studies during match play in football (soccer) identifies in excess of 1,000 changes in activity during a match, 11 % of which can be classified as high intensity efforts occurring every 30 s and all-out efforts once per 90 s (Reilly & Thomas, 1976). Within XCO-MTB, terrain, individual strategies, opponents and mechanical or technical problems influence regularity of intensity. The first studies to investigate the physiological/work demand of XCO-MTB were limited by technological advancements in collecting data in the field and could only report HR in relation to specific physiological criterion identified through laboratory testing (Impellizzeri et al., 2002). Data collected over 4 successive races identified overall intensity to be 90 ± 3 % HR_{max}. Subsequent categorization around submaximal thresholds (AT and IAT) as easy (<AT), moderate (AT-IAT), and hard (>IAT) identified 27 ± 16' (18 ± 10 %) easy, 75 ± 19' (51 ± 9 %) moderate, and 44 ± 21' (31 ± 16 %) hard. While the overall intensity expressed as an average provides limited information, it is likely to result in a substantial loss of specific temporal information. The latter analysis enables comparison with other cycling specific data at least in terms of cardiovascular stress. Comparisons with professional road cycling (Padilla, Mujika, Orbañanos, & Angulo, 2000; Padilla et al., 2001) suggest XCO-MTB is performed at a higher intensity than stage races but more like short individual time trials (Padilla et al., 2000) even though the duration is significantly greater. It seems unlikely that such a high intensity could be upheld for such long periods of time while terrain is frequently changing (Figure 1.1) resulting in sections where no pedalling occurs with subsequently no propulsive work being done. Explanations for such high heart rate values over such long periods of time centre around the extra demand associated with terrain surface effects on rolling resistance, the pacing strategies used to gain positional advantage, plus the lack of benefit in drafting opponents. However, these are all factors that would still translate into a greater power output and as such does not help with regards to explaining the possible higher heart rates. A more feasible explanation is the addition of non-propulsive muscular work during XCO-MTB apparent through the need to manoevre the bike more frequently and the attenuation of shocks and/or vibrations caused by terrain surface. Even small muscle group static isometric work, such as in the case of the forearm in gripping the handlebars, is likely to cause an increase in blood pressure which would increase heart rate (Mitchell, Payne, Saltin, & Schibye, 1980). Interestingly, none of the above explanations have been investigated.

The advent of powermeters for XCO-MTB meant a more detailed insight into external propulsive work done could be gleened. The first study to investigate work done during XCO-MTB races (Stapelfeldt et al., 2004) advanced the aformentioned study (Impellizzeri et al., 2002) by quantifying submaximal thresholds (AT and IAT) with regards to the corresponding power outputs in the laboratory and categorizing time spent in the respective intensity zones. Unlike the limitations posed by using HR alone, this study was able to identify a zone greater than the W_{max} value reported from the laboratory. As such data from 11 national team cyclists competing over 15 XCO-MTB races provided quite different frequency distributions of intensity zones in comparison to earlier work (Figure 2.3).

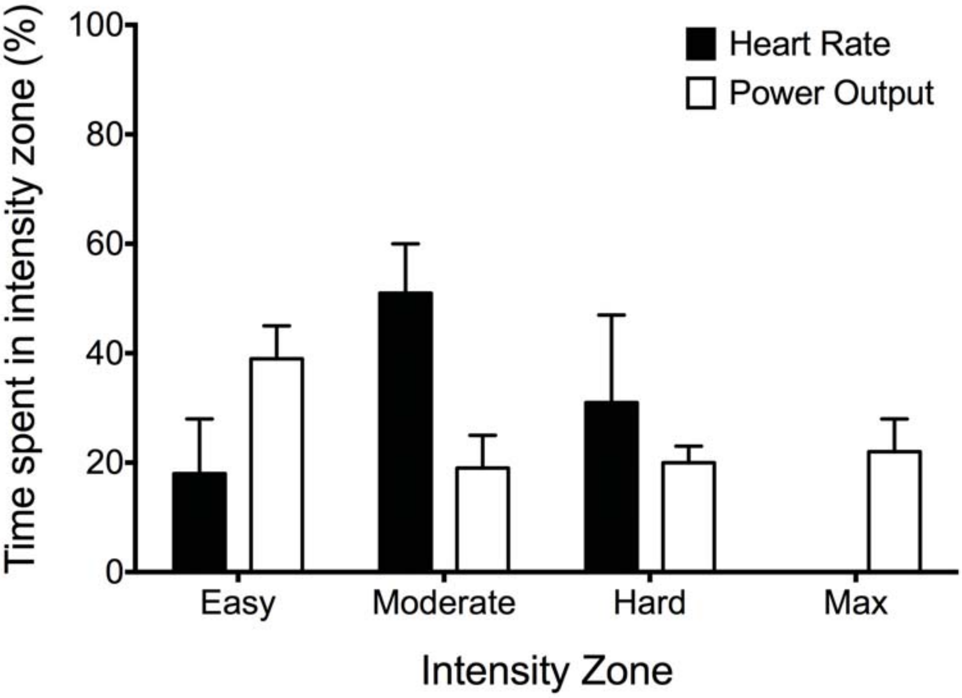


Figure 2.3: Categorisation of time spent during specific intensity zones during XCO-MTB racing based on laboratory determined submaximal thresholds (AT and IAT). Heart rate based data taken from Impellizzeri *et al*, 2002 and power output from Stapelfeldt *et al*, 2004.

The greater time spent in the easy zone for power output compared to heart rate indicates that changes in power output may be too frequent for HR to change at a similar rate, plus there could be a possible un-coupling of external work and metabolic cost. Further evidence could be garnered from the greater proportion of time spent in the hard-max category for power output analysis but again the duration of time spent is possibly so short that the heart rate response simply reflects an averaging of metabolic stresses experienced. That is, measuring heart rate will likely ‘hide’ the varying muscular metabolic stresses of participating in XCO-MTB.

While power profiles were smoothed to 50 data point rolling averages the data presented still had a reported co-efficient variation (CV) of 69 % (range 50-400 W). The authors also acknowledged that athletes would produce power outputs >1000 W at the start. This suggests that valuable information is missing with regards to the nature of power oscillation, work done during specific sections of the course, pedalling mechanics and subsequent physiological and metabolic response. The only other investigation to address the issue of work done during XCO-MTB (Hamilton, 2007) once again compared data across races of different classifications (Road vs XCO-MTB). In identifying the additional stress and strain XCO-MTB racing or training may impart on athletes compared to road cycling. The purpose of this conference presentation was to identify similarities between each disciplines power output profiles in recommending specificity of using road races for training leading into XCO-MTB races. As such, it was identified that XCO-MTB entailed significantly greater fluctuations in external power output throughout a race compared to hilly, mountainous, or flat road races along with individual time trials and criterium races. Key to this finding was that XCO-MTB had significantly greater surges (201) for power in the range >7.5 W·kg^{-1} but was closest to road races hilly in nature (155) rather than high mountainous (126) races or flat (100), time trials (8) or criterium race (36). There was also less time spent at low power outputs (<3.75 W·kg^{-1}) during XCO-MTB. Importantly, cadence was significantly lower during XCO-MTB races compared to other cycling disciplines and was <80 rpm for 57 % of the time compared to 3-33 % for XCO-MTB and road, respectively. Consequently, it is likely that XCO-MTB racing involves frequent high power output surges composed of low frequency, high torque pedal actions. These would involve sporadic (determined by course characteristics and race strategies) periods of low power outputs composed of low frequency, low torque pedal actions. Additional to the periods of low power output, we could hypothesise that non-propulsive work to necessitate bike handling, shock attenuation and vibration damping must occur. Subsequently diminishing any physiological recovery that might otherwise occur in other cycle disciplines such as road cycling, especially during descents. In this respect, a descriptive investigation into power output during downhill mountain biking (Hurst & Atkins, 2006) identified athletes only pedal 38 times per run, had a peak power output of 834 ± 129 W (10.7 ± 1.3 $W \cdot kg^{-1}$) with a mean power output of 75 ± 26 W, yet heart rate average 168 ± 9 bpm or 89 % age predicted maximum. It was also shown that power output and cadence did not correlate to performance time and thus competitive ranking highlighting the importance of riding dynamics and how dynamic and isometric muscular efforts required to negotiate the course (probably in concert with sympathetic stimulation) can drive cardiovascular response. This is a particularly interesting aspect of XCO-MTB that needs further exploration, as it could present an important aspect required in athlete development and training in order to maximise individual potential.

Non-propulsive work

During the quest for optimal performance XCO-MTB athletes have to negotiate a pre-determined lap a set number of times. The surface-terrain curvature of the course is non-uniform and transport across it on a bicycle continuously changes throughout a XCO-MTB race. This is partly due to the volume of athletes and the errosion effects but also because the route taken by the individual cyclist varies within the dimensions of the track available. As such this uncontrollable aspect exposes riders to vibrations which are a series of mostly random, mechanical oscillations. These are complex in nature containing many frequencies (ranging from 1-80 Hz), occur in several directions (x, y and z axis) and result in the distribution of oscillatory motion and forces within the body (Iso, 1997). Combined with the negotiation of obstacles throughout the course which produce impact related shocks (Figure 2.2), an effect known as wheel hop or skip occurs. These occurances result in little or no wheel contact with the ground for very short periods of time meaning no propulsive work is done, causing a form of negative resistance to forward momentum. In order to negate these occurances and limit the negative effect on forward momentum, the energy must be absorbed in the mechanical-biological system (bicycle-human body) particularly at the point of contact including: handlebar-arm, pedal-foot-leg, and the saddle-lower back interfaces when cycling. Vibration energy at frequencies >30 Hz is likely absorbed at these points of contact during XCO-MTB and will have little effect on the rest of body (Grether, 1971). Exposure to vibrations whilst in a seated position and inclusive of the aforementioned interfaces have been referred to as whole body vibration (Iso, 1997).

This whole body vibration has been associated with discomfort and pain for some time, being first recognised in coachmen during the 17th Century who were subjected to prolonged vibration exposure and suffered ensuing back pain (Mester, Spitzenfeil, Schwarzer, & Seifriz, 1999). As awareness and understanding of the human physiological/pathological response to vibration increased, universally recognised dose-response relationships were introduced as industry standards (Iso, 1997). Despite understanding that vibrations cause various threats to human health and that many aspects of normal life and industry are subject to strict guidelines regarding exposure levels and durations (Iso, 1997), the same rules do not apply to sport. However, it is likely that many sports expose athletes to possibly dangerous vibration loads (Mester et al., 1999), yet little is known regarding the exact levels of exposure and the subsequent effects on performance.

Traditionally, cycling is considered a non-impact sport (Stewart & Hannan, 2000) yet mountain bike riders are subject to forced vibrations and shocks that could be harmful or potentially detrimental to performance. The latter could be as a result of an increase rate of fatigue development, decreased traction and control of the bicycle (Titlestad, Fairlie-Clarke, Davie, Whittaker, & Grant, 2003). The interaction of the bicycle wheel with the riding trail surface generates these forced vibrations which are then transferred through the bicycle to the rider (De Lorenzo & Hull, 1997; Faiss, Praz, Meichtry, Gobelet, & Deriaz, 2007; Levy & Smith, 2005). All matter, including human beings, has a natural frequency (Figure 2.4) and the closer the stimuli (forced vibrations) are to this, the greater the consequences in terms of non-propulsive work. This ensuing effect is referred to as resonance, to which the human response depends on frequency, amplitude, duration of exposure and specific muscle tension and stifness. The impact of which can range from feelings of discomfort, to influencing speech capability, breathing patterns and muscular contractions which ultimately reduce motor co-ordination (Rasmussen, 1982). It has been suggested that every biological system and subsystem could be affected (Mester et al., 1999).

When the body is exposed to forced vibrations, such as those that occur during XCO-MTB the biological reaction is to protect the axial body via stabilization. This is possible as mechanical excitation of skeletal muscle occurs at the appendicular tendons or muscle via a reflex contraction (specifically fast twitch fibres) which acts as a vibration dampener. This occurs through the joints in order to decrease the resonance when excitation frequency is close to the specific body segments natural frequency (Wakeling, Nigg, & Rozitis, 2002). The closer the stimuli to the natural frequency (Figure 2.4) the greater the muscle response and thus the greater rate of energy expenditure as a result of increased spatial recruitment. This suggests that fewer motor units would then be available for external propulsive work development and for an increased potential advancement of muscular fatigue development (Mester et al., 1999).

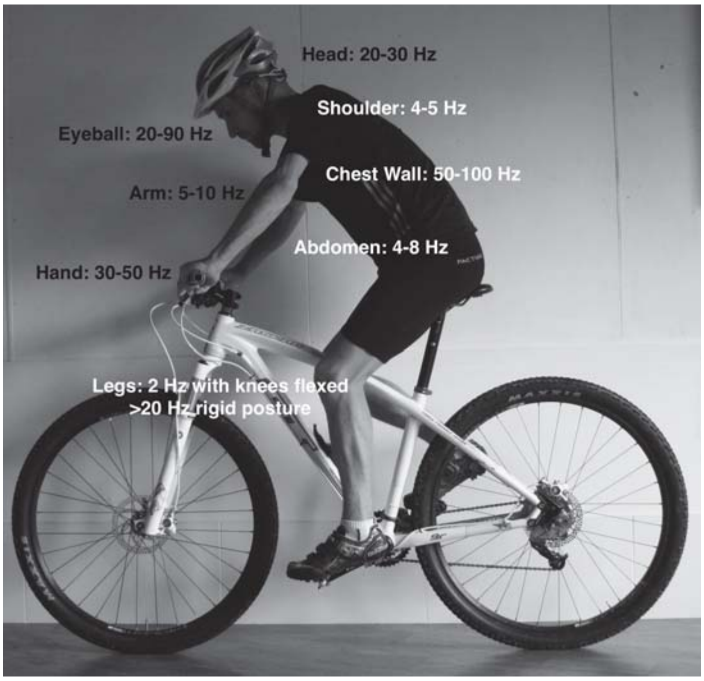


Figure 2.4: Image showing the human bodies resonance frequency ranges of various body sections whilst seated on a XCO-MTB (Wisner, Donnadieu, & Berthoz, 1964).

Alternatively, the increased demand on the neuromuscular system and subsequent markers of stress (Smith & Myburgh, 2006) possibly caused by the addition of vibrations could provide additonal stimulus and subsequently greater adaptation. As such understanding vibration exposure in sports such as XCO-MTB could be critical to performance through decreasing non-propulsive energy expenditure and enhancing gross economy.

There are two important issues arising from this for the XCO-MTB industry and/or athlete, and they include; the level of vibrations XCO-MTB athletes are exposed to; and the bicycles' technological capability of reducing vibration exposure in order to enhance gross economy or overall performance.

In the first instance there has been limited information available due to the difficulty in capturing and logging field data in a wireless mode. As such the only information available regarding vibration exposure levels during XCO-MTB have been recorded in a simulated environment with very small sample data collection epochs. Initial work (Levy & Smith, 2005) looked at the difference between riding on a gravel surface compared to a XCO-MTB trail for a period of 4-s. The results showed that the trail elicited greater amplitude lower frequency vibrations than the gravel road condition, suggesting that accelerations of frequencies >25 Hz were attenuated by frame while those <25 Hz were attenuated by the suspension system and the rider. Although, data collection periods were limited with regards to the variations typically found over a complete lap of a XCO-MTB course they did indicate that vibrations >7.5 $m \cdot s^{-2}$ decreased mobility in the wrists, elbows and shoulders. The authors concluded that a reduction of acceleration exposure had potential to improve performance in the long term. Further work (Vibert, Redfield, & Rudolf, 2007) identified the effect of performing a simulated jump typical of that experienced in racing situations during XCO-MTB. Participants bicycles experienced accelerations of 4g on landing impact, attenuated to 2.6g in the shoulders and 2g in the head. This shows that the bicycle suspension and body parts only partially attenuated impact accelerations which could pose health risks as shown by four particpants who were free of otoneurological symptoms prior to completing intense XCO-MTB but were subsequently diagnosed with symptoms of benign paroxysmal vertigo several hours after the exercise without suffering any head trauma (Vibert et al., 2007). The results of the aformentioned studies identify a need for more specific field work in order to determine the overall dose-response with regards to the effects of terrain induced vibrations, their effects on performance and physiological responses, and subsequent technological interactions on reducing the exposure.

While to date there have been no specific studies measuring terrain induced vibrations and the transferance to bicycle and body, laboratory work (Samuelson, Jorfeldt, & Ahlborg, 1989) has exposed cyclists to vibrations of fixed intensity; 20 $m \cdot s^{-2}$ at a frequency of 20 Hz (amplitude 1.8 mm) to determine the effects on endurance performance. Transferance to body segments resulted in accelerations of 20 $m \cdot s^{-2}$ at the foot, 8 $m \cdot s^{-2}$ at the knee, 4 $m \cdot s^{-2}$ at the saddle, 3 $m \cdot s^{-2}$ at the hip and 2 $m \cdot s^{-2}$ at the head. This highlights the importance of dissipating energy from terrain in the periphery before it reaches the central nervous system. Importantly, this study also looked at the effects of vibrations on cycling performance determined by time to exhaustion. The fixed load effort revealed a 21 % decrease in performance on a cycle ergometer. The latter finding is important and has subsequently generated considerable interest with regards to the effects of bicycle suspension systems on performance and energy expenditure. While transferance of acelerations from bicycle to body have never been replicated in the field for XCO-MTB there has been considerable interest in the effect of MTB suspension systems on performance and physiological variables. The premise of using suspension systems during MTB is that they provide a more comfortable ride and therefore efficient ride through a decrease in energy expenditure (Berry, Woodward, Dunn, Edwards, & Pitt-Man, 1993; Titlestad et al., 2003). However, initial work (Wang & Hull, 1996) showed that bicycles with front and rear suspension (full suspension) dissipated 6.9 W compared to 0.5-2.0 W in a front suspension only bicycle (hardtail). While both suspension types seem to negatively affect performance, the small loss for the hardtail was seen to be inferior to the benefits. However, subsequent research looking at full suspension verses hardtails with regards to performance has been equivocal with regards to performance capability, the work done and the physiological costs. Several studies have shown that while it is possible to achieve the same level of performance (Ishii, Umerura, & Kitagawa, 2003; Macrae, Hise, & Allen, 2000; Nishii, Umemura, & Kitagawa, 2004) on a full suspension bicycle there is significantly greater work done (Macrae et al., 2000) and physiological cost as suggested via greater HR (Seifert, Luetkemeier, Spencer, Miller, & Burke, 1997) and $\dot{V}O_2$ (Ishii et al., 2003; Macrae et al., 2000). Contrary to these findings is a laboratory simulation exposing participants to a bump, 30 mm height, at a frequency between 2.9-4.0 Hz during a 10 minute submaximal trial (Titlestad et al., 2006b). This study isolated the effect of rear wheel impact with a controlled bump and the subsequent physiological and performance comparisons whilst riding a hardtail and full suspension bicycle. Firstly, the bumps made significant ($p<0.05$) differences to all variables when using the full suspension compared to hardtail bicycle. This included an increase in $\dot{V}O_2$ by 9.9 $ml \cdot kg^{-1} \cdot min^{-1}$, HR by 38 bpm and a decrease in comfort by 3.0 units in the hardtail, indicating that bumps at this level of exposure could signifciantly affect gross economy and subsequent performance. Interestingly the use of a full suspension bicycle during the bumpy condition only elevated $\dot{V}O_2$ by 0.8 $ml \cdot kg^{-1} \cdot min^{-1}$ and HR by 3 bpm compared to the hardtail, smooth condition, which was also accompanied by a 1.3 decrease in comfort. The smooth condition provided no significant differences between suspensions systems and conditions.

In addition to suspension systems it has been proposed (Wilson, 2004) that increased wheel diameter reduces vibration in any format. This is interesting and an issue which the bicycle manufacturing industry has recently embraced with the introduction of a variety of wheel sizes (post-Study one) and tyre dimensions (post-Study 4). The unsubstantiated premise being that bigger wheels enhance overall ride performance and reduce surface-terrain induced vibration exposure.

Therefore, with the recently improved ability to quantify vibration exposure levels in the field it is possible to determine the ‘real world’ effects of XCO-MTB racing on accelerations transferred from terrain to bicycle and from bicycle through the body. Secondly, this brings about the opportunity to assess the effects of these on physiological function, performance, and finally, the implementation of technology aimed at reducing vibration exposure.

CHAPTER THREE: THESIS STRUCTURE

There is limited information regarding the work patterns and subsequent physiological responses for the sport of XCO-MTB. It has been suggested but unsubstantiated that the continuously elevated cardiovascular response is partly due to the discontinuousness changes in exercise intensity in combination with the non-propulsive demands determined by surface terrain. Therefore, it is important to further understand the dynamics of work done with specific reference to propulsive and non-propulsive elements in regards to surface terrain. Once these demands have been confirmed the next step is to establish the influence of surface terrain on accelerations experienced at the bicycle and rider level. Subsequent interactions of vibration damping and shock attentuation in relation to additional physiological costs compared to smooth surface bicycle riding will enable comparison of interventions aimed at increasing gross economy and performance. As such the impact of suspension systems and wheel size on the relationship between work done and physiological responses are yet to be ascertained.

This thesis aimed to evaluate the effects of surface terrain on the transferance of accelerations between bicycle and body, their effects on riding economy and whether technological developments can attenuate the extra demand, improve riding economy and increase performance. The thesis is presented as a collection of manuscripts (Table 1) that have been published in peer review journals. This thesis is comprised of an introductory literature review and four original investigations (Figure 3.1).

Table 1.1. Structure of the thesis and summary of the aims covered by each chapter.

Literature Review	Ch.1 Introduction to the scientific and descriptive characteristics of XCO-MTB.	
	Ch.2 Review of the available literature regarding XCO-MTB and vibration exposure in sport.	
Original Investigations	Ch.4 Mechanical work and physiological responses to simulated cross-country mountain bike racing.	Aim: Descriptively assess the intermittent work demand of cross-country mountain biking.
	Ch.5 Transferance of 3D accelrations during cross-country mountain biking.	Aim: Identification of frequency-magnitude relationship with terrain, bicycle and rider during cross-country mountain biking.
		Aim: Does a wheel size intervention affect the frequency-magnitude relationship between terrain, bicycle and rider; or athletic performance.
	Ch.6 The effects of vibrations experienced during road verses off road cycling.	Aim: To investigate the influence of terrain surface on accelometric output measures and their interaction with the bicycle and rider.
		Aim: Vibration-surface interaction and the subsequent effects on measures of performance and physiological work.
	Ch.7 The impact of uphill cycling and bicycle suspension on downhill performance during cross-country mountain biking.	Aim: Determine mechanical, physiological, and performance differences and observe economy whilst riding a downhill section of a cross-country course prior to and following the metabolic "load" of a climb at race pace.
		Aim: The effect of suspension systems on vibration exposure and subsequent performance and physiological measures of cycling economy.
Ch. 8 Summary of findings, limitations & future directions.		

Aims and Hypothesis

1. Assess the work demand of a simulated XCO-MTB lap performed at race pace in the field with reference to physical and physiological requirements.

This aim was addressed via a descriptive field study (Chapter 4) which reported cycling dynamics (cadence, force and power) in accordance with terrain (profile and directional changes) and the subsequent physiological responses.

Hypotheses:

- A highly varied (intermittent) work requirement would be apparent.
- Mean cadence would include significant periods of low cadence, high force during uphill sections and high cadence, low force during shorter downhill sections.
- A much greater intermittent anaerobic contribution is required during XCO-MTB compared to traditional cycling disciplines.
- Due to the oscillating nature of power output, acute physiological responses would show minimal fluctuations throughout the trial.

2. a. Describe the relationship between vibration mechanics and their interaction with terrain, bicycle and rider.

b. Evaluate and investigate the effect of two commonly manufactured wheel sizes on the interaction of vibration mechanics.

The aims were addressed by the completion of a counterbalanced trial consisting of two conditions determined by wheelsize (traditional 26” and new 29”). Participants were instructed to ride a known XCO-MTB lap at race pace (Chapter 5). Accelerations measured on the bike and rider illustrated the effects of surface and the interaction between bike and body with regards to acceleration attenuation.

Hypotheses:

- Accelerations experienced at the head and lower back (axial skeleton) would be significantly less than those at the bicycle and limbs (appendices).
- The interaction of frequency-magnitude relationship would differ with ascent and descent.
- 29" wheels would dampen vibrations to a greater extent than 26" wheels.

3. Investigate the effect of terrain surface on the level of vibrations experienced. The extent of attenuation and the subsequent effects on work demand and physiological cost.

The aim was addressed by the completion of a counterbalanced trial over a hill climb of identical characteristics for distance, elevation and gradient but distinguished by two conditions differentiated by surface type including tar-sealed and off-road single track (Chapter 6). Participants were instructed to ride at the same predetermined speed in order to compare vibrations experienced and the level of damping required to protect the central nervous system. Work done and physiological responses were recorded to enable comparison of gross economy during the two conditions.

Hypotheses:

- Off-road single-track riding would produce more vibrations.
- The increase in vibrations experienced would lead to greater muscle damping.
- Greater muscle damping would equate to increased work demand and metabolic cost.

4. Investigate the impact of uphill cycling and bicycle suspension on downhill performance during XCO-MTB.

The aims were addressed by a two condition single trial counterbalanced experiment (Chapter 7) where participants completed a downhill section of a XCO-MTB track in a rested state followed immediately by a XCO-MTB climb at a power output asscoiated with respiratory compensation point, directly followed by the aforementioned downhill section to allow comparison between unloaded (no prior work) and loaded (on completion of an uphill section) conditions. As such this design enabled comparison of metabolic cost between unloaded and loaded conditions. Participant completed the trial on the same bicycle with front suspension only (hardtail) and both front and rear suspension (full suspension). Thus enabling the interaction of bicycle suspension on vibration exposure, the extent of acceleration attenuation, metabolic cost and downhill bicycle performance.

Hypotheses:

- There would be no significant difference between performance parameters of unloaded and loaded XCO-MTB downhilling.
- Significant increases in physiological variables during loaded downhill XCO-MTB would occur as a consequence of recovery from prior work done during the climb.
- The full suspension condition would decrease acceleration attenuation leading to decreased metabolic cost.

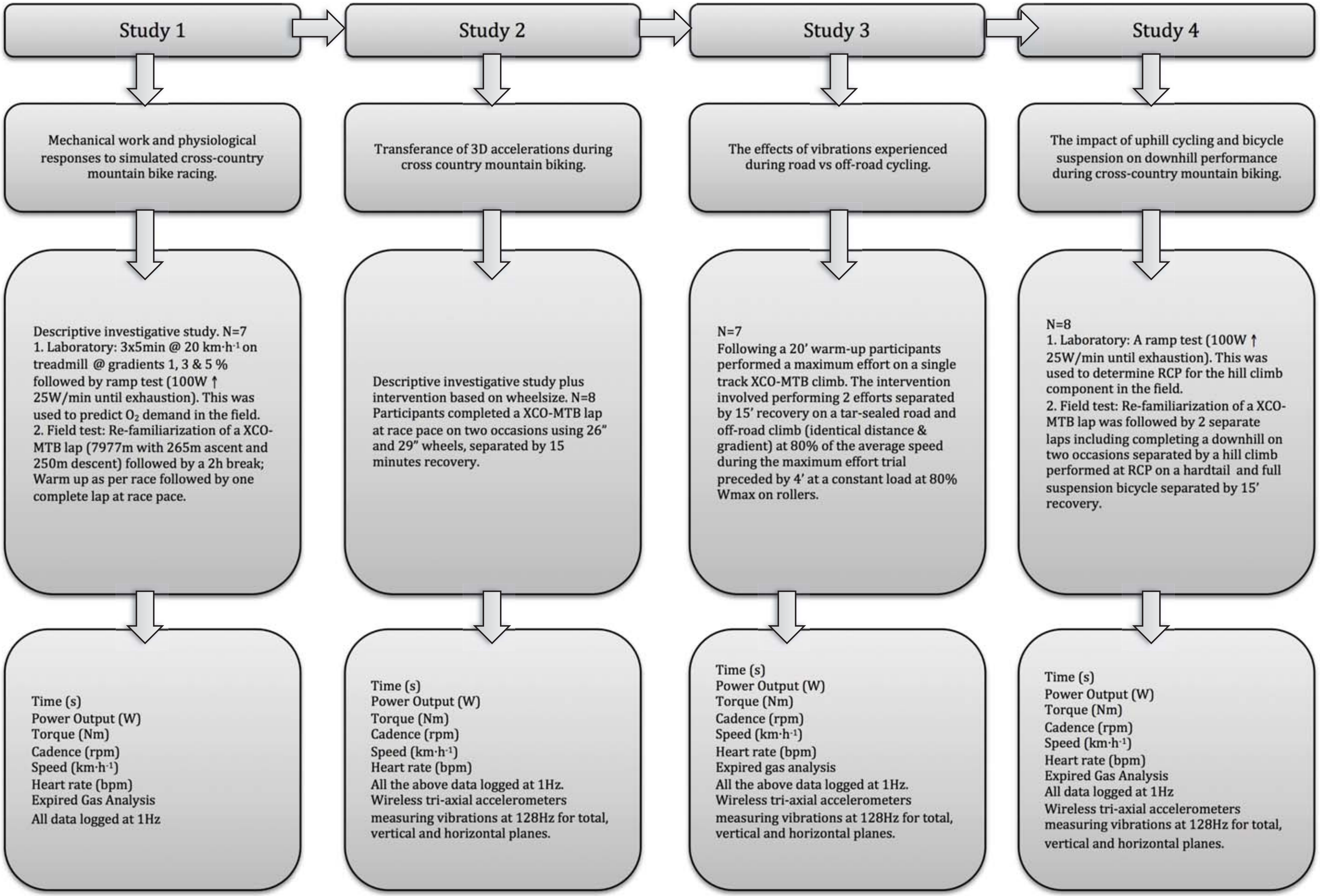


Figure 3.1. The four original investigations of this thesis.

CHAPTER FOUR: STUDY ONE

MECHANICAL WORK AND PHYSIOLOGICAL RESPONSES TO SIMULATED CROSS-COUNTRY MOUNTAIN BIKE RACING.

Macdermid Paul W., Stannard R. Stephen.

The following paper has been submitted and published in the *Journal of Sports Science* and prepared according to their guidelines. For evidence of publication and statement of contribution to doctoral thesis see Appendix 1.

Abstract

The purpose was to assess the mechanical work and physiological responses to cross-country mountain bike racing. Subjects (n=7) cycled on a cross-country track at race speed whilst $\dot{V}O_2$, power, cadence, speed, and geographical position were recorded. Mean power during the designated start section (68.5 ± 5.5 s) was 481 ± 122 W, incurring an O_2 deficit of 1.58 ± 0.67 $L·min^{-1}$ highlighting a significant initial anaerobic (32.4 ± 10.2 %) contribution. Complete lap data produced mean (243 ± 12 W) and normalized (279 ± 15 W) power outputs with 13.3 ± 6.1 and 20.7 ± 8.3 % of time spent in high force-high velocity and high force-low velocity, respectively. This equated to, physiological measuring for $\%\dot{V}O_{2\,max}$ (77 ± 5 %) and % HR_{max} (93 ± 2 %). Terrain (uphill vs downhill) significantly ($p<0.05$) influenced power output (70.9 ± 7.5 vs 41.0 ± 9.2 % W_{max}),the distribution of low velocity force production, $\dot{V}O_2$ (80 ± 1.7 vs 72 ± 3.7 %) and cadence (76 + 2 vs 55 ± 4 rpm) but not heart rate (93.8 ± 2.3 vs 91.3 ± 0.6 % HR_{max}) and led to a significant difference between anaerobic contribution and terrain (uphill, 6.4 ± 3.0 vs downhill, 3.2 ± 1.8 %, respectively) but not aerobic energy contribution. Both power and cadence were highly variable through all sections resulting in one power surge every 32 s and a supra-maximal effort every 106 s. The results show that cross-country mountain bike racing consists of predominantly low velocity pedalling with a large high force component and when combined with a high oscillating work rate, necessitates high aerobic energy provision, with intermittent anaerobic contribution. Additional physical stress during downhill sections affords less recovery emphasized by physiological variables remaining high throughout.

Keywords: Cycling; Intermittent; Field Testing; Oxygen Deficit.

Introduction

In order to prescribe optimal training guidelines for a particular sport, a thorough understanding of the interaction between physical work done during competition and the physiological response to that work is required. Published research (Gregory, Johns, & Walls, 2007b; Impellizzeri et al., 2002; Impellizzeri, Marcora, et al., 2005; Lee et al., 2002; Stapelfeldt et al., 2004; Wilber et al., 1997) on the sport of Olympic format cross-country mountain bike racing has concentrated on basic laboratory descriptors of endurance capabilities with relation to both absolute and relative workload(s) in the field. Such measures might not directly relate to cross-country mountain bike race performance (Baron, 2001; Gregory et al., 2007a; Prins et al., 2007) and may mislead coaches to prescribe ineffective training.

The geographical profile of a cross-country mountain bike course varies dramatically. The nature of the sport means positional advantage at the start of the race is vital (Macdermid & Morton, 2012). The result is an explosive pace off the start followed by intermittent bursts for 1.5-1.75 h (Stapelfeldt et al., 2004).

The limited research thus far on cross-country mountain bike racing has focused on smoothed data (Stapelfeldt et al., 2004) and terrain (uphill, flat, downhill) averages (Gregory et al., 2007b) with little regard for the oscillating nature of the work demand, particularly the changing ratio of cadence to torque in producing the requisite power. Supra-maximal efforts in short bursts or short rest periods, as required in cross-country mountain biking in order to save time, are not detected if data is smoothed or data collection rates are slow. If this occurs there may be a training over-emphasis on constant intensity work and aerobic capacity. Yet in terms of muscle fibre recruitment and the physiological differences, periods of supramaximal and constant intensity work are important, especially when specificity of stimulus is required for training purposes.

There is a dearth of scientific research regarding the nature of work demand during cross-country mountain bike racing with specific reference to the true physiological/physical requirements of the sport. This thus limits the effectiveness of both the sport scientist and coach in being able to develop and prescribe effective training strategies. Therefore, the aim of this study was to assess the intermittent work demand of a simulated cross-country mountain bike lap performed at race pace in the field with reference to physical and physiological requirements.

We hypothesise that, unlike the consistent work protocols administered in the laboratory to test mountain bikers, in the field, a highly varied work requirement will include significant periods of low cadence, high force during uphill sections and higher cadence low force periods during temporally shorter downhill sections. For this reason, we further hypothesise that a much greater intermittent anaerobic contribution is required during cross-country mountain bike racing than during more traditional cycling disciplines including the first few minutes.

Methods

Participants

Seven male nationally competitive cross-country mountain bike cyclists (mean ± SD: age 23 ± 9 years, height 176 ± 4 cm, mass 66.9 ± 7.7 kg, $\dot{V}O_{2\,max}$ 67.6 ± 5.3 $ml \cdot kg^{-1} \cdot min^{-1}$) were recruited to perform in this study. Prior to participation, all participants provided written consent in accordance with the NZ Central Regional Ethics Committee. Although all participants were well-trained cross-country mountain bike athletes they had no prior experience of the specific tests conducted and as a result undertook a familiarisation period one month prior to testing. Familiarisation entailed riding on a treadmill (TechnoGym, Italy) until comfortable at the different speeds and gradients and riding the cross-country mountain bike course whilst wearing an automated, breath by breath portable gas analyser (Cortex Metamax 3B, Cortex, Biophysik, Leipzig Germany). Time taken to become familiar with treadmill riding was participant dependent but was deemed successful when they could ride as per normal. One participant (not included in any data analysis) pulled out of the study because they were unable to complete this part of the trial.

Laboratory tests

On the initial visit to the laboratory participants were weighed (with and without cycle clothing and the portable gas analyser plus mountain bike with the powermeter (PowerTap, USA) to be used during the trial) and measured (cm). Participants used their own cross-country mountain bikes but all used the same set of wheels (Stans Alpine rims, ZTR front hub and PowerTap rear hub) and tyres (Continent Race King, supersonic 2.2, Ger.). Tyre pressure was adjusted to that preferred by the rider in the field (SmartGauge, TOPEAK, Ger.). They were then allowed a warm-up period (5 mins at 15 $km \cdot h^{-1}$ and 5 mins at 20 $km \cdot h^{-1}$ with the treadmill set at 0 % gradient) which also acted as a re-familiarisation with the test equipment, followed by a sub-maximal test on the treadmill in order to obtain the Power:$\dot{V}O_2$ relationship (Medbo et al., 1988a). This test consisted of three incremental bouts of exercise of 5 min duration at a constant speed of 20 km·h^{-1} whilst treadmill gradient was set at 1, 3, and 5 %. Power output and $\dot{V}O_2$ data was logged every second throughout the trial and averaged along with $\dot{V}O_2$ data over the final two minutes of each stage (Medbo et al., 1988a). This enabled an individual power:$\dot{V}O_2$ relationship to be formed whilst riding their own cross-country mountain bike, which could then be extrapolated to predict O_2 demand (Gastin, 2001; Medbo et al., 1988b) during the field test. Following a 30 min active recovery period a ramp test (starting on 100 W and increasing by 25 W every minute) to exhaustion (Lucia, Hoyos, Perez, & Chicharro, 2000) was performed. During the test, expired gas data were collected continuously, logged every second and averaged over 60 s periods to enable the calculation of $\dot{V}O_{2\,max}$ and respiratory compensation point (Macdermid & Edwards, 2010).

Field Test Trials

Two days after the laboratory trial, participants attended a day at a purpose-built mountain bike course (Pukeora MTB Park, Central Hawkes Bay, NZ) where they completed a re-familiarisation of the XCO-MTB course. All subjects had previously ridden the course on at least three separate occasions. The course was broken down into sections based on terrain (ascent or descent) of which the characteristics are provided (Figure 4.1). Data taken from the Garmin Edge 705, during the trials showed the course length was 7977 ± 68 m in length (CV = 0.85 %) had an ascent of 265.2 ± 3.6 m (CV = 1.34 %) and descent of 250.4 ± 3.4 m (CV = 1.34 %) showing good reliability of the Garmin device.

After a 2-h break (including a light carbohydrate based meal and drink), and following a warm-up matching that performed prior to a competition (individually specific), subjects performed one lap in race conditions with the same cross-country mountain bike as during the laboratory trial, wearing the automated, portable gas analyser and using the portable power meter (data logging every second). They were required to approach the starting straight as normal in a cross-country mountain bike race where athletes work at supra-maximal intensities (Stapelfeldt et al., 2004) to gain positional advantage over opponents.

Power Output (W), cadence (rpm), and speed ($km \cdot h^{-1}$) were continuously sampled and logged every second. Absolute power output (W) data was subsequently analysed to provide relative data with respect to body mass (kg) and total mass (participant and equipment).

Normalization of power output (Allen, 2006) was performed enabling a more direct comparisons with other forms of cycling that are more consistent with regards to the variability of effort (Jobson, Passfield, Atkinson, Barton, & Scarf, 2009) and is calculated as:

$$\text{Normalized Power Output} = \sqrt[4]{\sum (30\text{''moving averages}^4)}$$

Quadrant analysis (Abbis et al., 2006) used in conjunction with a scatterplot of the average effective pedal force and circumferential pedal velocity enables the separation of force-velocity into quadrants and was calculated based on the following equations:

$$\text{Average effective pedal force (N)} = (\text{power output (W)}*60) / (\text{cadence (rpm)}*2*Pi*\text{crank length (m)}))$$

$$\text{Circumferential pedal velocity } (m \cdot s^{-1}) = (\text{cadence}*\text{crank length}*2*Pi/60)$$

Each participants corresponding values for the respiratory compensation point (Macdermid & Edwards, 2010) taken from the laboratory trial was used to separate the force and velocity scatterplot into quadrants (Figure 4.4B) reflecting force-velocity characteristics used during the activity (I: high-force/high-velocity; II: high-force/low velocity; III: low-force/low-velocity; IV: low-force/high-velocity).

Physiological variables continuously sampled and logged every second included $\dot{V}O_2$ ($L \cdot min^{-1}$) and HR (bpm) which, along with power output (W) were analysed with regards to the terrain sections (Figure 4.1).

The $\dot{V}O_2$ and power output data, averaged for each 5” period of the field test and in conjunction with the linear relationship data established via the laboratory test was used to estimate O_2 deficit and subsequently energy system contribution to exercise based on the following calculations:

O_2 *demand = mx + b*

where, m is the slope and b is y-intercept of the power: $\dot{V}O_2$ relationship determined in the laboratory test, and x is the 5” smoothed average of power output measured during the field test.

O_2 *deficit =* O_2 *demand – Actual* $\dot{V}O_2$

Five second averaging was used for this data analysis as it was expected cadences would be relatively low and breathing frequencies high. As power is a function of torque * cadence, shorter data collection periods would mean incomplete pedal revolutions and thus power would be a poor representation of muscular effort.

Statistical Analyses

Data recorded throughout the laboratory and field trials were transmitted to a conventional PC and processed with the Garmin Training Centre, Saris PowerAgent and Metamax 3B software provided with the relevant hardware. Descriptive data (mean, standard deviation (SD)) were calculated for all dependant variables using GraphPad Prism (version 5.0). A two-way repeated-measures ANOVA, with two within-subject variables (terrain and order) were used to test differences between mechanical and physiological responses while a two-way ANOVA was used to assess the effect of terrain on the force-velocity relationship for quadrant analysis. Where an overall significant difference was found the main effect was analysed using Bonferroni post-hoc testing for pairwise comparisons, significance set at $p<0.05$.

Results

Laboratory tests

Table 2.1 shows the participants responses to the sub-maximal and maximal laboratory tests used in the analysis of field data. Manual calibration of the treadmill for this test meant that 'real' speed during the three-stage sub-maximal test was actually 19 km·h^{-1}.

Field tests

The starting straight consisted of a fast tarmac surface of 500 m in length with an average gradient of 2.5 % before feeding into single track off road surface. The time taken to complete this section was 68.5 ± 5.5 s, relating to a mean ± SD power output from a standing start of 481 ± 122 W, 5.9 ± 1.8 W·∑kg^{-1}, or 6.63 ± 1.34 W·kg^{-1}. The mean total O$_2$ deficit incurred during this period equalled 1.58 ± 0.67 L·min^{-1} and resulted in an estimated aerobic (67.6 ± 10.2 %) and anaerobic (32.4 ± 10.2 %) contribution to the work done over the start. Quadratic analysis showed that 82.4 ± 2.6 % of the time during the allocated period was high force of which 86.6 ± 12.1 % was high-force/high-velocity. Figure 4.2 highlights the nature of the aforementioned variables during this short period reflecting a cross-country mountain bike race start.

Over the whole lap the average time equalled 1701 ± 50 s which was characterised by a mean, power output of 243 ± 12 W; 3.00 ± 0.14 W·∑kg^{-1}; or 3.62 ± 0.18 W·kg^{-1}, normalized power output of 279 ± 15 W; 3.5 ± 0.2 W·∑kg^{-1}; or 4.1 ± 0.3 W·kg^{-1}, cadence of 67 ± 5 rpm. Mean distribution of the quadrant analysis of the average effective pedal force and circumferential pedal velocity shows that 57.2 % of time was spent at low velocity (including 20.7 ± 8.3 and 36.5 ± 5.4 % for high-force/low-velocity and low-force/low-velocity, respectively) while 42.8 % was spent at high velocity (including 13.3 ± 6.1 and 29.5 ± 8.2 % for high-force/high-velocity and low-force/high-velocity, respectively) with a high force contribution of 34 % compared to 66 %

low force during cross-country mountain bike racing. An individual participant's quadrant analysis is provided in figure 4.4B.

Absolute $\dot{V}O_2$ for the same periods was 3.45 ± 0.22 $L \cdot min^{-1}$ (77 ± 5 % $\dot{V}O_{2\,max}$), while heart rate was 175 ± 6 bpm (93 ± 2 % of HR_{max}). Figure 4.3 shows how physiological and work variables were distributed (percentage of time) during the field test, highlighting the dissociation of variance between power output and physiological measures over the duration of the trial. This is further highlighted in Figure 4.4 A, showing five second averages for one subject over the entire field test duration.

Comparison between physiological measures during laboratory treadmill cycling (20 $km \cdot h^{-1}$ @ 5% gradient) and cross-country mountain biking in the field (using exactly the same equipment) provided no statistical difference in mean absolute power output (p=0.117, 249 ± 20 vs 243 ± 12 W) or relative $\dot{V}O_2$ (p=0.331), yet HR (161 ± 6 vs 175 ± 6 bpm, respectively) was significantly different (p=0.004).

The lap (Figure 4.1) was composed of eight distinguishable sections which were predominantly ascent (range 127-281 s) or descent (range 62-293 s). Two-way repeated-measures ANOVA analysis of section specific data (Figure 4.1, Table 2.2) highlights the difference between terrain with regards to order within the lap. As expected there is a significant interaction between terrain and order for all variables measured. Further analysis of power data for terrain indicated that mean distribution of the quadrant analysis of the average effective pedal force and circumferential pedal velocity whilst ascending indicated that greater time was spent in high-force/low-velocity (29.2 ± 12.2 %) compared with high-force/high-velocity (16.3 ±9.3 %) but with more overall time spent in the low-force/low-velocity and low-force/high-velocity (25.1 ± 8.4 vs 29.5 ± 11.4 %) respectively. Conversely, distribution of time for descending showed the majority of time was spent in low force pedalling (low-force/low-velocity (49.3 ±

4.7 %) and IV (35.4± 6.0 %), while high force pedalling made-up 10.4 ± 4.9 and 11.5 ± 6.8 % for high-force/high-velocity and high-force/low-velocity, respectively. Two-way ANOVA indicates an overall interaction between quadrant and terrain ($p<0.001$) with no overall effect of terrain ($p=0.353$) but an effect of quadrant ($p=0.002$). Post-hoc analysis only showed significant differences for terrain for high-force/low-velocity (29.2 ± 12.2 vs 11.5 ± 6.8 %, $p<0.05$) and low-force/low-velocity (25.1 ± 8.4 vs 49.3 ± 4.7 %, $p<0.001$).

Terrain is not only defined by a change in gradient but can also include negotiation of corners and/or obstacles. Such occurrences are often met with decelerations and accelerations, resulting in surges of power output. Figure 4.5 shows the mean ± SD number of surges that occurred during the simulated lap at race pace. This equated to a mean total for all subjects of 53 ± 5 surges (3 consecutive readings). Due to the nature of the terrain it is hard to surmise the regularity of such efforts required by cross-country mountain bike athletes but it does relate to one surge every 32 s and 1 supra-maximal effort every 106 s.

With such an intermittent nature to the sport, estimated energy system contribution via oxygen deficit indicates a mean ± SD of 94.0 ± 1.2 and 6.0 ± 1.2 %, $p<0.001$ for aerobic and anaerobic contribution to work done. Analysis of terrain data indicates no difference ($p>0.05$) between aerobic contribution for ascending (93.7 ± 3.0 %) and descending (96.0 ± 2.4 %), while a significant difference was found between anaerobic contribution ($p<0.05$) for ascending (6.4 ± 3.0 %) and descending (3.2 ± 1.8 %).

Discussion

This investigation set out to assess the mechanical work and physiological responses to a simulated cross-country mountain bike, race paced lap. The main findings were: (a) power output and cadence constantly oscillate during cross-country mountain bike racing, predetermined by terrain. (b) Low velocity pedalling constitutes the majority of cross-country mountain bike racing with a large contribution of high force-low velocity muscular contraction; (c) cross-country mountain biking is predominated by the requirement of a well-developed aerobic capacity but key movements of the sport emphasize a high demand on anaerobic energy provision; (d) cross-country mountain bike courses have distinguishable sections in terrain profile but athletes are not afforded the same nature of recovery as road cyclists, emphasized by physiological variables remaining high.

In setting out to simulate a race start, all subjects were asked to approach the designated starting straight with an effort similar to that which they would make in a race. Although impossible to simulate the physical drive for positional advantage, it was felt due to the supramaximal power outputs obtained (Figure 4.2 A-B), that all athletes approached this section as requested. Consequently, work completed over the first minute of the field test produced supra-maximal power outputs (greater than the power output associated with $\dot{V}O_{2\,max}$) by way of high force-high velocity muscular power, resulting in a large anaerobic energy contribution. Figure 4.2 (C-D) profiles the physiological implications of the simulated start. The mean energy system contributions over this comparatively short time period agreed with previous findings with regards to one off, all-out efforts and time scales (Gastin, 2001). However, in the sport of cross-country mountain bike racing, athletes are required to continue for at least a further 90 mins making the sport unique in events of this duration.

Investigations into optimal pacing strategies for performance in events lasting less than 2 minutes indicate that an all-out strategy produces the best performances (Bishop, Bonetti, &

Dawson, 2002; De Koning, Bobbert, & Foster, 1999) with slightly longer events (4,000 m pursuit cycling) following a pattern of all-out effort for the first 12 seconds followed by an even pace thereafter as per Figure 4.2A (Aisbett, Rossignol, & Sparrow, 2003; De Koning et al., 1999). Even short (800 kJ) time trials have supported a constant pacing strategy (Atkinson, Peacock, & Law, 2007), and as a result it would be easy to suggest that such strategies employed by cross-country mountain bikers (Stapelfeldt et al., 2004) and used in this study could be detrimental to performance. However, our analysis of male competitors (n=79) during the 2010 World Championship showed that even though this strategy is used, mean individual CV ± 95 % CI of lap times amongst well trained athletes was 1.93 ± 1.43 %. It must also be remembered that in this instance we are investigating a race not a time trial, and the rules which confine the sport mean that positional advantage from the start could outweigh the negative effects from initially working too hard (Macdermid & Morton, 2012). Data reported in table II reveals that although participants engaged supra-maximal effort from the start (to gain positional advantage into the single track, Figure 4.2), a more sustainable effort ensued.

Taking the whole lap average data into consideration, absolute power output data (243 ± 12 W) and % HR_{max} data (93 ± 2 %) are very similar to those previously reported (Impellizzeri et al., 2002; Stapelfeldt et al., 2004) in elite national athletes during a number of complete cross-country mountain bike races. However, this study did produce slightly lower (77 ± 5 %) values compared with estimations of % $\dot{V}O_{2\ max}$ (84 ± 3 %) made previously (Impellizzeri et al., 2002). Such small discrepancies could easily be due to course characteristics which might affect the ability of the subjects to maintain work rate during sections of the course. Also, the previously reported data was taken from actual races which may have an additive (psychological) effect on slightly higher physiological values derived from HR . The very low SD's around the means for the aerobic and anaerobic contribution to the complete lap indicate homogeneity for the demands of this particular course and form of racing.

When the raw power outputs are converted to normalized power data from this study is similar to criterium road race data and is subsequently similar to the constant power output of a flat time-trial. Such data agrees with the use of normalized power rather than mean power to make cross comparisons between cycling disciplines or training sessions (Jobson et al., 2009). However, the manner in which the work was completed could be of the upmost importance and will determine the specificity of stimulus for training requirements. An example of this, that requires further investigation is the quadrant analysis data that highlights a large component of high force-low velocity muscle contraction suggesting strength maybe more important for cross-country mountain bike athletes in order to negotiate terrain compared to other cycling disciplines.

Figure 4.3 C-D emphasizes the large variation in both power output and cadence over the course of a cross-country mountain bike lap which is underlined by the spread of the mean distribution of the quadrant analysis of the average effective pedal force and circumferential pedal velocity (individually represented, Figure 4.4B) . In contrast, % HR_{max} and to a lesser extent % $\dot{V}O_{2\,max}$ show much less variation (Figure 4.3 A-B). An explanation for such a difference between mechanical and physiological variation can be explained partly, due to a muscle-lung vascular transit delay pushing the rising phases of short bursts of effort into recovery phases or in this case blunting the response of lower power output bouts (Hurst & Atkins, 2006; Turner et al., 2006). The effects of downhill cross-country mountain biking on the dissociation between power output and HR have been attributed to increased energy demands of movements not associated with pedalling but rather negotiating the course (Gregory et al., 2007a; Stapelfeldt et al., 2004). The separation of the data into terrain sections (Figure 4.1) identifies a significant difference between the start phase of the lap (hill 1) with hills 2, 3 and 4. Overall, power output decreased in subsequent climbs, which is not unexpected considering the quest to gain positional advantage from the start. However, HR increased while $\dot{V}O_2$ remained relatively unchanged following hill 1.

Laboratory studies regarding constant power outputs (>LT) and O_2 kinetics have showed consistently that there is no achievement of an early steady state after 3 minutes with $\dot{V}O_2$ continuing to rise until exercise is terminated or exhaustion supervenes (Barstow & Mole, 1991; Roston et al., 1987). In the case of this field study it is possible to suggest that participants arrived at the pinnacle of the first climb prior to exhaustion, allowing them to continue at a pace that would enable completion of race distance (1.5-1.75 h).

The fact that there was no decrease in $\dot{V}O_2$ but an increase in HR suggests that recovery was inadequate adding to the reduced oscillatory effect of power on heart rate and to a lesser extent $\dot{V}O_2$. This is supported by previous studies into repeated bouts of high intensity rowing and HR kinetics (Mavrommataki, 2006) where 1.5 and 3 minutes recovery was not deemed sufficient in order to maintain power output over 1000 m bouts of rowing. Whereas, laboratory studies have used constant load tests to demonstrate the slow component $\dot{V}O_2$, the data presented here shows dissociation between a declining power output, $\dot{V}O_2$, and heart rate, and thus mimics the inverse of such trials. While the changes in both HR and $\dot{V}O_2$ are minor it does suggest either a probable reduction in stroke volume, or in oxygen extraction at the muscle but the latter is unlikely. Feasible explanations for such occurrences could also be linked to the effect downhill terrain could have on the sympathetic nervous system. It is possible that increased catecholamine responses could drive HR up, above what is necessary in terms of oxygen delivery. Alternatively, increased thermal load may drive up cardiac output to increase skin blood flow, producing a HR above that which is necessary in terms of O_2 delivery to the working muscles (Périard, Cramer, Chapman, Caillaud, & Thompson, 2011).

In addition the explanation is compounded by the course characteristics used in this study and potentially all cross-country mountain bike courses. Figure 4.1 highlights some of the potential issues regarding the classification of sections with regards to length, overall ascent and descent, mean gradient and the number of directional changes. Visual inspection of the data indicates that sections 1-2 and 7-finish are downhill overall but also contain a large number of directional changes along with a proportionally high gain in altitude when compared with the hill sections. Such characteristics will influence the interpretation of overall terrain characteristics and their effects on physiological measures. Likewise, exercising at a power output shown to elicit 60 % $\dot{V}O_{2\,max}$ or reporting such a mean power output does not reflect the intermittent demands of cross-country mountain bike racing or the capabilities of athletes taking part. Gear selection and cadence are almost certainly influenced by the gradient of slope, changes in direction, and overcoming obstacles, and thus consequently cause large fluctuations in torque (Gregory et al., 2007a) and work rate. The course used in this study (Figure 4.1) had equal ascent and descent and thus time spent climbing was greater. Interestingly, the total number of changes in direction of 127 was not split evenly as there were 53 changes in direction ascending and 74 descending. This could have led to fewer power surges (Figure 4.5) as determined by the software (PowerAgent, Cycle Ops, USA) which determines a surge in power as a value lasting >3 s. Again, even with the use of such software there is the potential to underestimate the erratic nature of the sport which seems to have more in common with game sports than road race cycling. Participation in elite cross-country mountain bike racing, like such sports may be dependent on a high aerobic capability of the athlete (Impellizzeri, Marcora, et al., 2005) but it is likely that supramaximal intensities and all out surges are critical in deciding the result. The sport of cross-country mountain bike racing may be dominated by the aerobic energy system but it is potentially not the defining aspect of performance.

The use of estimating energy system contribution to exercise via oxygen deficit has previously been used in single bout exercise periods (Bishop, 2000; Gastin, 2001). However, issues regarding the changing linear relationships between power and $\dot{V}O_2$ for repetitive bouts of maximal exercise are unknown. Changes in the slope and Y-intercept of such a relationship with fatigue could potentially lead to a minor underestimation of anaerobic contribution to subsequent bouts. Even so, Figure 4.5 highlights the fact that there is a greater emphasis of anaerobic energy utilization during sections of the course that are predominantly ascending compared with descending as would be expected.

Conclusion

The results of the present study illustrate that the mechanical work performed and the physiological responses of cross-country mountain bike racing are discontinuous as a result of changes in terrain and course features. As a result cross-country mountain bike racing is predominated by high force-low velocity pedalling during ascent and combined with a high oscillating work rate necessitates high aerobic energy provision, with intermittent anaerobic contribution. Additional stress during downhill sections affords less recovery seen in other cycling disciplines, emphasised by non-variable physiological values in relation to terrain.

Practical Implications

The following are practical recommendations for athletes and coaches working with XCO-MTB athletes:

> Firstly, raining prescription should consider the importance of the interaction of energy system(s) development to a high level. A high aerobic capacity is essential but will almost certainly need to be trained in a different manner to the current practises of road cyclists taking into account the force-velocity relationship.
>
> Secondly, athletes must be accustomed to climbing for extended periods at intensities greater than 90 % $\dot{V}O_{2\,max}$ with supra-maximal surges and immediately be able to negotiate technical descents at high speed while under physiological stress.
>
> Lastly, cross-country mountain biking requires a large strength component compared to other cycling disciplines. For that reason athletes and coaches should be conscious of the need to perform short duration, high intensity efforts with cadences below 80 rpm.

Tables

Table 2.1. Laboratory test characteristics of the subjects (n=7) for the sub-maximal treadmill test and the maximal ergometer test. Where results are given per kg this refers to total weight of the individual subjects clothing, bike plus powermeter and the portable gas analyser.

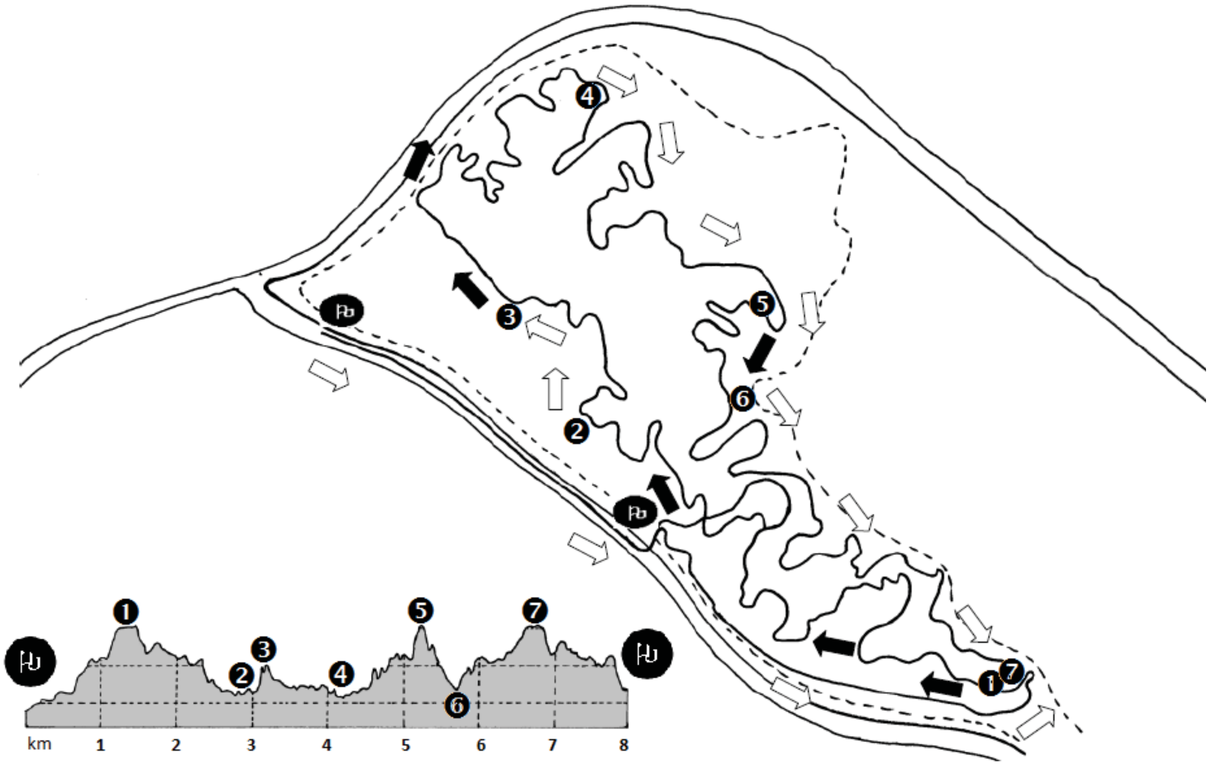
	19 km·h^{-1} @ 1%	**19 km·h^{-1} @ 3 %**	**19 km·h^{-1} @ 5 %**	**Max data were applicable**
Power Output (W)	92.3 ± 8.5	173.1 ± 13.7	249.1 ± 20.3	405.5 ± 31.3
Power Output (W·∑kg^{-1})	1.16 ± 0.08	2.20 ± 0.03	3.14 ± 0.06	5.26 ± 0.27
Cadence (rpm)	73 ± 5	76 ± 4	78 ± 5	N/A
$\dot{V}O_2$ (L·min^{-1})	1.52 ± 0.15	2.39 ± 0.23	3.25 ± 0.30	4.39 ± 0.59
$\dot{V}O_2$ (ml·∑kg^{-1}·min^{-1})	19.4 ± 1.0	30.4 ± 0.9	41.4 ± 0.8	56.8 ± 6.0
HR (bpm)	111 ± 8	134 ± 12	156 ±11	188 ± 4

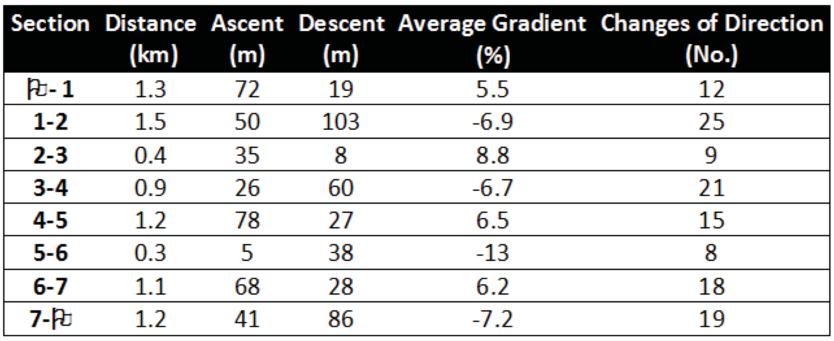
Table 2.2. Mean ± SD for performance, mechanical and physiological measures sampled throughout the field trial and separated based on terrain (hill (H) and downhill (DH)) and order as depicted in Figure 1.

	Hill 1	DH 1	Hill 2	DH 2	Hill 3	DH3	Hill 4	DH 4	Two-Way ANOVA
Time (s)	262.0±11.5	293.0±11.0	127.0±14.4	155.0±18.4	281.0±17.1	62.0±14.0	253.0±22.5	241.0±9.6	***; ###; †††
Power (% W_{max})	81.0±4.2	48.4±1.7	72.0±6.7	37.4±3.2	66.2±4.2	25.6±2.9	64.2±2.9	48.4±3.6	**; ###; ns
Cadence (rpm)	75.4±5.5	58.4±3.7	74.6±6.5	54.8±5.0	78.2±5.9	48.6±7.6	74.0±7.5	57.2±6.1	*; ###; ns
% $\dot{V}O_{2\,max}$	80.7±3.5	76.6±4.4	81.7±6.1	71.2±4.9	79.4±7.1	67.6±7.3	77.8±7.5	72.2±6.7	**; ns; †††
% HR_{max}	90.4 3.2	90.8±3.0	94.4±2.2	91.0±2.9	95.4±1.7	91.2±3.0	94.8±1.8	92.2±2.8	***; ###; †††

*** ($p<0.001$); ** ($p<0.01$); * ($p<0.05$) the interaction between the terrain (hill or downhill) and the order (1-4). ### ($p<0.001$); ns ($p>0.05$) signifies whether the occurrence of terrain with the lap affects the result. ††† ($p<0.001$); ns ($p>0.05$) tests the difference between the terrain (hill vs downhill).

Figures





Section	Distance (km)	Ascent (m)	Descent (m)	Average Gradient (%)	Changes of Direction (No.)
⚐- 1	1.3	72	19	5.5	12
1-2	1.5	50	103	-6.9	25
2-3	0.4	35	8	8.8	9
3-4	0.9	26	60	-6.7	21
4-5	1.2	78	27	6.5	15
5-6	0.3	5	38	-13	8
6-7	1.1	68	28	6.2	18
7-⚐	1.2	41	86	-7.2	19

Figure 4.1: Course outline for the XCO-MTB lap used during the study. Where ⚐ indicates start and finish, ⇨refers to a climb and ➔ signifies a descent. Numbers encircled 1-7 on the map are related to climbs or descents highlighted on the schematic profile of the course. Section characteristics are provided in the table below the schematic profile.

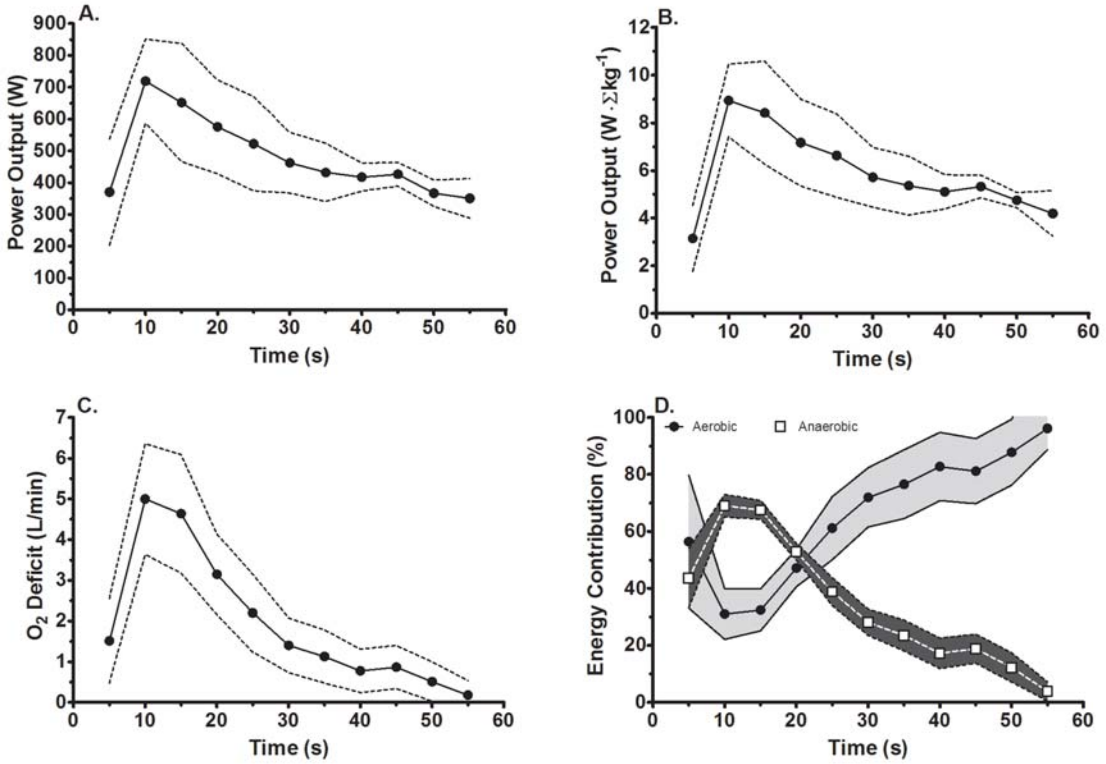


Figure 4.2: Data recorded (Mean ± SD) over the start straight and averaged every 5 s. A. Power output profile (W), B. Power output profile ($W\cdot\sum kg^{-1}$), C. Oxygen deficit ($L\cdot min^{-1}$), and D. Estimated aerobic and anaerobic contribution to work done (%).

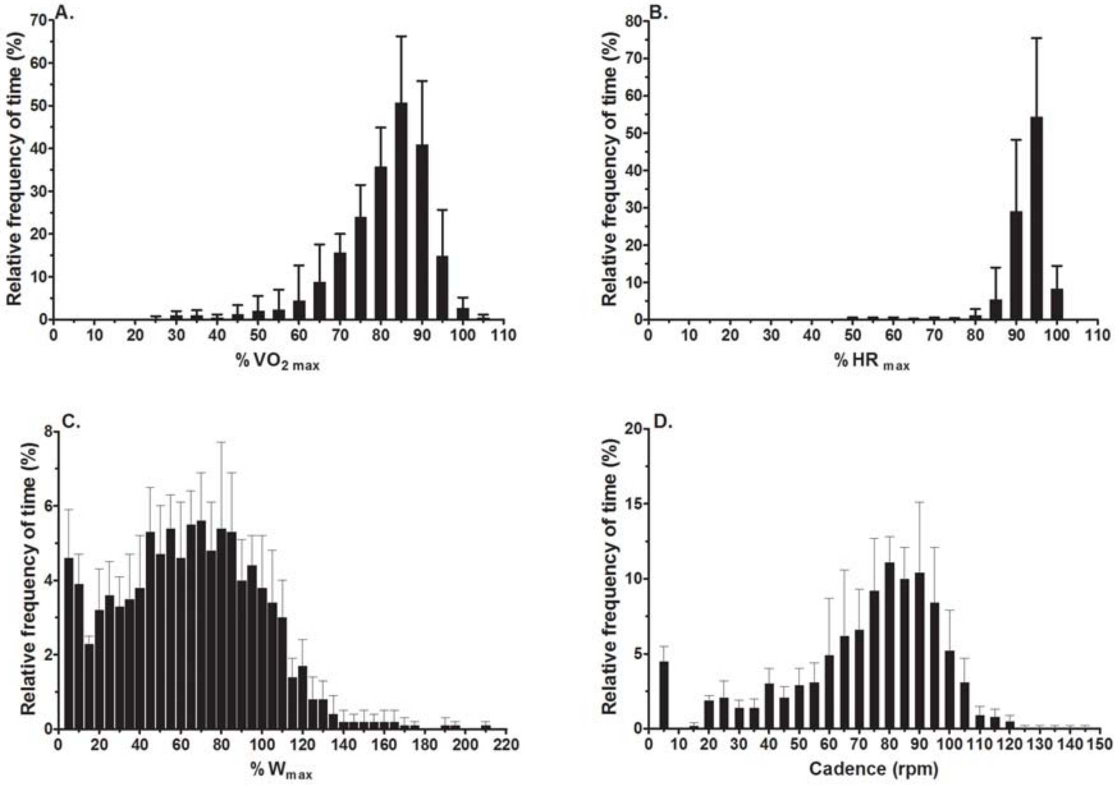


Figure 4.3: Frequency distribution (mean ± SD) for physiological variables during the field test represented as percentages of maximum from laboratory tests for A. % $\dot{V}O_{2\,max}$; B. % HR_{max}; and work variables C. % W_{max}'; and D. Cadence (rpm).

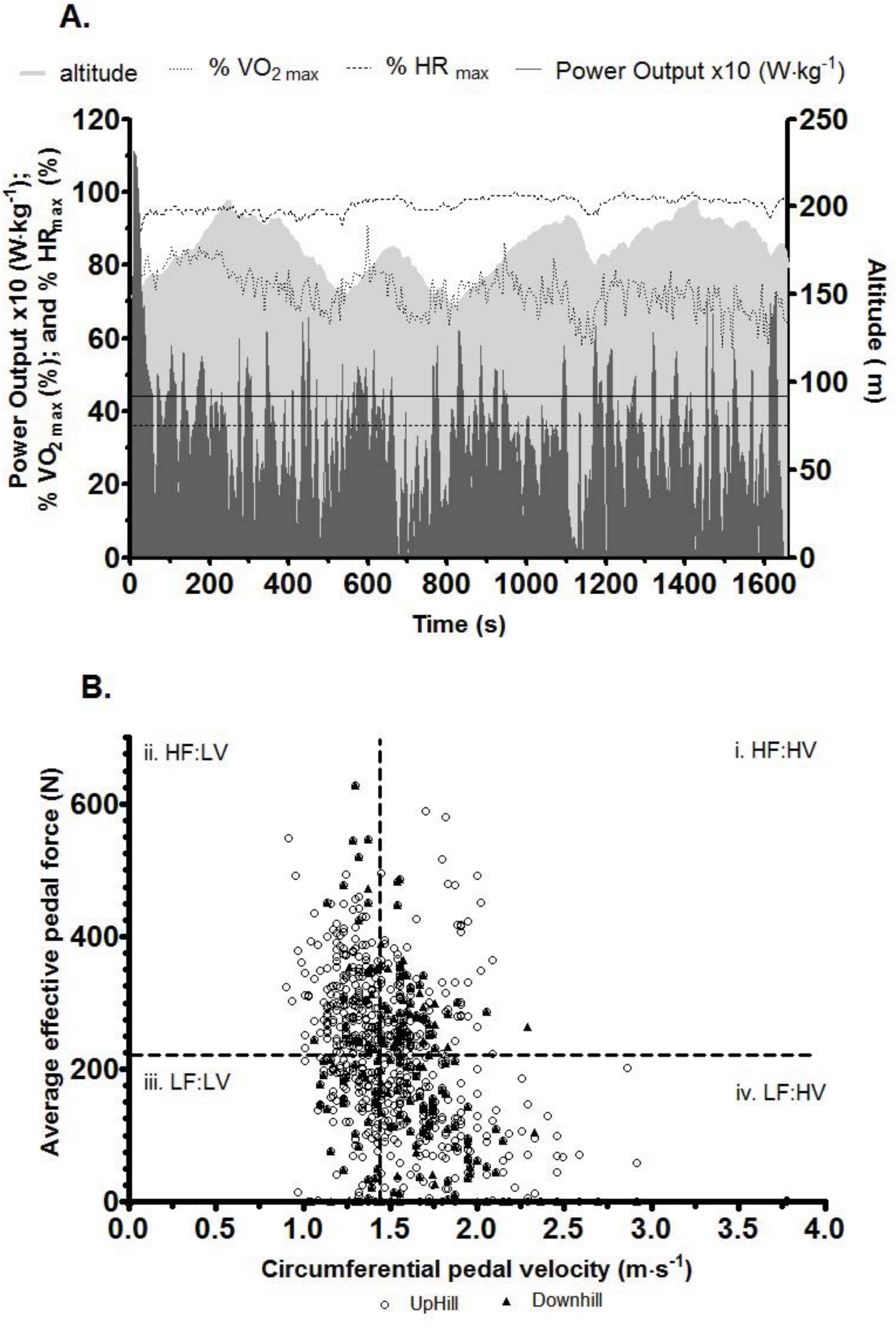


Figure 4.4: An individual subjects data over the whole lap for: **A.** Altitude (m), power output (W·kg^{-1}), % $\dot{V}O_{2\,max}$, and % HR_{max} averaged over 5 s periods for the whole field test duration, with the average power (horizontal dashed line) and normalized power (horizontal solid line); **B.** Quadrant analysis separated by the mean effective pedal force and circumferential velocity of that subject, at respiratory compensation point from laboratory test and indicating the difference between hill and downhill sections.

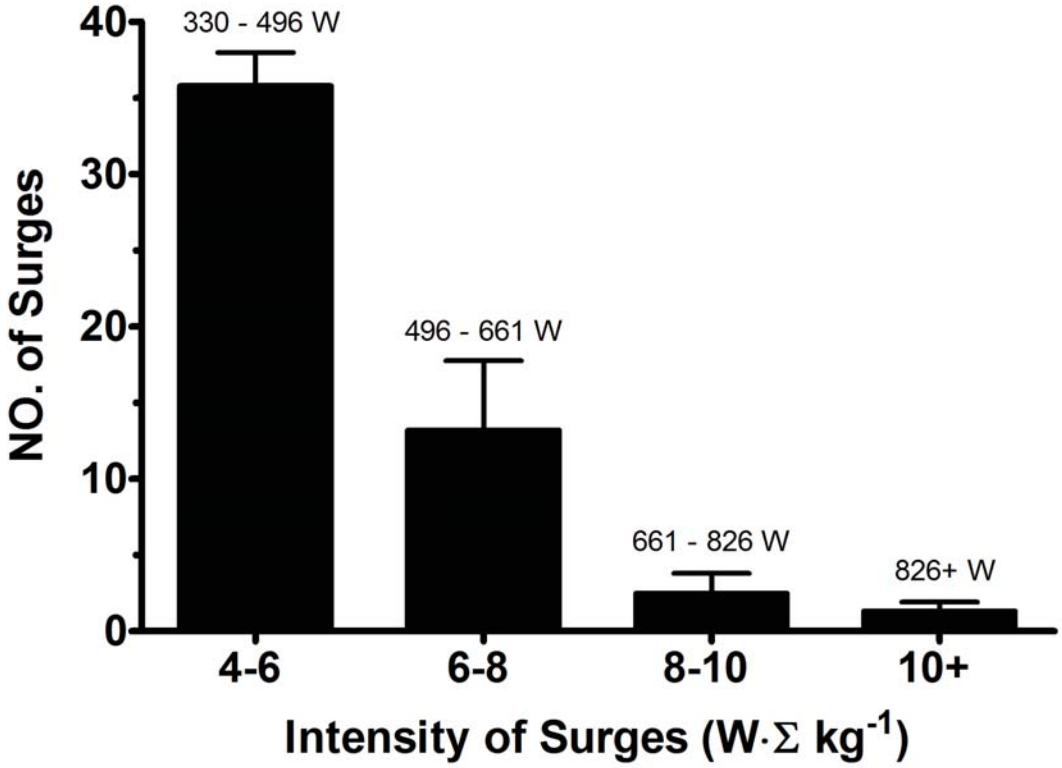


Figure 4.5: Mean SD surge analysis for subjects (n=7) over the whole lap and based on total weight of subject, bike and gas analyser.

CHAPTER FIVE: STUDY TWO

TRANSFERANCE OF 3D ACCELERATIONS DURING CROSS-COUNTRY MOUNTAIN BIKING.

Paul W. Macdermid, Philip W. Fink, Stannard R. Stephen.

The following paper has been submitted and published in the *Journal of Biomechanics* and prepared according to their guidelines. For evidence of publication and statement of contribution to doctoral thesis see Appendix 2.

Abstract

Investigations into the work demands of Olympic format cross-country mountain biking suggest an incongruent relationship between work done and physiological strain experienced by participants. A likely but unsubstantiated cause is the extra work demand of muscle damping of terrain/surface induced vibrations. The purpose of this study was to describe the relationship between vibration mechanics and their interaction with terrain, bicycle and rider during a race pace effort on a cross-country mountain bike track, on both 26” and 29” wheels. Participants completed one lap of a cross-country track using 26” and 29” wheels, at race pace. Power, cadence, speed, heart rate and geographical position were sampled and logged every second for control purposes. Tri-axial accelerometers located on the bicycle and rider, recorded accelerations (128 Hz) and were used to quantify vibrations experienced during the whole lap and over terrain sections (uphill and downhill). While there were no differences in power output ($p=0.3062$) and heart rate ($p=0.8423$), time to complete the lap was significantly ($p=0.0061$) faster on the 29” wheels despite increased vibrations in the larger wheels ($p=0.0020$). Overall accelerometer data (RMS) showed location differences ($p<0.0001$), specifically between the point of interface of bike-body compared to those experienced at the lower back and head. The reduction in accelerations at both the lower back and head are imperative for injury prevention and demonstrates an additional non-propulsive, muscular, challenge to riding. Stress was greatest during downhill sections as acceleration differences between locations were greater when compared to uphill sections, and thus possibly prevent the recovery processes that may occur during non-propulsive load.

Keywords: Mountain biking; Accelerations; Vibrations; Damping; Field testing

Introduction

Work demand during Olympic format cross-country mountain biking (XCO-MTB) does not reflect the physiological strain experienced by participants (Stapelfeldt et al., 2004). Explanations focus on non-pedal related work (Hurst & Atkins, 2006), which could include terrain induced vibration damping.

Bicycling is considered a non-impact sport (Stewart & Hannan, 2000) yet mountain bikes are subjected to vibrations (De Lorenzo & Hull, 1997; Faiss et al., 2007; Levy & Smith, 2005) which the bicycle-body must dissipate before the accelerations reach the central nervous system (Samuelson et al., 1989). As such, XCO-MTB has shown to provide a significant osteogenic effect compared to road cycling (Warner, Shaw, & Dalsky, 2002) but non-pedal related work such as that required to dampen energy from vibrations in XCO-MTB is not yet well quantified and could indirectly influence the total work done and thus performance in a race situation.

The majority of load components occurring at the bicycle level during off-road cycling have been shown to occur at <50 Hz (De Lorenzo & Hull, 1997; Levy & Smith, 2005). Higher frequencies have been found at the wheel itself, but these frequencies were not present at the interface with the rider (Levy & Smith, 2005) . The high frequency vibrations (25 -25,000 Hz) are associated with wheel rotations and tread configuration and are absorbed by the bicycle (Levy & Smith, 2005), and soft tissue at the point of interface (Issurin, 2005). Although this may occur in XCO-MTB it is likely that there will be many rapid and variable changes in track surface adding to the work required of the bike-body damping mechanisms. Alternatively, low frequency vibrations (<25 Hz) are less likely to be dealt with by the bicycle and are more difficult for the body to deal with as the frequency which propagates through contracted or stretched muscle is within the range of resonance reported for whole body (Mester et al., 1999) and individual muscles directly related to propulsion during cycling (Wakeling et al., 2002). Such vibrations are reported to increase muscle activity, a result of dampening, and increase motor unit involvement for a given production of muscle force (Mester et al., 1999) and thus decrease overall efficiency. Laboratory work placing cycle ergometers on vibration platforms (20 Hz, amplitude of 1.8 mm) decreased time to exhaustion by 21 % (Samuelson et al., 1989) while a novel study involving a bump simulator (bumps were 30 and 70 mm) for mountain bikes (Titlestad et al., 2003) showed that at frequencies of 2.9-4.0 Hz oxygen cost and heart rate increased by 50% and 35 %, respectively (Titlestad et al., 2006a). The addition of bumps in such trials, whether realistic or not, highlights the increased work demand as a result of vibration or shocks in XCO-MTB. These findings are supported by the addition of suspension systems to bikes with regards to comfort, economy, and performance (Nishii et al., 2004), with subsequent decreases in vibrations or shocks at the saddle level (Faiss et al., 2007). Even with these technological improvements, it is has been shown that the rider's upper body will perform significant work (Hurst et al., 2012), potentially due to bike handling and the damping of vibrations. Nevertheless, there is little empirical description of the transference of energy from the terrain surface to bike to human during XCO-MTB.

While traditionally XCO-MTB have used 26" wheels, the last few years has seen the introduction of 29" and 27.5"wheels. At the 2012 Olympic Games wheel size distribution amongst the top 10 males and females combined, equated to 70; 25; and 5 % for 29", 26" and 27.5" wheels respectively. It has been suggested that wheel diameter reduces vibration in any format (Wilson, 2004). A statement endorsed by industry led promotions claiming greater performance and a smoother ride and thus overall performance gain.

The primary aim of this study is to describe the frequency-magnitude relationship, the amplitude of accelerations and the interaction between the terrain, bicycle and rider during a typical XCO-MTB race lap whilst using 26" and 29" wheels. We hypothesised that accelerations experienced at the head and lower back will be significantly less than those at the bicycle and limbs, that the accelerations will be different for uphill and downhill riding, and that 29” wheels will dampen vibrations to a greater extent than 26” wheels.

Methods

Participants

Eight nationally competitive XCO-MTB athletes (mean ± *s*: age 25 ± 11 years, height 178 ± 12 cm, mass 63.0 ± 9.0 kg) performed a laboratory ramp style test commencing at 100 W and increasing by 25 W per minute (W_{max} 419 ± 68 W or 6.6 ± 0.2 $W \cdot kg^{-1}$, HR_{max} 197 ± 8 bpm) participated in this study. All participants provided written consent in accordance with the University Human Ethics Committee.

Field Test Trials

Participants attended a day at a purpose-built mountain bike course (Kohitere Forest, Levin, NZ) completing a re-familiarisation of the XCO-MTB course to be used. The course was broken down into sections based on terrain (Figure 5.1).

Participants were required to perform one lap of the course under two conditions (26” and 29” wheels), separated by 15 minutes to allow recovery. Because we wanted to quantify the accelerations during realistic conditions, participants were instructed to ride at race pace which has been previously reported at about 90 % HR_{max} (Impellizzeri et al., 2002). Each condition involved participants riding the same bicycle (GT Zaskar elite 29” hard tail, Optimized Force Constructed Carbon, USA), adjusted to personal requirements prior to the trial, and thus controlling posture, but fitted with either 26” or 29” wheels (X430 and X470, 32H, DT Swiss, CH.). By using the same frame built for 29” wheels the bike handling properties could have been compromised. However, mechanical trail, seen as a major determinant of a bicycles handling properties (Wilson, 2004), only differed by 10 mm and was unnoticed by participants.

Conditions were performed in a counter balanced order to prevent any order effect on the dependent variables of interest.

Outcome measures

Power output (W), cadence (rpm), speed ($km \cdot h^{-1}$), and heart rate (bpm) were continuously sampled and logged every second (SRAM QUARK S2275 MTB Power Meter, USA; Garmin, Edge 500, USA) in order to make comparisons between conditions for work done and physiological strain when comparing performance time (s). This powermeter system has a reported accuracy ± 1.5 % (Aguilar et al., 2008). However, factory recommended zero offset and factory slope settings were checked prior to use (*http://qalvin.quarq.com/slope.html#cs)*. Data recorded from the power meter, heart rate monitor transceiver and GPS device were transmitted to a conventional PC for processing.

Wireless, tri-axial accelerometer, magnetometers and gyroscope with a reported accuracy $0.0012\ m \cdot s^2 \cdot \sqrt{Hz^{-1}}$ (Emerald, APDM, OR, USA), were used in a synchronised data logging mode to measure accelerations in accordance with the International Standards (ISO 2631-1) for measuring vibrations (Iso, 1997). Use of accelerometers to measure vibrations on the human has been validated (Coza et al., 2010) and the Emerald accelerometers have been validated as a method for measuring vibrations (Carr, Meyen, Domingues, Newman, & Jacobs, 2012).

The accelerometers were placed on the handlebar centre; lower left arm (frontal distal position); left lower leg (frontal, distal position); seat post (within 10cm of saddle-rider contact area); lumbar region of lower back; and medial forehead (Figure 5.2). Based upon the positioning of accelerometers and the understanding that all excitations at the bike-body interface occurs at <50 Hz for off-road cycling (De Lorenzo & Hull, 1997; Faiss et al., 2007; Levy

& Smith, 2005; Wilczynski & Hull, 1994) accelerometers were sampled at 128 Hz, logged, transmitted to PC, converted to .h5 file and processed using MATLAB R2011b.

All data were analysed for total (XYZ), vertical (Z-axis), and horizontal (X- and Y- axis) accelerations. Root mean squares of accelerations were calculated to quantify the amount of vibration the participants experienced (Iso, 1997). A spectral analysis was also performed using a fast Fourier transform to examine the frequency of vibrations, and five measures were used for statistical analysis: 1) half frequency, the frequency at which half the total power was below the frequency, which quantified whether the accelerations were high or low frequency; 2) maximum frequency, the frequency at which the maximum amplitude was observed; and 3) maximum magnitude, the magnitude at that frequency. To separate the voluntary movements of the body or bicycle from the vibrations, maximum frequency and maximum magnitude were analysed at low frequency (<5 Hz), which contains the voluntary movements (in addition to vibrations), and high frequency (>5 Hz), which contains vibrations and physiological tremor. These values were chosen because previous research has indicated that 5 Hz is an upper limit for voluntary movements (Hines, O'hara-Hines, & Brooke, 1987; Jäncke, Steinmetz, Benilow, & Ziemann, 2004; Kay, Saltzman, & Kelso, 1991). This cut-off would also preserve the first two harmonics for a cyclist pedalling at 150 rpm, which was faster than the maximum cadence for any of the participants. Thus, the high frequency represents vibrations, while the lower frequency contains both vibrations and voluntary movement (e.g. pedalling).

Statistical Analysis

Descriptive data (mean and standard deviation) were calculated for all dependent variables and compared by paired Student's *t*-tests. A two-way repeated-measures analysis of variance (ANOVA), with two within-subject variables (terrain and wheel size) was used to test differences between time (s), power output (W), cadence (rpm) and heart rate (bpm) in order to assess performance variations between trials.

Accelerometer data comparisons were made via univariate analysis of variance (three-way ANOVA), including within-subject variables, wheel size, terrain and accelerometer location, tested for main effects and interactions (wheel size*Terrain*Location; wheel size * terrain; wheel size * accelerometer location; and terrain * accelerometer location) for variables maximum frequency and maximum magnitude for <5 Hz and >5 Hz.

Analysis of RMS included separate three-way ANOVA analysis, within-subject variables: wheel size, accelerometer location and axis (vertical and horizontal), tested for main effects and interactions (wheel size*Terrain*Location; wheel size * axis; wheel size * accelerometer location; and axis * accelerometer location).

Where an overall significant difference was found the main effect was analysed using Bonferroni post-hoc testing for pairwise comparisons. All statistical analyses were performed using IBM SPSS Statistics 20, significance set at P<0.05.

Results

Performance analysis

Participants were asked to complete a lap of the XCO-MTB course under two conditions (26" and 29" wheels) at race pace (self-determined). Although, paired Student's *t*-tests showed no significant differences were found for overall power output (245 ± 31 and 244 ± 38 W, $p=0.3062$) and heart rate (165±11 and 165±10 bpm, $p=0.8423$), overall time proved to be significantly slower on the 26" compared to the 29" wheels (635.4 ± 41.5 vs 616.6 ± 49.2 s, $p=0.0061$), respectively. Terrain categorisation data (Table 3.1) showed no interactions for wheel size * terrain ($p=0.9202$; $p=0.8899$; $p=0.9090$) for time, power and heart rate respectively. As expected there was significant differences for within-subject variable, terrain, when comparing time ($p<0.0001$), power output ($p<0.0001$), and heart rate ($p=0.0477$) but not for wheel size ($P>0.05$).

Accelerometer data

Three-way ANOVA analysis of total acceleration amplitude (RMS) showed that there was a significant main effect for wheel size ($F_{(1,168)} = 10.079$; $P=0.0020$), axis ($F_{(1,84)} = 1308.191$; $P<0.0001$) and accelerometer locations ($F_{(5,56)} = 301.72$; $P<0.0001$) plus an interaction ($F_{(1,168)} = 67.121$; $P<0.0001$) between axis (vertical and horizontal) and accelerometer location (Figure 5.3). Figure 5.4 A-F shows the terrain effect on accelerations for total, vertical and horizontal axis for each accelerometer location. Three-way ANOVA showed significant differences ($P<0.001$) for the total, vertical and horizontal accelerations for the main effects of terrain and accelerometer location. There was also a significant terrain*location interaction ($P<0.001$). Post-hoc analysis identified differences between downhill sections, between uphill and downhill section but not between uphill's.

Power spectra for all six accelerometer locations for a single participant using 26 inch wheels are shown in Figure 5.5. Overall, the power was much higher, particularly at high frequencies, in the downhill sections. Only the head and back locations showed accelerations similar to that seen in uphill riding, indicating the vibrations entering the bicycle were damped before reaching these parts of the bodies. In the uphill sections there is a low frequency (<2 Hz) spike in the leg acceleration, which was caused by the pedalling motion. Power spectra for all seven participants can be found in the supplementary material.

Results for vertical accelerations of frequency bandwidths (<5 Hz and >5 Hz) for wheel size, accelerometer location, and terrain section, expressed as mean ± SD, for maximum frequency, magnitude at maximum frequency are shown in Tables 3.2-3.3. Table 3.4 includes half frequency data (non-frequency banded) for wheel size, terrain and accelerometer location. Figure 5.5 illustrates an individual subject spectral analysis for vertical acceleration of each accelerometer location, and separated for terrain.

There were significant main effects for wheel size ($F_{(1,168)} = 4.378$, $P=0.037$ for <5 Hz frequency band but not >5 Hz, $F_{(1,168)} = 1.412$, $P=0.234$), accelerometer location ($F_{(5,56)} = 84.738$, $P<0.001$; $F_{(5,56)} = 95.221$, $P<0.001$) and terrain ($F_{(3,84)} = 54.498$, $P<0.001$; $F_{(3,84)} = 5.475$, $P=0.001$), plus terrain*location interaction ($F_{(15,56)} = 5.368$, $P<0.001$; $F_{(15,56)} = 8.279$, $P<0.001$) for maximum frequency (Table 3.2) at the frequency bands of <5 Hz and >5 Hz, respectively. Key findings from post-hoc analysis showed that there were overall significant differences ($P<0.05$) between hill 1 and hill 2, and between the uphill's and downhill's, but not between the two downhill's. Multiple comparisons between the accelerometer locations were significantly different ($P<0.05$) except handlebar-left arm, handlebar-seat post, left arm-seat post, lower back – head and handlebar-left leg, lower back-head for frequency bands <5 Hz and >5 Hz, where $P>0.05$.

Significant main effects of magnitude at maximum frequency for vertical accelerations were present for accelerometer location ($F_{(5,56)} = 90.784$, $P<0.001$; $F_{(5,56)} = 109.744$, $P<0.001$) and terrain ($F_{(3,84)} = 126.711$, $P<0.001$; $F_{(3,84)} = 482.101$, $P<0.001$), with a significant terrain*location interaction ($F_{(15,56)} = 19.720$, $P<0.001$; $F_{(15,56)} = 41.628$, $p<0.001$) for both frequency bands. Post-hoc analysis showed significant difference between all pair combinations of comparison between uphill and downhill's for the frequency band >5 Hz while all multiple comparisons showed significant differences for the frequency band <5 Hz. Multiple comparisons between the accelerometer locations were significantly different ($P<0.05$) for all accelerometer positions except the lower back and head, for both frequency bands.

Analysis of half frequency data (Table 3.4) highlighted significant differences ($F_{(1,168)} = 4.126$, $P=0.043$; $F_{(3,84)} = 4.126$, $P<0.001$; $F_{(5,56)} = 409.394$, $P<0.000$) between main effects wheel size, terrain and accelerometer location, respectively, but with no interactions other than terrain*location ($F_{(15,56)} = 11.886$, $P<0.001$).

Discussion

The primary aim of this study was to quantify the vibrations, from the bicycle during a typical XCO-MTB race lap, and to determine how the accelerations were dampened in the body whilst using 26" and 29" wheels. The main findings were: (a) variables of acceleration were significantly greater at the point of interface between bike-body compared with those located at the lower back and head; (b) terrain affected all locations by increasing measures associated with vibrations on downhill sections except in the case of the head where variables remained constant; (c) overall, 29" wheels were faster than 26" wheels; and (d) 29" wheels increased acceleration overall both in the vertical and horizontal planes when compared to 26" wheels.

Participants were asked to complete the laps at race pace, and the validity of the tests depended on their effort during the task. Participants were able to provide reliable efforts, as evidenced by the non-significant difference between wheel sizes in terms of heart rate or power (Table 4.1). Moreover, measures of workload and intensity are comparable with previous work on XCO-MTB race intensities (Stapelfeldt et al., 2004), indicating that the tests were valid measures of accelerations during race conditions.

In showing that there is a difference between the accelerations experienced at the bike-body interface compared with those of the lower back and head during XCO-MTB racing we have confirmed that a large amount of soft tissue damping occurs in order to protect the body via stabilization (Figure 5.3-5.4). This damping was similar to that seen in locomotion (Hamill, Derrick, & Holt, 1995; Mercer, Bates, Dufek, & Hreljac, 2003), where high frequency accelerations were greatly reduced at the head. While we had no measure of muscle tension or stiffness in the current study, based on previous research (Hurst et al., 2012; Mester et al., 1999; Wakeling, Liphardt, & Nigg, 2003) it is probable that the muscles played a key role in removing the acceleration. In addition, soft tissue acts as a wobbling mass that vibrates in a direct response to mechanical excitation (Nigg & Liu, 1999; Wakeling et al., 2002) and such additional work detracts from the force generating capability of the muscles (Issurin, 2005) as there is a greater demand on motor units for a given force production (Mester et al., 1999). Such a response would be detrimental to forward propulsion of the XCO-MTB athlete.

Laboratory studies (Samuelson et al., 1989) investigating cycling and the effects of vibration have shown that accelerations of 20 $m \cdot s^{-1}$ at the foot are damped to 2 $m \cdot s^{-1}$ at the head with a subsequent decrease in submaximal time to exhaustion of 21% compared with cycling under normal (no vibrations) conditions. The accelerations previously reported at the head during laboratory cycling (Samuelson et al., 1989) are comparable to the field data for XCO-MTB presented (Figure 5.3). Whatever the level of vibration experienced at the bike-body interface, it appears that muscular work is done to limit transference to the central nervous system and brain in order to maintain optimal visual acuity, vestibular signals and decision making processes (Grether, 1971; Newell & Mansfield, 2008; Pozzo, Levik, & Berthoz, 1995). This would necessarily be reflected in a decreased gross efficiency compared to ergometer or road cycling at the same absolute workload. Maintenance of such functions/skills is an essential quality to optimise performance and maintain safety while negotiating technical and synonymously bumpy XCO-MTB courses.

While Figure 5.3 provides an overview of vibration severity at the different accelerometer positions, Figure 5.4 supplies us with more detail regarding the nature of the course in relation to possibilities of energy expenditure for muscle damping of vibrations. The significant interaction between terrain*accelerometer location emphasizes that energy expenditure for dissipating vibrations is much smaller ascending compared to descending (Figure 5.4 and Tables 3.2-3.4). However, it must be stressed that terrain is not just about ascent or descent as post-hoc analysis showed differences between the two climbs (Hill 1 and Hill 2). Hill 1 was a hard packed forest road which is relatively smooth with minimal steering requirements and performed at a relatively constant pace, while hill 2 was a single track climb consisting of multiple switch back corners, tree roots and obstacles with fluctuating pace changes. An interesting observation was the greater proportion of horizontal accelerations during climbing compared to descending as part of overall acceleration. This would be reflected in the fact that there would be greater resistance to forwards movement as a result of irregular gradient, track directions and surface terrain changes (Bertucci, Rogier, & Reiser, 2013), but also the transference of effort from the upper body into force applied at the pedals. As reported in a previous study (Macdermid & Stannard, 2012) the torque applied during ascent in XCO-MTB is very high and requires a strength element not often seen in road cycling.

Comparisons of main effect for accelerometer location demonstrate that differences only occurred at the locations interfacing bike-body, further consolidating the increased demand of energy expenditure for muscles in a damping role. Combined with the knowledge that more time is spent climbing than descending (66 vs 34 % in this study) during XCO-MTB racing (Macrae et al., 2000) and the difficulties of passing when descending in race conditions (Macdermid & Morton, 2012), it is not surprising that the majority of international XCO-MTB athletes use a hard tail designed bike as opposed to a heavier full suspension design. This is contrary to peer reviewed literature suggesting that full suspension designs provide a more efficient ride over bumpy terrain (Titlestad et al., 2006b) but agreeing with a more recent study showing that the hard tail designed bikes are more efficient whilst climbing and consequentially faster over a race lap (Herrick, Flohr, Wenos, & Saunders, 2011), albeit using a somewhat out-dated suspension system. In an attempt to gain performance advantages there has been a rise in popularity in the use of 29” wheels (compared to traditional 26” wheels), hard tail designed bikes, with an unsubstantiated reported capability of reducing the impact of terrain induced vibrations.

Our hypothesis that 29” wheels would dampen vibrations and thus decrease the non-propulsive work was unfounded as 29” wheels, on this course at least, were faster than 26” wheels. The non-significant difference in mean power output and the highly significant difference in overall time make this a very important finding, equating to 167-186 s over a typical race distance. Table 3.I shows there was no significant difference between wheel size and performance over terrain sections, reflecting variance in the small number of subjects used, as mean times were between 2.3-3.5 % quicker on all sections. The source of the increase in velocity per unit power output is likely owing in part to a combination of decreased rolling resistance and aerodynamic drag. A reduction in rolling resistance would be attributable to less deformation and therefore energy loss of the 29" tyres as a result of their greater volume, while smaller increases and decreases in speed would lead to less work lost to air resistance. If this were true the low frequency component of the acceleration would favour the 29" wheels (Table 3.3), which it does not.

The angle between the wheel axle and the point of impact is greater in a larger wheel and has been implicated in greater momentum and reduced vibrations (Wilson, 2004) yet our data clearly shows vibrations were greater in both the vertical and horizontal directions with the 29" wheels. This difference may be a result of the higher velocities with the 29" wheels, and therefore comparisons of wheel size and their ability to attenuate vibration transference between bike and body are difficult. It is also important to acknowledge the fact that this study compared 29"with 26" wheels, so might not represent a true comparison of actual 26" and 29" bikes where the geometry differences may affect performance. However, by using the same frame, geometric measures associated with bike handling (head tube angle and mechanical trail (Wilson, 2004)) and just changing wheels we isolated the wheel diameter effect. A further study could aim to make comparisons between complete 26" and 29" bikes.

Practical applications

The study's primary aim of investigating the transference of accelerations from terrain-bike-body demonstrates an additional non-propulsive challenge to riding during XCO-MTB. This is represented by a change in accelerations experienced at the point of interface between bike-body compared to those experienced at the lower back and head. Additional stress as a result of vibrations is greatest during downhill sections, possibly, preventing the recovery process that may occur during non-propulsive load.

This information is useful to both athletes and coaches in a number of ways:

1. Although not part of the study a valuable finding none the less was that 29" wheels provided a greater velocity per unit of power output. This is important for anyone racing competitive XCO-MTB as performance benefits ranged from 2.3-3.5% in favour of the 29" wheels.

2. Planning specific training requirements and loading within the training plan in order to avoid overuse injuries.

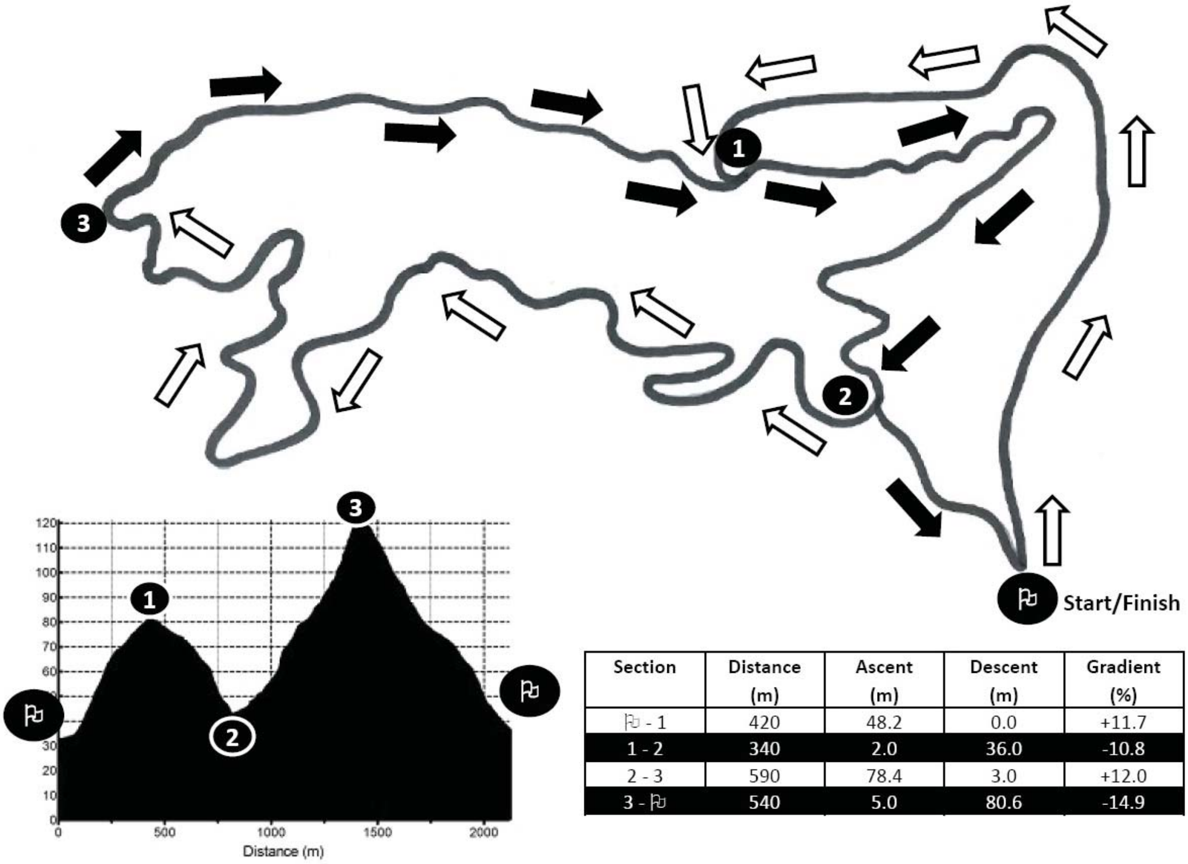
3. Enhance recovery rate from races or key training sessions. Reduction of such stresses during recovery/easy training sessions through alternative terrain options such as riding on a road or smoother surface may improve the quality of subsequent sport specific training sessions.

4. Athletes and coaches should be aware of the extra load associated with riding off-road and the potential increased risk to overuse injuries. Monitoring the total amount of exposure athletes are exposed too and coming up with individual limits could be a useful process.

5. If a large portion of training is to be completed off road on sport specific terrain athletes should consider alternative training bicycle to that traditionally used for racing in order to

alleviate vibration exposure. An example of this may be the use of a full suspension bike for easy- recovery training rides. However, it is unclear whether riders will just ride faster over sections of increased uneven terrain negating any benefit of such technological innovations.

Figures



Section	Distance (m)	Ascent (m)	Descent (m)	Gradient (%)
⚐ - 1	420	48.2	0.0	+11.7
1 - 2	340	2.0	36.0	-10.8
2 - 3	590	78.4	3.0	+12.0
3 - ⚐	540	5.0	80.6	-14.9

Figure 5.1: Course outline for the XCO-MTB lap used during the study. Where ⚐ indicates start and finish, ⇨refers to a climb and ➔ signifies a descent. Numbers encircled 1-3 on the map are related to climbs or descents highlighted on the schematic profile of the course. Section characteristics are provided in the table to the right of the schematic profile.

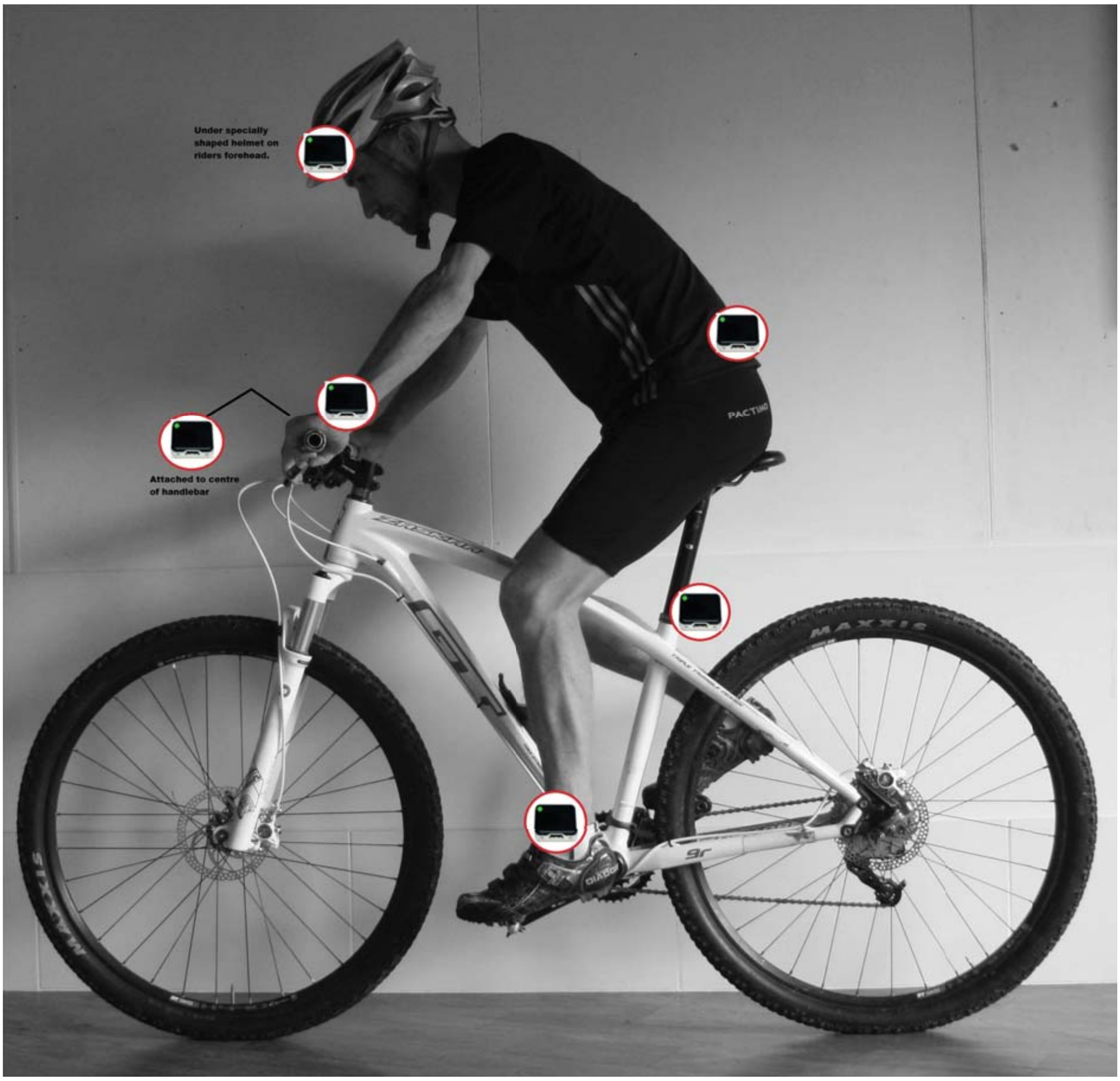


Figure 5.2: A photograph depicting accelerometer locations during the trial.

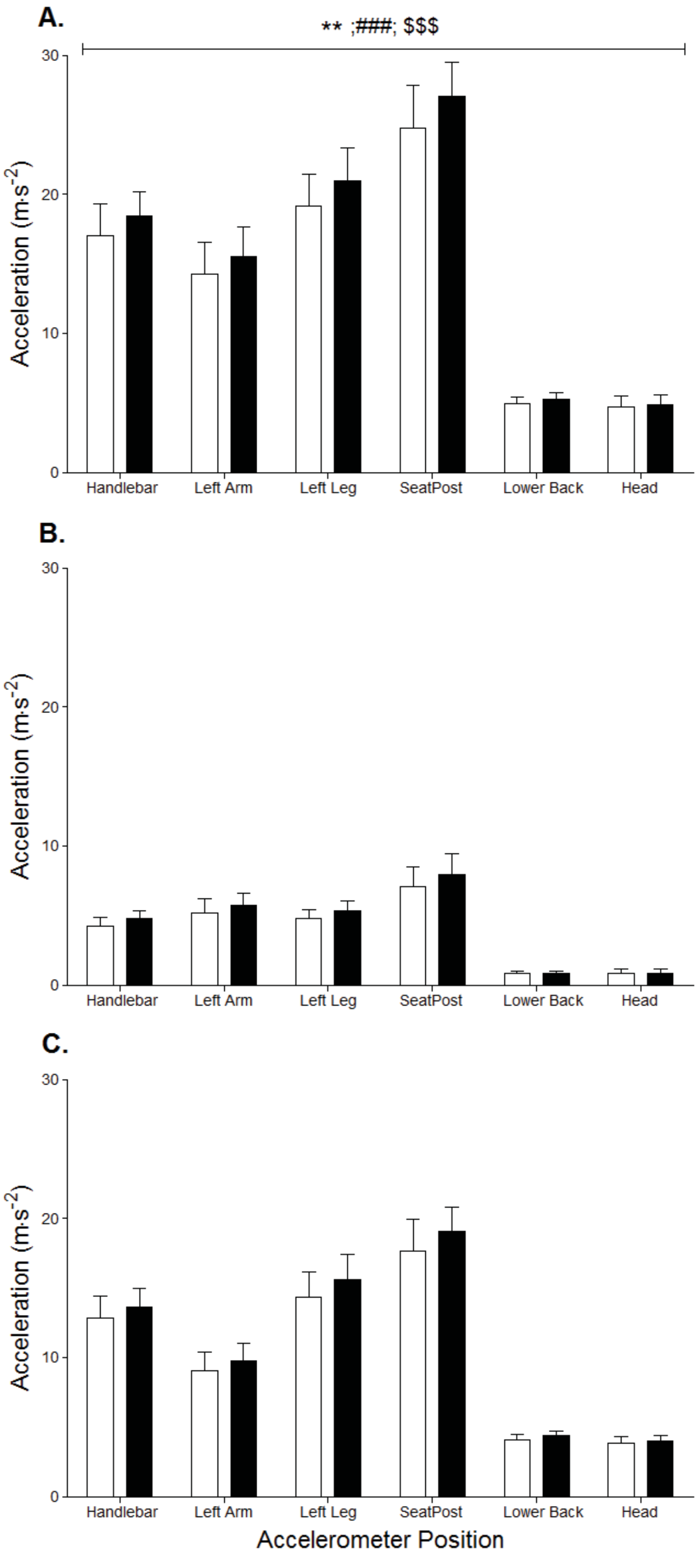


Figure 5.3: Mean ± s amplitude (RMS) for A. Total; B. Vertical; and C. Horizontal components of acceleration over the whole lap. ☐ signifies 26” wheel trial while ■ signifies 29” wheels.

** (*P*<0.01) main effect of wheel size; ### (*P*<0.001) main effect of accelerometer location; $$$ (p<0.001) axis*accelerometer location.

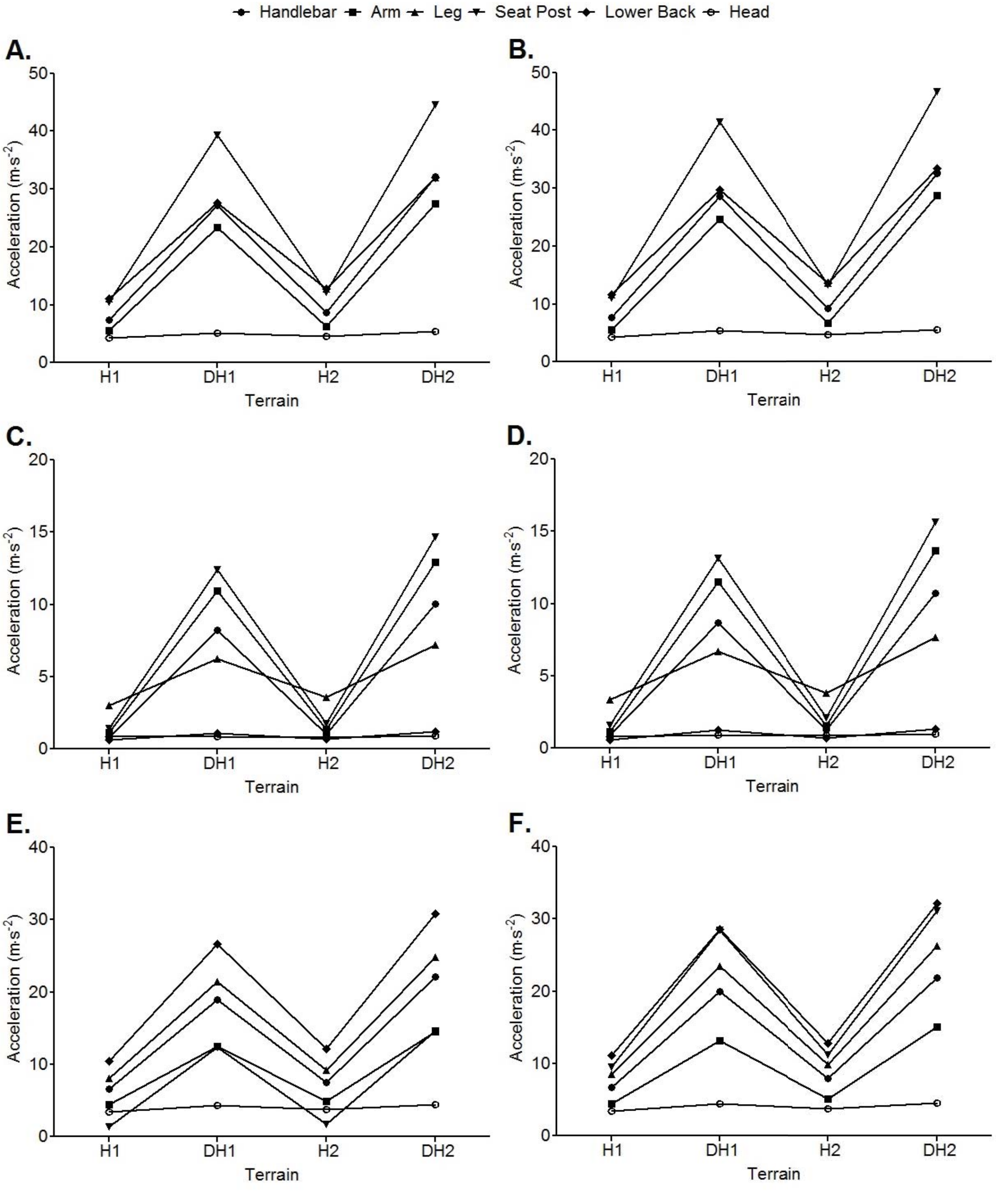


Figure 5.4: Mean acceleration expressed as RMS for accelerometer locations for different terrain segments as described in figure 1 (H1 = Uphill 1; DH1 = Downhill 2; H2 = Uphill 2; DH2 = Downhill 2). A. Total acceleration for 26” wheels; B. Total acceleration for 29” wheels; C. Vertical acceleration for 26” wheels; D. Vertical acceleration for 29” wheels; E. Horizontal acceleration for 26” wheels; F. Horizontal acceleration for 26” wheels.

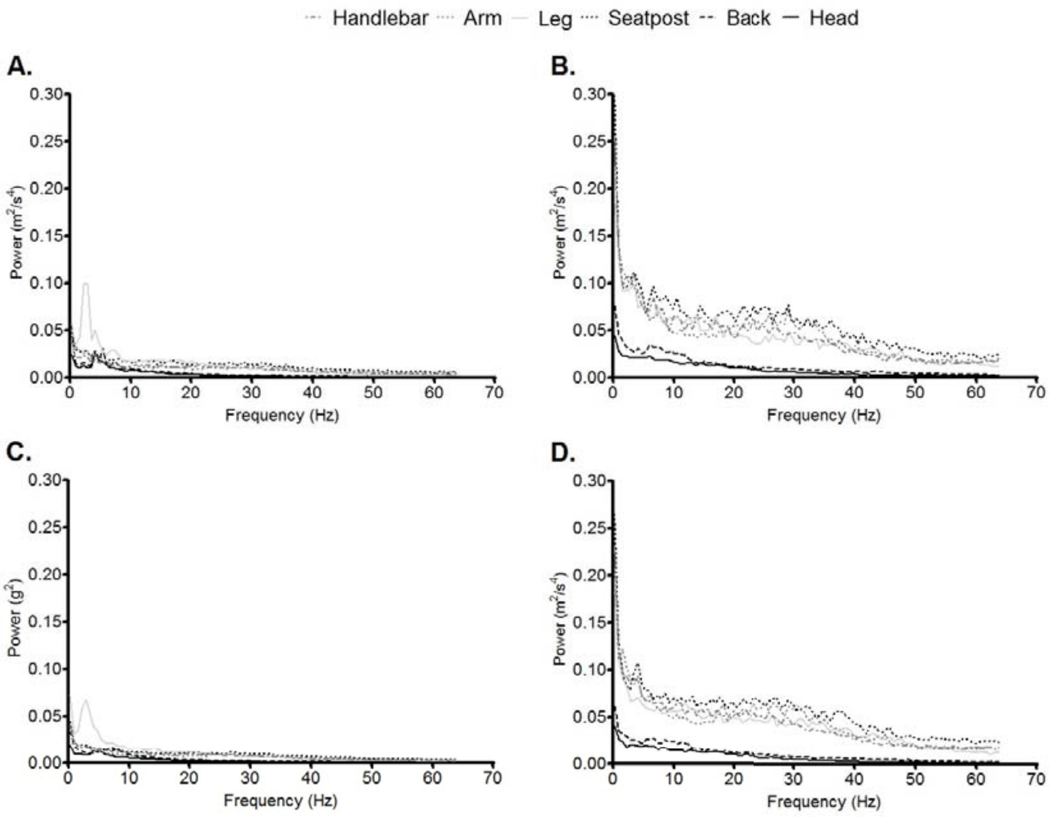


Figure 5.5: Spectral analysis of vertical accelerations for subject 3 during the different sections of the course. Where, A. is uphill 1; B. is downhill1; C. is uphill 2; and D. is downhill 2.

Tables

Table 3.1. Mean ± SD for performance variables measured throughout the field trial and separated based on terrain (Hill (H) and downhill (DH)) for the depicted order.

	Wheel Size (inches)	Uphill 1	Downhill 1	Uphill 2	Downhill 2	Two-Way ANOVA
Time (s)	26	129 ± 9	88 ± 7	290 ± 23	128 ± 10	WS p=0.242 Terr P<0.001 WS*Terr P=0.920
	29	126 ± 15	86± 8	280 ± 24	125 ± 12	
Power (W)	26	362 ± 48	93 ± 57	304 ± 33	65 ± 36	WS p=0.984 Terr P<0.001 WS*Terr P=0.846
	29	352 ± 58	81 ± 31	317 ± 38	74 ± 40	
Heart Rate (bpm)	26	165 ± 11	162 ± 13	170 ± 11	159 ± 12	WS p=0.821 Terr P=0.048 WS*Terr P=0.909
	29	163 ± 13	158 ± 9	171 ±9	161 ± 10	

Table 3.2. Mean ± SD for maximum frequency (Hz) of accelerations at points of contact between bike-body during a XCO-MTB lap, and separated for terrain, frequency banding and wheel size.

Accelerometer Location	**26" Wheels**				**29" Wheels**			
	Uphill 1	*Downhill 1*	*Uphill 2*	*Downhill 2*	*Uphill 1*	*Downhill 1*	*Uphill 2*	*Downhill 2*
Frequency Band (<5 Hz)								
Handlebar	2.5886 ± 0.5836	4.2049 ± 0.3865	2.5649 ±0.4408	4.3362 ± 0.4772	2.7128 ± 0.8429	4.1202 ± 0.6685	3.0253 ± 0.6821	4.0563 ± 0.4443
Left arm	2.2872 ± 0.2906	3.8030 ± 1.1836	2.7508 ± 0.4038	3.5787 ± 1.3051	2.3720 ± 0.6737	4.4542 ± 0.4506	3.0361 ± 0.5719	4.0525 ± 0.5563
Left leg	1.2100 ± 0.1643	1.5214 ± 0.1981	1.3790 ± 0.1190	1.8739 ± 0.4691	1.2467 ± 0.1784	1.4736 ± 0.2567	1.3872 ± 0.1609	1.7862 ± 0.2609
Seatpost	2.5839 ± 0.5664	4.1348 ± 0.3727	2.6636 ± 0.4313	3.9023 ± 0.9578	2.7275 ± 0.8689	4.1398 ± 0.7566	2.6695 ± 0.4213	4.0876 ± 0.5080
Lower Back	2.1906 ± 0.3439	2.5000 ± 0.6107	2.4408 ± 0.7278	2.5287 ± 1.0570	2.4063 ± 0.4803	3.0003 ± 0.8713	2.6686 ± 0.6146	2.6604 ± 0.9820
Head	2.2085 ± 0.1610	2.3810 ± 0.5833	2.3559 ± 0.2798	2.6429 ± 0.8873	2.3446 ± 0.7609	2.4625 ± 0.4605	2.3227 ± 0.2796	2.7956 ± 0.9635
Frequency Band (>5 Hz)								
Handlebar	11.5479 ± 3.6624	8.0184 ± 0.4146	8.3838 ± 3.1137	7.7079 ± 0.8894	12.9508 ± 4.6860	9.4889 ± 3.4710	8.9032 ± 2.3627	7.4205 ± 1.0044
Left arm	15.0403 ± 2.0706	12.0810 ± 2.4787	13.9667 ± 2.7886	13.830 ± 2.7830	15.5842 ± 2.6019	14.3738 ± 3.3495	13.5840 ± 1.3101	13.1108 ± 2.8850
Left leg	7.4420 ± 4.1788	13.4708 ± 2.4782	6.4915 ± 3.0441	11.4479 ± 4.2789	7.2764 ± 2.8482	13.1381 ± 4.8928	5.2644 ± 0.2734	13.0820 ± 3.0109
Seatpost	14.0130 ± 1.405	10.0799 ± 2.5423	12.6914 ± 2.4115	10.2124 ± 2.8376	14.4374 ± 3.7298	11.2226 ± 3.6646	11.9687 ± 2.6532	13.5728 ± 3.1709
Lower Back	5.6440 ± 0.7655	6.0253 ± 0.5550	5.1746 ± 0.1138	6.4741 ± 1.1317	5.6311 ± 0.7367	6.5419 ± 1.1428	5.6208 ± 0.3654	6.1394 ± 0.9143
Head	5.7459 ± 0.8424	6.8482 ± 1.3518	5.6552 ± 0.5066	6.5939 ± 1.7374	5.4094 ± 0.4349	6.4482 ± 1.7284	5.8718 ± 0.6557	6.0834 ± 1.3503

Table 3.3. Mean ± SD for magnitude (g^2) at maximum frequency of accelerations at points of contact between bike-body during a XCO-MTB lap, and separated for terrain, frequency banding and wheel size.

Accelerometer Location	**26" Wheels**				**29" Wheels**			
	Uphill 1	*Downhill 1*	*Uphill 2*	*Downhill 2*	*Uphill 1*	*Downhill 1*	*Uphill 2*	*Downhill 2*
Frequency Band (<5 Hz)								
Handlebar	0.4131 ± 0.1398	1.1653 ± 0.1623	0.3231 ± 0.1133	1.4079 ± 0.3269	0.4443 ± 0.1273	1.2272 ± 0.2127	0.3985 ± 0.1657	1.5901 ± 0.5990
Left arm	0.5903 ± 0.1581	1.3938 ± 0.1914	0.4447 ± 0.1795	1.8298 ± 0.5919	0.5850 ± 0.1603	1.5127 ± 0.4041	0.5276 ± 0.2481	1.9365 ± 0.8383
Left leg	0.8230 ± 0.3917	0.8055 ± 0.1828	0.4725 ± 0.0769	0.9601 ± 0.2391	0.9077 ± 0.3667	0.8686 ± 0.2077	0.4834 ± 0.0874	0.9904 ± 0.2474
Seatpost	0.6591 ± 0.2110	1.5352 ± 0.0891	0.4562 ± 0.1216	1.8255 ± 0.5691	0.6791 ± 0.2216	1.6120 ± 0.4049	0.5225 ± 0.2068	2.1895 ± 0.8327
Lower Back	0.5962 ± 0.2382	0.3810 ± 0.1339	0.2422 ± 0.0498	0.3722 ± 0.0907	0.5457 ± 0.1806	0.3550 ± 0.0946	0.2326 ± 0.0564	0.3517 ± 0.1117
Head	0.3131 ± 0.2179	0.2679 ± 0.0475	0.2098 ± 0.0766	0.2790 ± 0.0633	0.3084 ± 0.1557	0.3067 ± 0.0770	0.2039 ± 0.0803	0.2805 ± 0.0607
Frequency Band (>5 Hz)								
Handlebar	0.0741 ± 0.0131	0.3086 ± 0.0437	0.0675 ± 0.0129	0.3061 ± 0.0304	0.0852 ± 0.0201	0.3238 ± 0.0341	0.0731 ± 0.0146	0.3087 ± 0.0357
Left arm	0.0813 ± 0.0312	0.3669 ± 0.0664	0.0708 ± 0.0218	0.3846 ± 0.0885	0.0785 ± 0.0292	0.3788 ± 0.1062	0.0748 ± 0.0209	0.3553 ± 0.0724
Left leg	0.1287 ± 0.0270	0.2703 ± 0.0480	0.1178 ± 0.0217	0.2704 ± 0.0655	0.1402 ± 0.0136	0.2886 ± 0.0429	0.1289 ± 0.0207	0.2621 ± 0.0432
Seatpost	0.0959 ± 0.0152	0.4142 ± 0.0664	0.0843 ± 0.0192	0.3860 ± 0.0415	0.1053 ± 0.0142	0.4108 ± 0.0720	0.0878 ± 0.0353	0.4084 ± 0.0724
Lower Back	0.0910 ± 0.0282	0.1361 ± 0.0243	0.0717 ± 0.0120	0.1206 ± 0.0134	0.1074 ± 0.0632	0.1494 ± 0.0207	0.0708 ± 0.0110	0.1285 ± 0.0162
Head	0.1031 ± 0.0336	0.1109 ± 0.0231	0.0879 ± 0.0408	0.1081 ± 0.0251	0.1250 ± 0.0674	0.1296 ± 0.0253	0.0848 ± 0.0329	0.1101 ± 0.0284

Table 3.4. Mean ± SD for half frequency of accelerations at points of contact between bike-body during a XCO-MTB lap, and separated for terrain, frequency banding and wheel size.

Accelerometer Location	**26" Wheels**				**29" Wheels**			
	Uphill 1	*Downhill 1*	*Uphill 2*	*Downhill 2*	*Uphill 1*	*Downhill 1*	*Uphill 2*	*Downhill 2*
Handlebar	15.8624 ± 1.0477	14.5918 ± 1.0240	14.1362 ± 0.9059	14.6793 ± 1.1576	16.5617 ± 1.4037	15.3782 ± 1.5753	14.9690 ± 1.0991	15.6064 ± 1.5506
Left arm	17.3421 ± 0.7197	15.3079 ± 1.2644	15.4967 ± 0.9427	15.3220 ± 1.2542	17.9721 ± 1.2566	15.7504 ± 1.2666	15.7387 ± 0.4797	15.6458 ± 1.1853
Left leg	10.0112 ± 2.4305	15.6915 ± 2.8369	9.7534 ± 2.6260	16.2162 ± 2.7882	10.9057 ± 2.5868	14.9042 ± 4.5278	11.1205 ± 2.7368	15.2911 ± 5.0433
Seatpost	16.8318 ± 1.4104	15.9063 ± 0.6317	15.4923 ± 1.1290	15.9806 ± 0.6732	17.3226 ± 0.8898	16.3659 ± 0.6833	15.9265 ± 0.8271	16.3350 ± 0.6041
Lower Back	4.6051 ± 1.0238	8.0323 ± 1.3014	5.6807 ± 1.1265	8.5386 ± 1.0915	5.5449 ± 1.5778	8.2586 ± 0.8061	5.8891 ± 1.0114	8.5927 ± 1.4153
Head	3.7280 ± 1.1997	7.5154 ± 1.4194	4.0316 ± 1.1196	8.3477 ± 1.2322	3.8560 ± 1.3861	7.5236 ± 1.0461	4.2690 ± 1.2837	8.5165 ± 1.6393

CHAPTER SIX: STUDY THREE

THE EFFECTS OF VIBRATIONS EXPERIENCED DURING ROAD VS OFFROAD CYCLING.

Paul W. Macdermid, Philip W. Fink, Stannard R. Stephen.

The following paper has been submitted and published in the *International Journal of Sports Medicine* and prepared according to their guidelines. For evidence of publication and statement of contribution to doctoral thesis see Appendix 3.

Abstract

The purpose of this investigation was to compare the effects of vibrations experienced during off-road and road cycling. It was hypothesised that additional damping will be expressed through a greater work demand and increased physiological markers when travelling at the same speed over an identical terrain profile. Participants ascended a tar-sealed road climb and a singletrack off-road climb at a predetermined speed. Time, speed, power, cadence, heart rate and $\dot{V}O_2$ were sampled and logged every second while tri-axial accelerometers recorded accelerations (128 Hz) to quantify vibrations experienced. Statistical analysis indicated accelerations to be greater during the off-road condition ($p<0.0001$) with post-hoc analysis exposing differences ($p<0.001$) for handlebar, arm, leg and seatpost but not the lower back or head. The increase in accelerations during off-road riding are associated with increased vibrations and rolling resistance experienced. This led to increases in the work done (road: 280 ± 69 vs off-road: 312 ± 74 W, $p=0.0003$) and consequentially, physiological markers $\dot{V}O_2$ (road: 48.5 ± 7.5 off-road 51.4 ± 7.3 $ml \cdot kg^{-1} \cdot min^{-1}$, $p=0.0033$) and heart rate (road: 161 ± 10 off-road 170 ± 10 bpm, $p=0.0001$) were significantly increased during the off-road condition. Such physiological differences and their causes are important to understand in order to provide suitable training recommendations or technological interventions to improve competitive performance or recreational enjoyment.

Keywords: Mountain biking; accelerometers; rolling resistance; cycling economy; performance

Introduction

It is important to understand the factors affecting performance in any sport if enhancements of technical, mechanical, and training methods are to be achieved. Recent investigations (Gregory et al., 2007b; Macdermid & Stannard, 2012) intimate that the work demand and therefore physiological stresses for Olympic format Cross-country Mountain biking (XCO-MTB) differ from road racing. Power and cadence data reported for XCO-MTB races (Stapelfeldt et al., 2004) and simulated race pace efforts (Macdermid & Stannard, 2012) highlight large, possibly terrain induced, variability with considerable emphasis on low velocity high force, and pedal mechanics (Macdermid & Stannard, 2012). The accompanying metabolic response suggests reduced economy whilst riding XCO-MTB, explanations for which have centred on non-propulsive dissipation, by skeletal muscle, of terrain-induced vibrations to improve comfort and performance (Issurin, 2005; Levy & Smith, 2005; Samuelson et al., 1989; Wakeling et al., 2002), but ultimately to protect the central nervous system and brain (Samuelson et al., 1989; Vibert et al., 2007).

The mechanical oscillation of a wheel and bicycle in this case are difficult to predict but occur at the bicycle point of contact with the ground and thus provides periodical mechanical oscillation applied to the athlete’s body (Redfield, 2005). As such a likely explanation to any reduced economy is the combined effect of rolling resistance (tyre-terrain level) and the consequential vibration damping effect.

The gradient of vibration dissipation from the body-bike interface (hands and feet) through the appendages to the lower back and head have been used to explain vibration mechanics in XCO-MTB (Macdermid, Fink, & Stannard, 2014c); this is supported by observations of increased muscular work of the upper body (Hurst et al., 2012). Non-cycling specific studies (Bongiovanni, Hagbarth, & Stjernberg, 1990; Mester et al., 1999; Wakeling et al., 2002) identify the negative effect of vibration on muscle force production through reduced temporal recruitment (Issurin, 2005). Such superimposed muscle vibrations are typically associated with force reductions of ~8 % (Bongiovanni et al., 1990) but vary according to protocol used. For that reason, reductions in vibrations during cycling should not only improve performance during XCO-MTB, but also reduce the work demand and associated physiological stresses. Although the latter statement is unsubstantiated, the effects of suspension systems used on mountain bikes have been shown to reduce either vibrations (Faiss et al., 2007) and/or physiological variables associated with increased rider efficiency (Ishii et al., 2003; Macrae et al., 2000; Nishii et al., 2004; Titlestad et al., 2006b).

On the other hand, acute effects of the addition of vibrations to a non-vibration load include increased local and general blood circulation, enhanced oxygen delivery to the working muscle, increased muscle temperature, and enhanced muscle activation (Issurin, 2005). While contrary to the conclusions from XCO-MTB specific studies (Macdermid et al., 2014c; Macdermid & Stannard, 2012) the benefits or detriments of vibration are unconfirmed either way since no comparison between XCO-MTB and road has been performed over comparable terrain such as a climb which is particularly important for XCO-MTB athletes (Abbiss et al., 2013).

The aim of this study therefore was to investigate the work demand and physiological consequences of riding at the same speed on a tar-sealed road climb compared to a comparable (distance and gradient) off-road single-track mountain bike climb. We hypothesised that off-road single-track riding produces significantly more vibrations requiring greater muscle damping, equating to greater work demand, and increased metabolic requirement and associated physiological stress.

Methods

Participants

Seven nationally competitive XCO-MTB athletes (mean ± SD: age 27.2 ± 10.7 years, height 178.0 ± 7.5 cm, mass 61.5 ± 6.0 kg) participated in this study which consisted of one laboratory trial and one field test trial comprising two conditions. All participants provided written consent in accordance with the University Human Ethics Committee.

Laboratory Test

On visiting the laboratory participants were weighed in minimal clothing and then performed a ramp style test on an electronically-braked cycle ergometer (Lode Excalibur Sport, NL). The test workload commenced at 100 W and increased by 25 W per minute until the participant could no longer maintain the required power output (Macdermid & Stannard, 2012). Throughout this test heart rate (Polar Electro, Kempele, Finand) and expired respiratory gases were collected for analysis using a breath-by-breath system (K42b, Cosmed, Italy). Expired air data averaged every 15 s enabled calculation of $\dot{V}O_2$ peak, respiratory compensation point (RCP), and ventilatory threshold (VT) (Lucia et al., 2000).

Field Test Trial

Participants attended a 3 h testing session where they were fitted to the same mountain bike (GT Zaskar elite 29” Full Suspension, Optimized Force Constructed Carbon, USA) with the same settings (fork and tyre pressure), the portable gas analyser, heart rate monitor and accelerometers (Emerald, APDM, OR, USA), whereupon they commenced a 20 min warm-up period including a minimum of one ascent on each of the road climb and single-track climb to be used as conditions for this study. Both had comparable characteristics (except track surface): a distance of 740m with a vertical ascent of 31m providing an average gradient of 4.2 %.

Following a 5 min recovery epoch participants were instructed to complete a maximal effort on the single-track climb. As previous work (Macdermid et al., 2014c) has indicated that speed affects magnitude of accelerations this study controlled speed. Immediate data recall from the Garmin bicycle computer (Garmin Edge 500 including GSC+10 speed sensor, USA) following the maximal effort climb on the single-track, enabled determination of speed ($km \cdot h^{-1}$), set to 80% of average speed from the maximal trial for use during the two conditions.

Each condition commenced with a 4 min constant load effort (equating to 80% W_{max} taken from the initial laboratory test) on rollers positioned at the start of the climb. The purpose of this period was to allow physiological variables to stabilize. However, there was a small delay (< 6 s), on completion of this effort to remove the mountain bike from the rollers and onto the start line of the designated climb. On reaching the start line participants commenced the climb at the set speed previously determined, controlled by viewing speed on the Garmin Edge. A counter balanced order (seperated by 15 min epochs for recovery) was used to prevent any order effect on the dependent variables of interest.

Outcome measures

Speed ($km \cdot h^{-1}$), power output (W) and cadence (rpm) were continuously sampled and logged every second (SRAM QUARK S2275 MTB Power Meter, USA) throughout the trial. The Quark CinQo powermeter has been previously used for such studies (Macdermid et al., 2014c) and has a reported accuracy ± 1.5 % (Aguilar et al., 2008). Data recorded from the power meter and GPS device were transmitted to a conventional personal computer and processed with the Garmin Training Centre software (version 3.6.5).

Participants completed each condition wearing the automated, portable gas analyser (Cosmed K42b) enabling continuous breath by breath sampling. Data for $\dot{V}O_2$ (ml·min^{-1}·kg^{-1}) and heart rate were logged every second allowing comparisons between conditions for work done and physiological strain when compared to performance time (s) and power output (W).

Wireless, tri-axial accelerometer, magnetometers and gyroscope with a reported accuracy 0.0012 m·s^{2}·√Hz^{-1} (Emerald, APDM, OR, USA), were used in a synchronised data logging mode to measure accelerations in accordance with the International Standards (ISO 2631-1) for measuring vibrations (Iso, 1997) and reported elsewhere in similar studies (Macdermid et al., 2014c). The accelerometers were placed on the lower left arm (frontal distal position); left lower leg (frontal, distal position); seat post (within 10cm of saddle-rider contact area); lumbar region of lower back; and medial forehead (Macdermid et al., 2014c). The Emerald accelerometers were synchronised with the Garmin Edge 500 and the Cosmed K42b, were sampled at 128 Hz, and all data were logged to a standard personal computer, converted to a hierarchal data format file (.h5) and processed using MATLAB R2014a. All data were analysed for total (XYZ), vertical (Z-axis), and horizontal (X- and Y- axis) accelerations. Root mean squares of the accelerations were calculated to quantify the amount of vibration the participants experienced (Iso, 1997; Macdermid et al., 2014c). Spectral analysis was performed using a Fast Fourier transform in order to determine whether the acceleration characteristics were induced voluntarily or involuntarily. Measures included: (1) half frequency, used to determine the frequency at which half the total power was below the frequency; (2) Maximum frequency and maximum magnitude at <5 Hz enabling more detailed quantification of voluntary movements or vibrations, and >5 Hz for vibrations and physiological tremor (Hines et al., 1987; Jäncke et al., 2004; Kay et al., 1991; Macdermid et al., 2014c).

Statistical Analyses

Descriptive data (mean ± SD and (95% CI) where relevant) were calculated for variables measured during the laboratory ramp test and all dependent variables over the field trial. Data analysis of speed, power, time, heart rate, and $\dot{V}O_2$ between conditions (Road and Off-Road) were compared by paired Student's *t*-tests to assess overall control and performance of the study.

Accelerometer data comparisons (Acceleration RMS) for total, vertical and horizontal axis plus additional spectral analyis data were made via univariate analysis of variance (two-way ANOVA), including within-subject variables, surface and accelerometer location, tested for main effects and interactions (Surface*Location).

Where significant difference was found the main effect was analysed using Bonferroni post-hoc testing for pairwise comparisons. All statistical analyses were performed using IBM SPSS Statistics 20, significance set at P<0.05.

Results

Laboratory fitness assessment provided mean ± SD (95% CI) descriptive data for participants W_{max} 408 (363-452) W or 6.6 (6.5-6.8) $W \cdot kg^{-1}$; $\dot{V}O_2$ peak 66.7 (64.7-68.9) $ml \cdot kg^{-1} \cdot min^{-1}$; HR_{max} 187 (175-199) bpm; VT 258 (231-284) W or 4.2 (4.0-4.4) $W \cdot kg^{-1}$; RCP 321 (290-352) W or 5.2 (5.1-5.4) $W \cdot kg^{-1}$.

The main aim of the study was to complete two climbs of identical distance and gradient but with different track surfaces (tar-sealed road and off-road single-track) at the same speed. Paired Student's t-test analysis showed no significant difference between road and off-road condition for time (160.9 ± 13.12 and 162.3 ± 11.61 s; $t_{(6)}$=1.474, p=0.1908) speed (16.7 ± 1.4 and 16.5 ± 1.2 $km \cdot h^{-1}$; $t_{(6)}$=1.520, p=0.1793) or cadence (78 ± 5 and 78 ± 6 rpm; $t_{(6)}$=0.4300, p=0.6822), respectively.

Measurement of total accelerations experienced by participants (Figure 6.1A) revealed significant interactions between terrain surface*accelerometer position ($F_{(5,72)}$=15.24, p<0.0001) along with a main effect for both surface ($F_{(1,72)}$=150.35, p<0.0001) and accelerometer location ($F_{(5,72)}$=120.42, p<0.0001). Post-hoc analyses revealed significant differences between conditions (road vs off-road) for handlebar ($t_{(6)}$=7.228, p<0.001), left arm ($t_{(6)}$=11.800, p<0.001), left leg ($t_{(6)}$=3.731, p<0.010) and seatpost ($t_{(6)}$=3.965, p<0.010), but not the lower back ($t_{(6)}$=1.637, p>0.05) or head ($t_{(6)}$=1.678, p<0.05). When seperated to individual axis, acceleration in the vertical and horizontal plane (Figure 6.1B-C) shows significant interaction between terrain surface*accelerometer position $F_{(5,72)}$=2.78, p=0.0235; $F_{(5,72)}$=2.62, p=0.0314, respectively. There were also main effects for surface ($F_{(1,72)}$=27.31, p<0.0001 and $F_{(1,72)}$=23.98, p<0.0001) and accelerometer position ($F_{(1,72)}$=10.81, p<0.0001 and $F_{(1,72)}$=41.91, p<0.0001), respectively. Post-hoc analysis identified differences for handlebar and left arm (p<0.05) but not left leg, seatpost, lower back or head in both vertical and horizontal plane (Figure 6.1B-C).

Two-way ANOVA of spectral analysis data provided a significant interaction between terrain surface and accelerometer position ($F_{(5,60)}=2.40$, $p=0.0476$) for half frequency with post-hoc analysis identifying significantly ($p<0.0001$) greater values for the seatpost during the road condition and the leg during the off-road condition (Figure 6.2). There were no interactions (terrain surface*position) for maximum frequency or maximum magnitude when analysed for bands <5Hz and >5Hz. All spectral analysis showed significant ($p<0.0001$) main effects for acceleration positions (Table 4.1).

Paired student's *t*-test of power output (Figure 6.3A) confirms the significant ($t_{(6)}=7.419$, $p=0.0003$) increased demand of bicycling off-road (312 ± 74 (244-380) W) compared to the tar-sealed road (280 ± 69 (215-344) W). Accordingly, physiological measures (Figure 6.3B-C) including $\dot{V}O_2$ (48.5 ± 7.5 (41.6-55.4); 51.4 ± 7.3 (44.6-58.2) $ml\cdot kg^{-1}\cdot min^{-1}$; $t_{(6)}=4.717$, $p=0.0033$) and heart rate (161± 10 (151-171); 170 ± 10 (161-180) bpm; $t_{(6)}=9.037$, $p=0.0001$) were less for the road compared to off-road condition, respectively.

Discussion

The aim of this study was to assess the work demand (propulsive and non-propulsive) and the physiological consequences during a climb of identical distance and gradient on two different surfaces (road and off-road) whilst riding at the same speed on the same bicycle. The main findings were: (a) A single-track MTB climb (off-road) exposed the riders to significantly greater accelerations at the point of contact with bicycle when compared to a comparable tar-sealed road; (b) while there was no difference between accelerations experienced at the head and lower back for either conditions; and (c) the metabolic demands and cardiovascular stress (HR) were greater during the off-road compared to the road.

Participants successfully completed the two conditions at identical speeds and cadence suggesting that differences in accelerations and subsequent physiological variables could be largely attributed to either condition rather than any difference in speed (Macdermid et al., 2014c) of bicycle or cadence of participants (Chavarren & Calbet, 1999).

It has previously (Wakeling et al., 2002) been identified that the measurement of total acceleration (X+Y+Z) is most useful in quantifying vibration exposure in humans. This is because in studies such as this, soft tissue oscillation tends to occur in all orthogonal directions. Our data (Figure 6.1A) indicate significantly greater total, vertical and horizontal accelerations experienced during the single-track off-road climb. This is important as hysteric losses in tyre-ground interaction could potentially be the cause of the extra energetic demand associated with XCO-MTB (Hurst et al., 2012; Macdermid et al., 2014c; Macdermid & Stannard, 2012). As such, the difference between the tar-sealed road and off-road conditions suggest that hysteric losses as caused by the terrain surface play an important part in additional propulsive and non-propulsive work demands (Macdermid, Fink, & Stannard, 2014a). However, the greater rigidity (firmness) and evenness of the tar-seal combined with tyre tread protrusions could cause an increase in high frequency involuntary vibrations experienced during road cycling on the a mountain bike compared to off-road cycling where there is greater plasticity in the relationship. This is supported through spectral analysis half-frequency data (Figure 6.2), which suggests a greater proportion of accelerations occur at higher frequencies for the road condition compared to off-road. Accelerometer specific differences occurred at the leg and seat post level but not at the handlebar. This suggests that the front suspension system helps to damp some of the high frequency vibration. However, no further differences when comparisons for maximum frequency or magnitude (<5 Hz or > 5Hz) were uncovered, making any association between tread pattern - surface interaction difficult. Table 4.1 shows the variability between accelerometer locations and differences between surfaces, which is the probable cause for non-significance and possibly due to dissimilarities in participant technique. Interestingly, but not soft tissue related, there seems to be some trend for greater maximum frequency values in the <5 Hz band for the off-road and >5Hz for the road. This aspect requires further research focussing specifically on vibrations at the bike level and how they interact with soft tissue and the relationship between terrain surface and tyre tread patterns.

An important finding of this study is the confirmation that while surface terrain affected total vibrations experienced at the bicycle level and the appendages, there was no effect on levels experienced at the axial body (lower back or head). This confirms a recent XCO-MTB study (Macdermid et al., 2014c) which proposes that damping occurs within the limbs perhaps to protect the central nervous system and brain from damage (Samuelson et al., 1989), but also to limit the effects of disturbance to co-ordination and balance (Mester et al., 1999). As such, if the vibrations experienced at either the bicycle or outer extremities are less, it might be assumed that measures associated with physiological work would also be lower during a trial with decreased damping. To this extent total accelerations experienced were significantly greater during off-road single track riding (Figure 6.1) and there were subsequently greater power outputs required to maintain the same speed during an uphill trial (Figure 6.3 A). Consequently, physiological demand increased and was expressed through both heart rate and $\dot{V}O_2$ (Figure 6.3

B-C). Therefore, any intervention that can reduce damping could well lead to an improvement in overall performance during XCO-MTB racing through an improvement in cycling economy. An alternative view might be that the additional stress of vibrations during exercise to the neuromuscular system (Mester et al., 1999) could serve to increase long term training adaptions and ultimately, the overall performance of road cyclists.

A limitation of this study is the inability to differentiate between the extra demand as a result of voluntary and involuntary movements and their interactions. While in all likelihood the total vibrations experienced is the most important factor for a performance based analysis (Aguilar et al., 2008), it is useful to understand the influence of involuntary movements experienced and the subsequent effect on performance.

Conclusion

Riding at the same speed over an identical distance, on a track of the same gradient, but differing in surface (tar-sealed vs off-road single track) caused participants to experience greater vibrations at the bicycle level and points of contact between bicycle and body whilst riding off-road. There were no differences for vibrations experienced at the head and lower back indicating a greater amount of non-propulsive work performed during XCO-MTB compared to road cycling. The increased damping led to increases in measures of work done and associated physiological variables explaining the decreased economy associated with XCO-MTB when compared to road cycling.

Tables

Table 4.1. Mean ± SD for maximum frequency (Hz) and magnitude (g^2) of accelerations during the hill climb, separated for frequency banding and condition.

Accelerometer Location	**Road**		**Off-Road Singletrack**		**Two-Way ANOVA**
	Maximum Frequency	**Maximum Magnitude**	**Maximum Frequency**	**Maximum Magnitude**	
	Frequency Band (<5 Hz)				
Handlebar	3.009 ± 0.427	0.090 ± 0.079	2.701 ± 0.413	0.163 ± 0.096	Cond*A.Loc: NS Cond: NS A.Loc: P<0.0001
Left arm	2.767 ± 0.328	0.130 ± 0.070	2.858 ± 0.274	0.203 ± 0.124	
Left leg	1.361 ± 0.090$_{(Hb;\ La)}$	1.434 ± 0.352$_{(Hb;\ La)}$	1.346 ± 0.074$_{(Hb;\ La)}$	1.430 ± 0.250$_{(Hb;\ La)}$	
Seatpost	2.801 ± 0.143$_{(LL)}$	0.078 ± 0.023$_{(LL)}$	3.074 ± 0.518$_{(LL)}$	0.120 ± 0.025$_{(LL)}$	
Lower Back	2.728 ± 0.555$_{(LL)}$	0.355 ± 0.259$_{(LL)}$	2.626 ± 0.369$_{(LL)}$	0.395 ± 0.183$_{(LL)}$	
Head	2.872 ± 0.510$_{(LL)}$	0.235 ± 0.176$_{(LL)}$	3.078 ± 0.481$_{(LL)}$	0.362 ± 0.127$_{(LL)}$	
	Frequency Band (>5 Hz)				
Handlebar	14.585 ± 2.419	0.146 ± 0.059	15.198 ± 2.955	0.272 ± 0.043	Cond*A.Loc: NS Cond: NS A.Loc: P<0.0001
Left arm	12.349 ± 6.108	0.243 ± 0.178	10.647 ± 4.494	0.357 ± 0.081	
Left leg	5.466 ± 2.472$_{(Hb;\ La)}$	1.243 ± 0.630$_{(Hb;\ La)}$	8.442 ± 4.859$_{(Hb;\ La)}$	1.190 ± 0.535$_{(Hb;\ La)}$	
Seatpost	14.614 ± 2.024$_{(LL)}$	0.087 ± 0.023$_{(LL)}$	14.075 ± 2.604$_{(LL)}$	0.215 ± 0.040$_{(LL)}$	
Lower Back	5.467 ± 0.249$_{(Hb;\ La;\ SP)}$	0.260 ± 0.224$_{(LL)}$	5.476 ± 0.365$_{(Hb;\ La;\ SP)}$	0.363 ± 0.212$_{(LL)}$	
Head	5.415 ± 0.232$_{(Hb;\ La;\ SP)}$	0.203 ± 0.178$_{(LL)}$	5.477 ± 0.280$_{(Hb;\ La;\ SP)}$	0.302 ± 0.160$_{(LL)}$	

*Where, Cond*A.Loc refers to the two-way interaction between conditions (Cond) and accelerometer location (A.Loc). NS signifies a non-significant effect ($p>0.05$). Within condition differences ($p<0.05$) for specific accelerometer position shown via subscript abbreviations with regards to positions differing from. Where, Hb = handlebar; LA = left arm; LL = left leg; SP = seatpost; LB = lower back; and H = head*

Figures

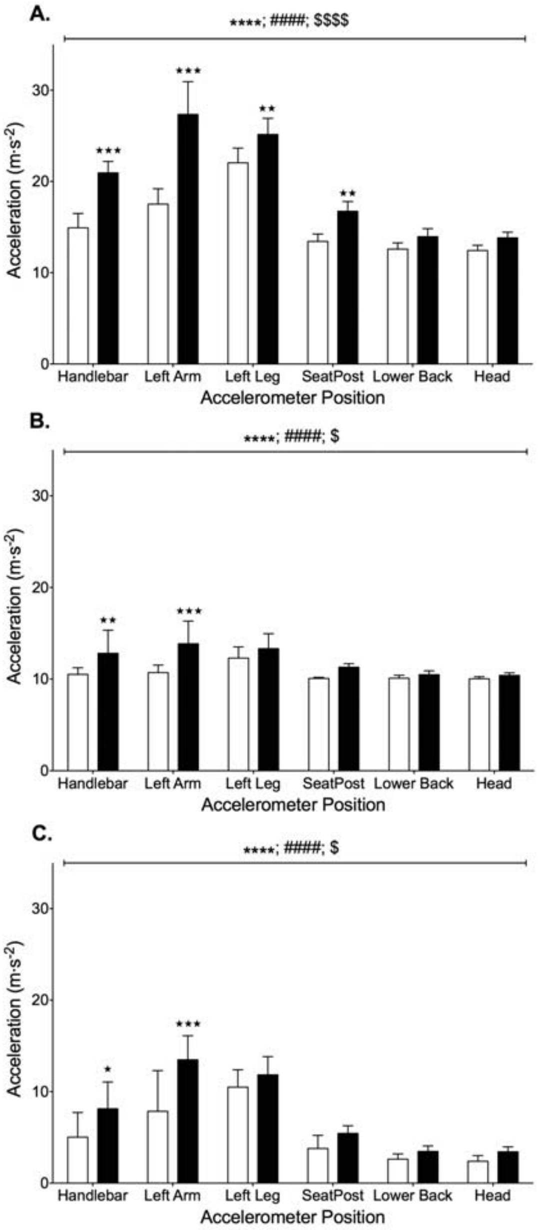


Figure 6.1: Mean ± SD amplitude (RMS) for A. Total; B. Vertical; and C. Horizontal components of acceleration over the climb. □ Signifies the tar-sealed road condition, while ■ signifies single-track off-road condition.

**** (*P*<0.0001) main effect of terrain surface; #### (*P*<0.0001) main effect of acceleration location; $$$$ (*P*<0.0001), $ (*P*<0.05) terrain surface*accelerometer location interaction; Post-hoc analysis differences★★★ (P<0.001), ★★ (P<0.01) and ★ (P<0.05) when tar-sealed Rd is compared to single-track off-Rd (MTB).

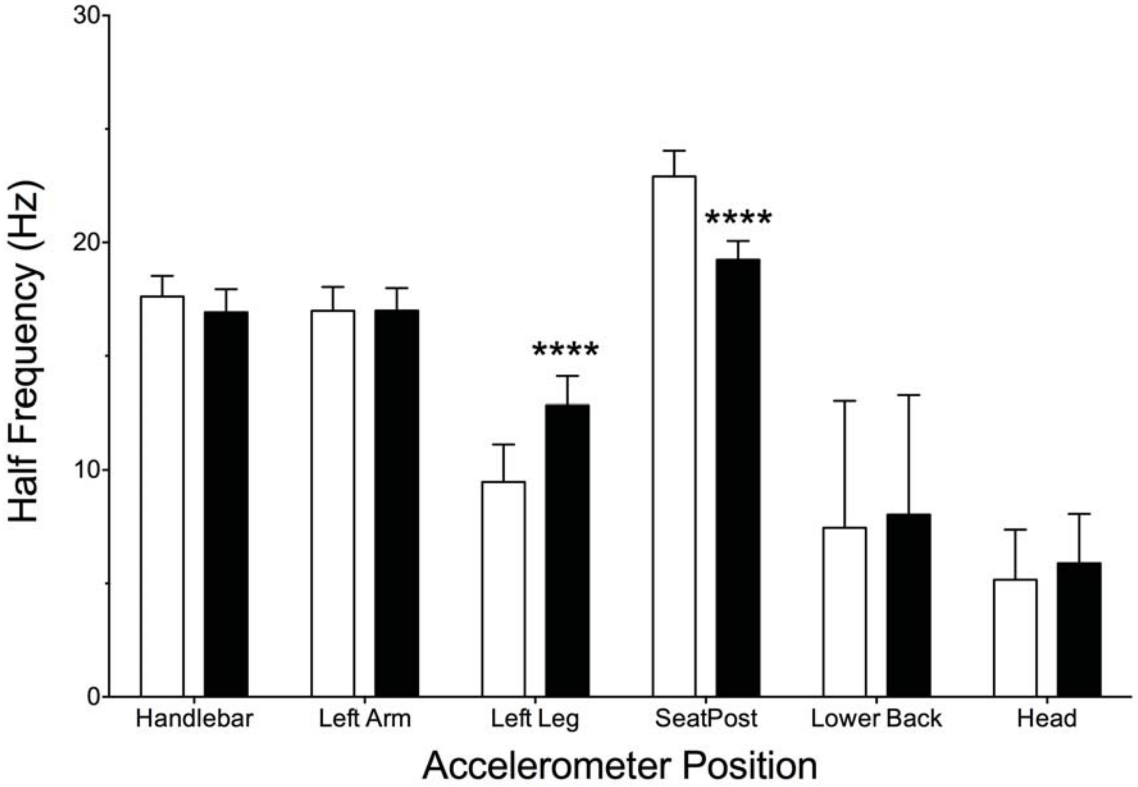


Figure 6.2: Mean ± SD for half frequency data from spectral analysis for each condition (tar-sealed road □ and the single-track off-road ■) and accelerometer position.

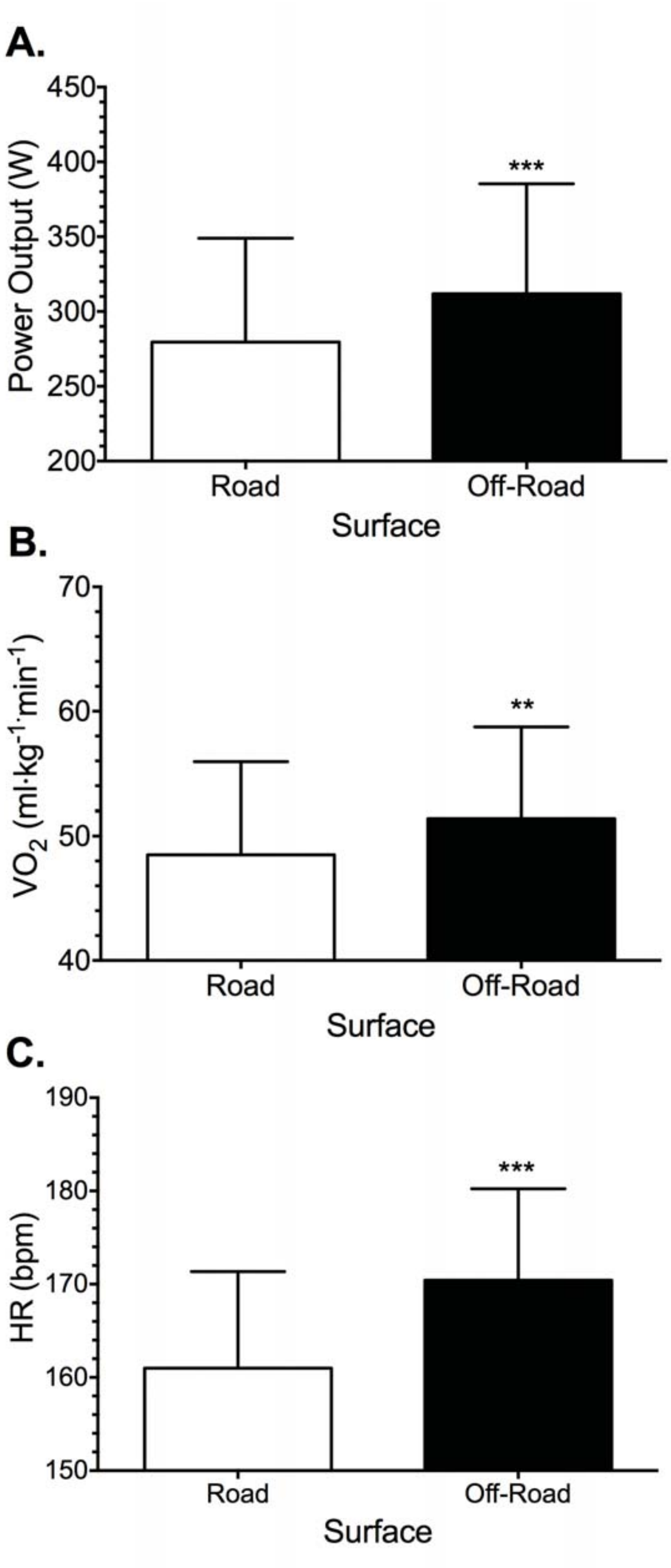


Figure 6.3: Mean ± SD for A. Power Output (W); B. $\dot{V}O_2$ (ml·min^{-1}·kg^{-1}); and C. Heart Rate (bpm) for both the tar-sealed road □ and the single-track off-road ■.

Where, *** ($P<0.001$) and ** ($P<0.01$) single-track off-road is significantly different to road.

CHAPTER SEVEN: STUDY FOUR.

THE IMPACT OF UPHILL CYCLING AND BICYCLE SUSPENSION ON DOWNHILL PERFORMANCE DURING CROSS-COUNTRY MOUNTAIN BIKING.

Paul W. Macdermid, Philip W. Fink, , Matthew C Miller, Stannard R. Stephen.

The following paper has been submitted to the *Journal of Sports Science* and prepared according to their guidelines.

Abstract

Non-propulsive work demand has been linked to reduced energetic economy of cross-country mountain biking. The purpose of this study was to determine mechanical, physiological, and performance differences and observe economy whilst riding a downhill section of a cross-country course prior to and following the metabolic "load" of a climb at race pace under two conditions (hardtail and full suspension) expected to alter vibration damping mechanics. Participants completed one lap of the track incorporating the same downhill section twice, under two conditions (hardtail and full suspension). Performance was determined by time to complete overall lap and specific terrain sections. Power, cadence, heart rate and oxygen consumption were sampled and logged every second while tri-axial accelerometers recorded accelerations (128 Hz) to quantify vibration. No differences between overall performance times ($p=0.6542$) or power outputs ($p=0.6060$) were observed while physiological demand of loaded downhill riding was significantly greater ($p<0.0001$) than unloaded. Full suspension decreased total vibrations experienced ($p<0.01$) but had no effect on performance ($p=0.9697$) or physiological ($p>0.05$) measures. Any small positive effect of a full suspension bicycle during downhill riding is negated by small negative effects during ascent and as such it is recommended that hardtail bicycles are used for racing cross-country races in there current format.

Introduction

Measures of cycling economy during constant load laboratory trials have been found to be reliable measures of whole body efficiency (Coyle, Sidossis, Horowitz, & Beltz, 1992; Lucia, Hoyos, Perez, Santalla, & Chicharro, 2002) but little is known regarding field measures of cycling economy for Olympic format Cross-country mountain biking. This is important as understanding the interactive factors (athlete, equipment and riding technique) of such sports and the resultant physiological improvements could be key to future developments in competitive and recreational mountain biking alike.

Previous work has identified a greater inefficiency while riding cross-country mountain bikes compared with road cycling. This is reported by the association of high physiological measures including heart rate and oxygen consumption (Gregory et al., 2007a; Impellizzeri, Marcora, et al., 2005; Macdermid & Stannard, 2012; Stapelfeldt et al., 2004) with relatively low power outputs compared to laboratory measures taken to indicate athlete fitness levels (Lee et al., 2002). Since the early descriptive studies of cross-country mountain biking (Hurst & Atkins, 2006; Impellizzeri et al., 2002; Impellizzeri & Marcora, 2007; Lee et al., 2002), research interest is now focused around exploring possible causes of energy loss within the bike-rider system. Current emphasis has focused on non-propulsive work, including quantification of vibration dissipation and it’s potential implication to performance (Hurst et al., 2012; Macdermid et al., 2014c). The assumption that significant reductions in accelerations from where the accelerations enter the body to the head indicates additional, non-propulsive work (Macdermid et al., 2014c) is suported by electromyographic data for increased muscle activity whilst downhill riding (Hurst et al., 2012). However, neither of the aforementioned studies measured physiological variables that would enable valid quantification of rider efficiency. Earlier studies did (Gregory et al., 2007a; Impellizzeri et al., 2002; Macdermid & Stannard, 2012) but made no attempt to compare the antecedent metabolic load of an ascent and its subsequent recovery component during descents. Such knowledge would be very useful in investigating potential performance enhancements as a result of fitness, technique or equipment changes, especially on the downhill sections of the race.

The additional metabolic demands for cross-country riding as a direct result of vibration damping can be substantiated through non-specific laboratory work showing vibration frequencies of 2-12 Hz, with amplitudes of 6-12 m·s-2 associated with increased blood pressure, heart rate, cardiac output, oxygen consumption, and minute ventilation (Samuelson et al., 1989). While such measures (amplitudes and frequencies) fit with total accelerations taken during climbing for simulated cross-country mountain bike race effort in the field (Macdermid, Fink, & Stannard, 2014b), amplitudes reported during the downhill component are much greater (Macdermid et al., 2014c) possibly exacerbating physiological stress during subsequent parts of the race. However, this is unsubstantiated as no comparison between loaded and unloaded cycling in the field has been made with regards to vibrations experienced. Although early field work (Seifert et al., 1997) intimates that the addition of suspension and thus reductions in vibrations experienced, enables riders to produce greater power outputs for non-significant differences in physiological variables. It seems likely that the increase in weight afforded a full suspension bike could negate any benefit over a full lap not taking terrain into account (Macrae et al., 2000; Nishii et al., 2004). Alternatively, the acknowledgement of performance as the main component of interest (Ishii et al., 2003) as opposed to measures of economy must be acknowledged. In fact it has been postulated that low-intensity vibrations (15-50 Hz) experienced throughout the legs can increase blood and thus oxygen supply, oxidative metabolism, muscle temperature control, and muscle activation (Issurin, 2005). Hence, it could be surmised that a downhill component as experienced in cross-country mountain biking could enhance recovery from preceding uphill efforts enable greater performance or increase cycling economy for the ensuing climb.

Therefore, the aims of this study was to investigate the true (unloaded) physiological cost of the downhill component during simulated race paced efforts in comparison with completing the same downhill in a “real world” setting where performers complete a climb prior to descending (loaded). An additional aim was to assess the impact of suspension systems on performance and any physiological responses to the aforementioned. We hypothesised that there will be no significant difference between performance parameters of unloaded and loaded cross-county downhill mountain biking, but there will be significant increases in physiological variables during loaded compared to unloaded downhill riding. Additionally, a dual suspension bicycle will decrease vibrations experienced during riding, increasing cycling economy when compared to hard-tail bicycles typically used in cross-country mountain bike racing.

Methods

Participants

Eight nationally competitive athletes (mean ± s: age 30 ± 10 years, height 179 ± 9 cm, mass 63.0 ± 9.0 kg) participated in this study which consisted of one laboratory trial and one field test trial comprising two conditions. All participants provided written consent in accordance with the University Human Ethics Committee.

Laboratory Test

On visiting the laboratory participants were weighed and then performed a ramp style test (Lode Excalibur Sport, NL) commencing at 100 W and increasing by 25 W per minute until the participant could no longer maintain the required power output (Macdermid & Stannard, 2012). Throughout this test heart rate (Polar Electro, Kempele, Finand), expired air (K42b, Cosmed, Italy) and power output (W) were measured. Expired air data averaged every 15 s enabled calculation of peak oxygen consumption and respiratory compensation point (Lucia et al., 2000) to determine exercise intensity for the hill climb component of the field trial. It has previously been shown that this marker resembles the intensity of competitive cross-country racing (Impellizzeri, Marcora, et al., 2005; Macdermid & Stannard, 2012).

Field Test Trial

Participants attended a day at a purpose-built mountain bike course (recently logged Woodpecker Forest, Palmerston North, NZ) completing a re-familiarisation of the track to be used. This consisted of one singletrack downhill section performed on two occasions (Downhill 1 and Downhill 2), but separated by a forest road uphill section (Hill 1) as shown in Figure 7.1.

The surface terrain for the downhill section was primarily hardpack mud but did include loose rocks, roots and ruts, plus small jumps typical of XCO-MTB courses. Data taken from the global positioning system device (Garmin, Edge 500, USA), during the trial period (n=16) showed the overall course length was 1796 ± 37 m (CV= 2.07 %) in length compared to trundel wheel measurement 1957 m, had a total ascent of 53.6 ± 2.5 m (CV= 4.67 %) and descent of 103.0 ± 3.14 m (CV= 3.05 %).

Following a re-familiarisation period of the course and equipment used, participants were given a 15 min recovery epoch commencing the trial which included riding the complete course (Downhill 1-Hill 1-Downhill 2) as per Figure 7.1. In order to quantify any differences between unloaded and loaded descending during realistic conditions, participants were instructed to ride at race pace during the downhill sections. Intensity of the uphill section was controlled through power output associated with respiratory compensation point and monitored by participants using the Garmin Edge 500 computer attached to the bicycle. Each condition involved participants riding the same bicycle (GT Zaskar elite 29" Full Suspension medium size, Optimized Force Constructed Carbon, USA), adjusted to personal requirements prior to the trial. This included adjustments to the saddle (height, fore and aft position); handlebar height; stem length; pedal design (riders used their own pedals); and tyre inflation pressure which was set to 0.3 psi per total weight (bike + fully clothed and helmeted cyclist (Macdermid et al., 2014a)). For each condition the bicycle was fitted with either a rear suspension system (Fox Float CTD, USA) in place and switched to trail ride (full suspension) or a solid suspension replacement part allowing no mechanical damping in the rear end of the bicycle (hardtail). Suspension settings were as per the manufacturers recommendations which equated to 25 % (12.5 mm) sag settings in the Fox Float CTD rear suspension, while the Rockshox Recon 100 mm, solo air, front forks have a recommended rider weight air setting attached to the forks e.g. 63-72 kg = 70-85 psi. The front fork setting was kept the same for both conditions. By using the same bike, mechanical trail, seen as a major determinant of a bicycles handling properties (Wilson, 2004) and bicycle weight were controlled. Conditions were performed on the same day, in a counter balanced order (separated by 15 min epochs) to prevent any order effect on the dependent variables of interest.

Outcome measures

Power output (W) and cadence (rpm) were continuously sampled and logged every second (SRAM QUARQ S2275 MTB Power Meter, USA; Garmin, Edge 500, USA) throughout the trial. The Quark CinQo powermeter has been previously used for such studies (Macdermid et al., 2014c) and has a reported accuracy ± 1.5 % (Aguilar et al., 2008). Data recorded from the power meter and global positioning device were transmitted to a conventional personal computer and processed with the Garmin Training Centre software (version 3.6.5).

Participants completed each condition wearing an automated, portable gas analyser (Cosmed K42b, Rome, Italy) enabling continuous breath by breath sampling. Data for oxygen consumption (ml·min-1·kg-1) and heart rate were logged every second allowing comparisons between conditions for work done and physiological strain when compared to performance time (s) and power output (W). Mean values of cycling economy were calculated for each terrain section and expressed in (W·L-1·min-1) (Lucia et al., 2002).

Wireless, tri-axial accelerometer, magnetometers and gyroscope with a reported accuracy 0.0012 m·s2·√Hz-1 (Emerald, APDM, OR, USA), were used in a synchronised data logging mode to measure accelerations in accordance with the International Standards (ISO 2631-1) for measuring vibrations (Iso, 1997) and reported elsewhere in similar studies (Macdermid et al., 2014c). The accelerometers were placed on the lower left arm (frontal distal position); left lower leg (frontal, distal position); seat post (within 10cm of saddle-rider contact area); lumbar region of lower back; and medial forehead (Macdermid et al., 2014c). The Emerald accelerometers were synchronised with the Garmin Edge 500 and the Cosmed K42b enabling specific terrain sections to be marked across all units (Figure 7.1). The accelerometers were sampled at 128 Hz. All data were logged, later transmitted to a standard personal computer, converted to a hierarchal data format file (.h5) and processed using MATLAB R2014a. All data were analysed for total (XYZ), vertical (Z-axis), and horizontal (X- and Y- axis) accelerations. Root mean squares of the accelerations were calculated to quantify the amount of vibration the participants experienced (Iso, 1997; Macdermid et al., 2014c).

Statistical Analysis

Descriptive data (mean, standard deviation and 95% CI where necessary) were calculated for variables measured during the laboratory ramp test (Table 5.1) and all dependent variables over the field trial. Overall data analysis of power, time, heart rate, oxygen consumption and cycling economy between conditions were compared by paired Student's t-tests to assess overall control and performance of the study. Further analysis of terrain specific sections (Figure 7.1) incorporated the use of two-way repeated-measures analysis of variance (ANOVA), with two within-subject variables (terrain*suspension) used to test differences between power output as a control measure. Performance was assessed through analysis of time while physiological effects involved the analysis of heart rate, oxygen consumption and cycling economy between conditions.

Accelerometer data comparisons (Acceleration RMS) were made via univariate analysis of variance (three-way ANOVA), including within-subject variables, suspension, terrain and accelerometer location, tested for main effects and interactions (suspension *Terrain*Location; suspension * terrain; suspension * accelerometer location; and terrain * accelerometer location).

Where significant difference was found the main effect was analysed using Bonferroni post-hoc testing for pairwise comparisons. All statistical analyses were performed using IBM SPSS Statistics 20, significance set at P<0.05.

Results

Table 5.1 shows mean ± SD values for the laboratory ramp style test.

Overall data analysis

Participants were asked to complete a lap of the course under two conditions (hardtail and full suspension) at a self-determined pace for the downhill sections (instructed to ride at race pace) and set at a power output associated with respiratory compensation point for uphill sections. Paired Student's t-tests showed no significant overall differences for power output (227 ± 43 and 232 ± 40 W, p=0.6060), time (384.9 ± 18.5 and 385.7 ± 20.8 s, p=0.6542), heart rate (156 ± 8 and 160 ± 10 bpm, p=0.3100) and V̇O2 (51.0 ± 4.4 and 51.4 ± 4.1 ml·min-1·kg-1, p=0.5647) between hardtail and full suspension, respectively.

Terrain specific data analysis

Further analysis (Two-way ANOVA) of terrain specific sections (Figure 7.1) confirmed that participant work rate was controlled as there was no interaction (terrain*condition, F(2,24)=0.1518, P=0.8600) for power output. While no main effect for suspension systems used were visible (F(2,24)=0.04903, P=0.8285) there was a significant difference over terrain (F(2,24)=171.4, P<0.0001) highlighting the greater work done climbing when compared to descending (167 ± 64, 178 ± 65 for downhill 1; 320 ± 28, 319 ± 29 for hill 1; and 129 ± 56, 135 ± 49 for downhill 2 for hardtail and full suspension, respectively (Figure 7.2B).

Analysis of performance time indicates that condition had no interaction effect on performance over the three splits (F(2,28)=0.0308, P=0.9697). A main effect for terrain (F(2,28)=559, P<0.0001) confirms greater time was spent on climbing compared with the downhills 1 or 2, but there were no post-hoc differences between downhill 1 and downhill 2 (Figure 7.2A).

Acceleration data analysis

Three-way ANOVA analysis of total acceleration amplitude (RMS) showed that there was a significant main effect for suspension (F(1,237) = 10.145; P=0.0017), terrain (F(2,235) = 324.530; P<0.0001) and accelerometer locations (F(4,231) = 577.920; P<0.0001) plus an interaction (F(8,223) = 37.092; P<0.0001) between terrain and accelerometer location (Figure 7.3 A-C). Key findings from post-hoc analysis showed that there were overall significant differences (P<0.0001) between both downhill 1 and hill 1 (95% CI, 6.7069-8.2829), and, downhill 2 and hill 1 (95% CI, 6.0656-7.6413), but not (P>0.05) between the downhill 1 and downhill 2 (95% CI, -0.1468-1.4292). Multiple comparisons between the accelerometer locations were significantly different (P<0.0001) except in the case of lower back and head (p<0.05, 95% CI = -0.6639-1.7280).

Significant main effects for vertical acceleration amplitude (RMS) for suspension (F(1,237) = 5.254; P=0.0229), accelerometer location (F(4,231) = 174.165; P<0.0001), and terrain section (F(2,235) = 122.984; P<0.0001) expressed as mean ± SD are shown in Figure 7.3 E-F. There were no interactions between variables involving suspension (suspension*terrain (p=0.915); suspension*location (p=0.402); or suspension*terrain*location (p=0.988)) although an interactions between terrain*location was identified (F(8,223) = 174.165; P<0.0001). Post-hoc analysis showed significant differences (p<0.0001) for terrain comparisons (downhill 1 and hill 1; downhill 2 and hill 1; but not between downhill 1 and downhill 2) and accelerometer location differences (p<0.01) for all monitors except the left leg and seatpost (p=0.967) and the lower back and head (p=1.0000).

Horizontal accelerations showed similar characteristics (Figure 7.3 G-I) to vertical accelerations in that there were main effects for suspension (F(1,237) = 8.468; P=0.0040), terrain (F(2,235) = 323.757; P<0.0001) and accelerometer location (F(4,231) = 664.000; P<0.0001). There were no interactions involving suspension (suspension*terrain (p=0.995); suspension*location (p=0.960); or suspension*terrain*location (p=0.965)) although terrain*location proved significant (F(8,223) = 32.727; P<0.0001). Post-hoc analysis identified differences (p<0.0001) between downhills and uphill but not downhill 1 and downhill 2. All accelerometer locations were significantly different except for the lower back and head (p>0.05).

Physiological data analysis

While variables of work indicate that the study was well controlled (Figure 7.2 A-C) and acceleration data highlights differences for the two conditions tested, the physiological measures (Figure 7.4 A-C) all showed a highly significant main effect of terrain on heart rate (F(2,42)=21.31, P<0.0001), oxygen consumption (F(2,42)= 48.60, P<0.0001), and cycling economy (F(2,42)=45.16, P<0.0001). Post-hoc analysis identified significantly lower heart rate for downhill 1 when compared to hill 1 and downhill 2 but no difference between hill 1 and downhill 2 (Figure 7.4 A). Oxygen consumption values were significantly lower for downhill 1 compared with hill 1 and downhill 2 there was also a significant difference between hill 1 and downhill 2 (Figure 7.4 B). Cycling economy mirrors oxygen consumption data to a certain extent (Figure 7.4 C) although there is a suprising decrease in cycling economy during downhill 2 when compared to both downhill 1 and hill 1.

There was no interaction between condition*terrain for heart rate (F(2,42)=0.02232, P=0.9779) and no main effect for condition (hardtail and full suspension, F(1,42)=1.570, P=0.2183) with mean ± SD equalling 140 ± 11, 164 ± 8; 157 ± 7, 144 ± 12; and 167 ± 9, 162 ± 12 bpm for downhill 1; hill 1; and downhill 2, respectively. No interactions (condition*terrain) or main effect of condition for oxygen consumption (F(2,42)=0.01612, P=0.9840; F(2,42)=0.1642, P=0.6874) or cycling economy (F(2,42)=0.07926, P=0.9240; F(2,42)=0.06065, P=0.8069) were observed with mean ± SD for oxygen consumption (41.0 ± 4.8, 41.7 ± 4.7; 58.5 ± 3.9, 58.7 ± 3.0; 48.4 ± 6.2, 49.3 ± 6.3 ml·min-1·kg-1) and cycling economy (63.3 ± 16.0, 66.1 ± 18.2; 87.8 ± 12.4, 86.8 ± 6.8; and 41.3 ± 12.4, 42.4 ± 11.3 W·L-1·min-1) for hardtail and full suspension respectively.

Three-way ANOVA (suspension, downhill No. and time) of both heart rate and oxygen consumption values averaged every 5 s (Figure 7.5) showed a main effect of downhill No. (F(1,16)=270.680, P<0.0001; F(1,16)=246.428, P<0.0001) and time (F(14,224)=3.746, P<0.0001; F(14,224)=9.474, P<0.0001) but not for suspension (F(1,16)=0.338, P=0.562; F(1,16)=0.458, P=0.499), respectively. Post-hoc analysis of comparisons between downhill 1 and downhill 2 highlights significant differences ranging from p<0.05 to p<0.0001 (Figure 7.5) for 5 s average epochs between downhill 1 and downhill 2 up to 20 s and 40 s for heart rate while differences for oxygen consumption were visible up to 25 s and 30 s for hardtail and full suspension, respectively. Significant interactions between suspension* downhill No. (F(1,16)=4.437, P=0.0362) and downhill No.*time (F(14,224)=17.478, P<0.0001) were seen for heart rate while downhill No.*time was the only significant interaction (F(14,224)=26.622, P<0.0001) for oxygen consumption.

Discussion

The aim of this study was to quantify the physiological effort associated with the unloaded compared to a loaded downhill component of cross-country mountain biking and to additionally assess the impact of two commonly used bike suspension formats (hardtail vs full suspension) on vibrations experienced and their impact on physiological measures. The main findings were: (a) overall physiological variables were significantly greater during loaded compared to unloaded descending; (b) downhill terrain increased measures associated with vibrations compared with hill climbing but not between unloaded and loaded descending; and (c) the addition of rear suspension to a bicycle significantly reduced measures of vibrations but did not create physiological or performance differences when compared to a hard-tail bicycle.

Participants were asked to complete the downhill component at race pace and the uphill component at a predetermined power output (laboratory determined respiratory compensation point). Validity of the testing depended on subjects pacing reliability, corroborated by the non-significant difference between power output and time for terrain specific sections and the overall lap between conditions (Figure 7.2). This is important as differences in participant speeds during the downhill sections could affect the level of vibrations experienced and subsequently any inference of physiological or performance differences (Macdermid et al., 2014c). Notably, all riders were very familiar with both the climb a descent, having frequently trained on the course. The similarity of accelerations within conditions and between downhill 1 and downhill 2 (Figure 7.3 A vs C; D vs F; and G vs I) indicates that vibrations were not the cause of any physiological differences that may have arisen. Previous work (Hurst & Atkins, 2006; Hurst et al., 2012; Macdermid et al., 2014c; Macdermid & Stannard, 2012) acknowledged the increased work demand of downhill riding during mountain biking, explained via the muscular work required to dampen vibrations. However, only one study (Macdermid et al., 2014c) quantified vibrations experienced while one other looked at muscle activity (Hurst et al., 2012), yet neither related their findings to any physiological variables and thus potential effects on athletic performance. Such elevated physiological variables during downhill riding could also be associated to prior work done during climbing (Macdermid & Stannard, 2012) and its subsequent metabolic effects (Gaesser & Brooks, 1983). Union Cycliste Internationale (UCI) rules govern that events must not start with downhill sections meaning that riders always negotiate downhill components under stress from high intensity efforts associated with climbing (Stapelfeldt et al., 2004). Therefore, the large differences seen between downhill 1 and downhill 2 (Figure 7.5) are likely a product of the time required for oxygen consumption and heart rate to attain a new steady state from an almost resting state as occurred for downhill 1. The participants' response to the demand of downhill 1 is similar to constant-work-rate laboratory studies performed below ventilatory threshold (Linnarsson, 1974; Whipp, Ward, Lamarra, Davis, & Wasserman, 1982) which supports the findings of this study and the levels of post-hoc signifcant differences up to 40 s, where-upon a steady state is reached in both downhill 1 and downhill 2 (Figure 5). Interestingly, unloaded descending showed overall differences for heart rate and oxygen consumption to be ~10% less compared to loaded descending. The total rise in oxygen consumption for downhill 1 was 34.2 ± 8.3 ml·min-1·kg-1 while the decrease for downhill 2 equalled -11.3 ± 5.8 ml·min-1·kg-1. These findings suggest that the steady state values reached during unloaded downhilling are much closer to the efforts attained during climbing than resting and supports previous proposals (Gregory et al., 2007a; Macdermid & Stannard, 2012) that cross-country cyclists are not afforded the same recovery periods as road cyclist when negotiating downhill sections. Figure 7.5 confirms such an effect through significantly greater values for the first 30-40 s of downhill 2 where-after values become similar. This implies a large proportion of the elevated physiological variables previously seen during descending in simulated race efforts (Gregory et al., 2007a; Macdermid & Stannard, 2012) may not be due to the extra work of damping vibrations and requires further research. However, both heart rate and oxygen consumption are elevated beyond expectations for such low power outputs (Figure 7.2) during the last 40 s of the downhill 1, intimating work other than propulsive in nature affecting measures of cycling economy.

High cycling economy values (75-85 W·L-1·min-1) have been recorded for elite road cyclists (Coyle et al., 1992; Lucia et al., 2002) reflecting whole body efficiency, and have been suggested to account for 65% performance variation in cyclists with similar oxygen consumption values (Costill, Thomason, & Roberts, 1972). The cycling economy values for participants of this study during hill 1 (87 ± 7 W·L-1·min-1) are similar to those previously reported (Lucia et al., 2002). While it is acknowledged that mechanical efficiency decreases with a decreased intensity (Faria, Parker, & Faria, 2005) considerable reductions in values of cycling economy during both downhill sections (65 ± 17 and 42 ± 11, for downhill 1 and downhill 2, respectively) reflect increased oxygen consumption for a somewhat low power output (Figure 7.2 & 7.4). This elevated oxygen consumption can be explained in the first instance by recovery processes (Gaesser & Brooks, 1983; Laforgia, Withers, & Gore, 2006) following the exertion of the climb and subsequently as a result of dealing with manoeuvering the bicycle and vibration damping during downhill mountain biking. Importantly, competitive cross-country cyclists should focus on fitness aspects that will allow them to recover quicker and develop technical aspects of bike handling and/or technological bike componentary enabling greater efficiency during downhill riding and overall performance.

One aspect currently available to athletes that may increase cycling economy through diminished non-propulsive work as a consequence of reducing vibrations experienced and subsequent improved bike handling (Ishii et al., 2003; Nishii et al., 2004) is the use of full suspension bicycles (Macdermid et al., 2014c). Firstly, the data from this study supports the concept that a full suspension mountain bike significantly decreases accelerations in the vertical and horizontal planes (Figure 7.3) concurring beliefs of earlier works (Ishii et al., 2003; Nishii et al., 2004). More importantly with regards to non-propulsive work is the fact that post-hoc analysis showed no differences for accelerometers placed at the head and lower back. This agrees with previous findings measuring the effect of wheel size on non-propulsive work (Macdermid et al., 2014c) and confirms that greater damping and therefore work is required for a given power output during the hardtail condition compared to full suspension.

We hypothesized that reductions in vibrations experienced would lead to decreased physiological stress affording increased cycling economy. This did not occur as there were no significant differences between suspension type. Closer inspection of terrain through use of effect size (Cohen's D) implies a very small positive effect of the full suspension for cycling economy during downhills (downhill 1 = 0.16 and downhill 2 = 0.10) and a very small negative effect during the uphill (hill 1 = 0.15). However, 95% CI comparison between the hardtail and full suspension overlap in all instances agreeing with the non-significant p-value reported. While these findings disagree with laboratory work (Titlestad et al., 2006b) that found adding bumps to treadmill cycling increased oxygen consumption compared to a smooth treadmill, and field studies (Herrick et al., 2011) that found hardtails were quicker over a race distance while both heart rate and oxygen consumption were not significantly different. Neither of these studies attempted to control for bike weight with the full suspension bikes disadvantaged by 1.2-2 kg, which could explain any performance or physiological differences. As is likely, any reduction in resistance to forwards momentum offered by a full suspension bike is likely small and may be hidden with such weight differences reported. This may be the case but our terrain specific data analysis does not support this as subject variability for differences was quite high. Explanations for the small effects of full suspension on improving CE during downhill cycling are centred around the biological need to protect the upper body via stabilizing specific segments (Macdermid et al., 2014c; Mester et al., 1999). As such the additional work detracts from the muscles ability to generate propulsive force through decreased availability of high-threshold motor neurons (Bongiovanni et al., 1990; Mester et al., 1999). While downhill riding tends to show low average power outputs it consists of many spikes of supramaximal efforts for acclerations after any decelerations for cornering or obstacle negotiation. Typically, muscular contraction force has been shown to be reduced by ~8% following sustained vibrations as a result of decreased synaptic transmission at the neuromuscular junction (Issurin, 2005). As such we might expect to see considerable differences in a sport like cross-country mountain bike racing when vibrations are reduced, yet our data does not agree with this. It is also worth noting that the majority of time is spent climbing during a cross-country mountain bike race and overtaking manuoevers are more viable compared to downhilling due to terrain and riding dynamics. Therefore, the small disadvantage possibly caused by riding a full suspension bike uphill would outweigh the small advantage gained during descending. Future research needs to investigate the effects over downhills longer in duration and over the complete race distance (90 mins) to determine such effects with regards to rider fatigue and physiological responses.

Conclusion

This study set out to determine the physiological demand of unloaded compared to loaded downhill cycling and the influence of two popular suspension types on vibrations experienced and the impact on physiological measures. The hypothesis that loaded downhill cycling would have greater physiological values than unloaded was found to be correct and was attributed to the time delay to achieve steady state from a resting condition (unloaded) and/or from exertion of the hill climb (loaded). Additionally, a full suspension bike significantly decreased vibrations experienced by participants but no performance or physiological benefits from using such a bike in simulated race conditions were evident. Therefore it is reasonable to suggest that the non-propulsive work (vibration damping) experienced is not large enough to detract from the performance for the duration spent descending during cross-country mountain bike racing and the physical effort associated with overall forwards momentum during downhill mountain biking requires further analysis.

Figures

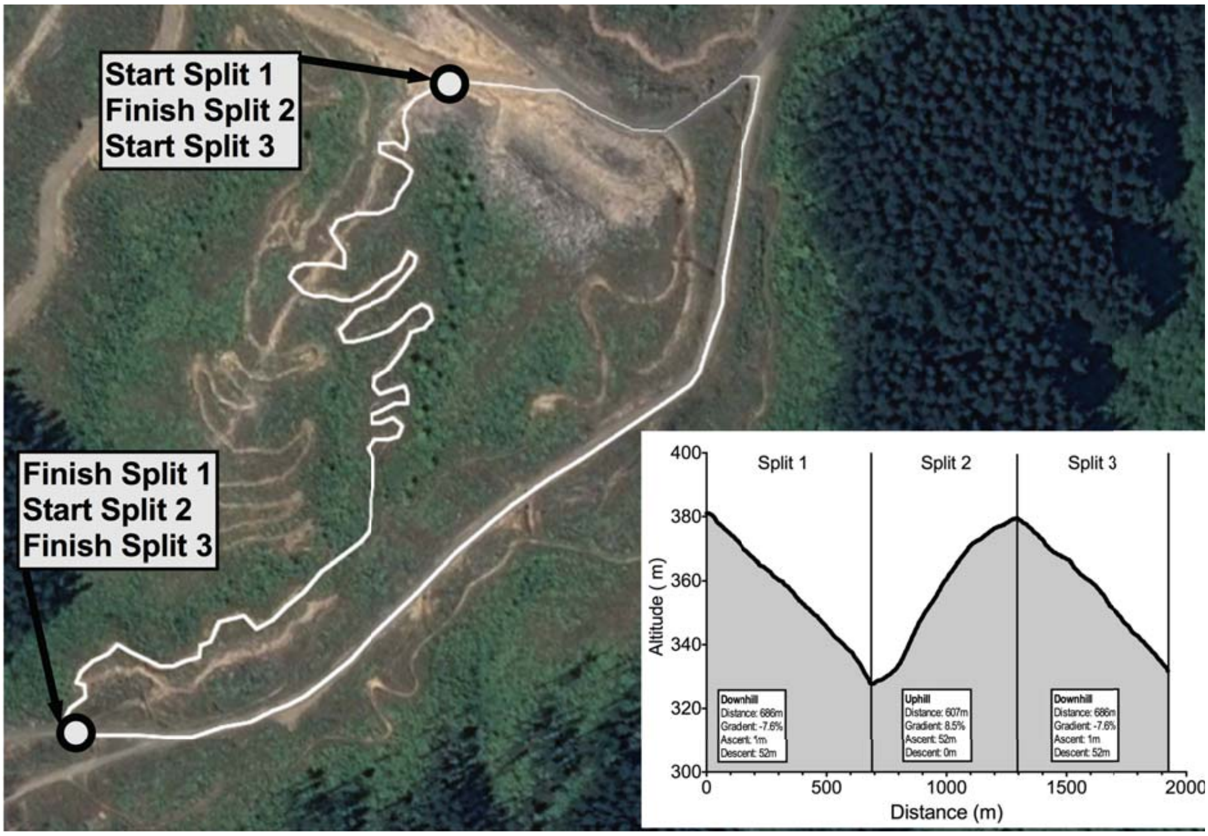


Figure 7.1: Course outline and profile signifying the terrain split sections for the field trial used in this study.

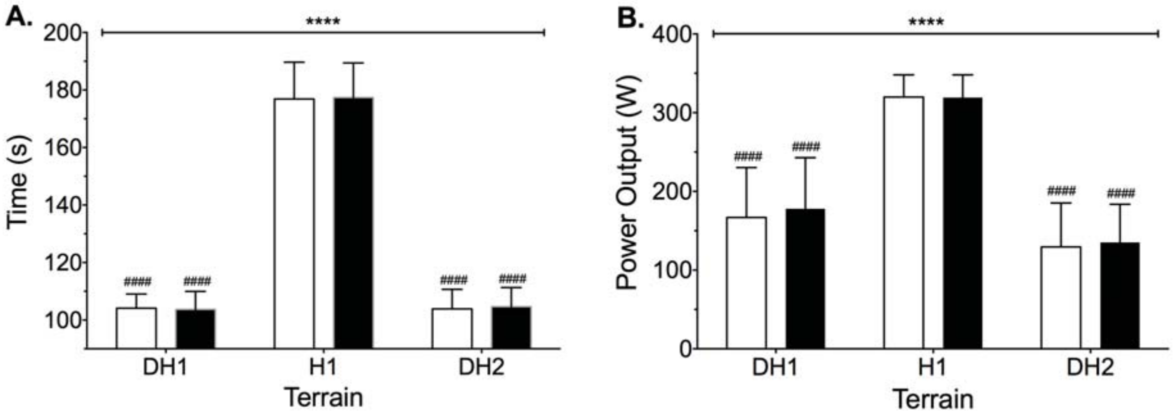


Figure 7.2: Mean ± SD for A. Time (s) ; B. Power Output (W) for terrain segments as described in figure 1 (DH1 = Downhill 1; H1 = Uphill 1; DH2 = Downhill 2). □ Signifies hardtail (HT) while ■ signifies full suspension condition.

**** (P<0.0001) main effect of terrain; Post-hoc differences within conditions when compared to H1 #### (P<0.0001).

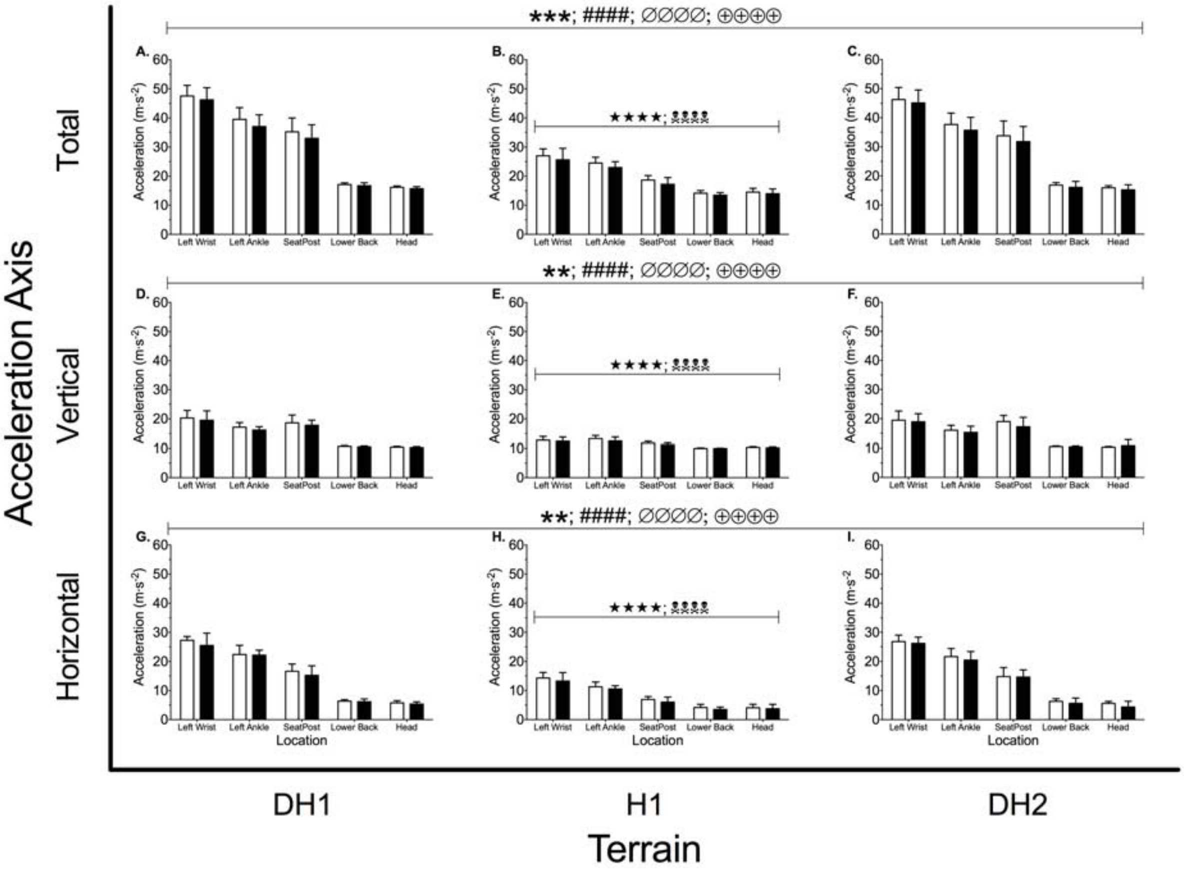


Figure 7.3: Comparisons between hardtail (HT) and full suspension (FS) for: A. Total accelerations for downhill 1 (DH1); B. Total accelerations hill 1 (H1); C. Total accelerations downhill 2 (DH2); D. Vertical accelerations downhill 1 (DH1); E. Vertical accelerations for hill 1 (H1); F. Vertical accelerations for downhill 2 (DH2); G. Horizontal accelerations for downhill 1 (DH1); G. Horizontal accelerations for hill 1 (H1); F. Horizontal accelerations for downhill 2 (DH2). ◻ Signifies hardtail (HT) while ■ signifies full suspension condition.

**** (P<0.001) main effect of suspension; #### (P<0.0001) main effect of terrain; Ø Ø Ø Ø (p<0.0001) main effect of location; ⊕⊕⊕⊕ (P<0.0001) interaction between terrain*location. Post-hoc analysis ★★★★ (p<0.0001) when compared to downhill 1; ☠☠☠☠ (P<0.0001), when compared to hill 1.

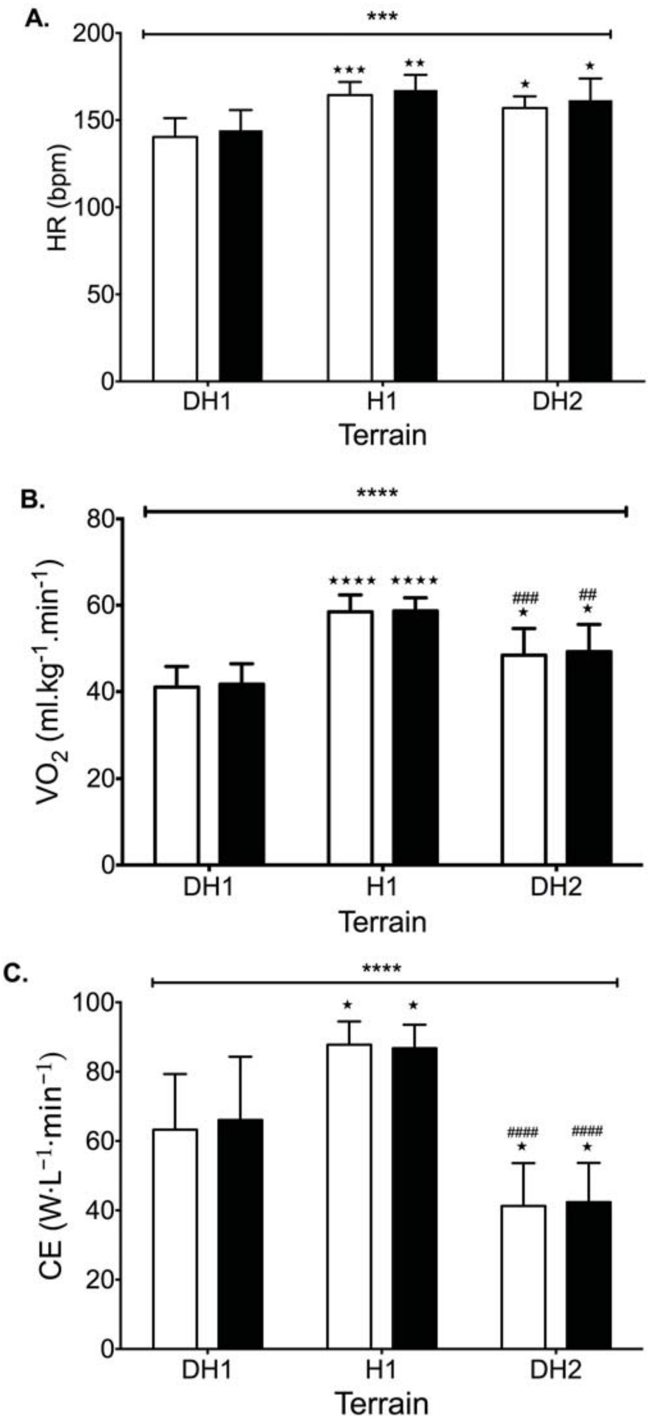


Figure 7.4: Mean ± SD for A. Heart rate (HR); B. Oxygen consumption (VO2); C. Cycling Economy (CE) for different terrain segments as described in figure 1 (DH1 = Downhill 1; H1 = hill 1; DH2 = Downhill 2). □ Signifies hardtail while ■ signifies full suspension condition.

**** (P<0.0001) main effect of terrain; ★ (P<0.05), ★★ (P<0.01), ★★★ (p<0.001) and ★★★★ (P<0.0001) when compared to DH1; ## (P<0.01), ## (P<0.001) and #### (P<0.0001) when compared to H1.

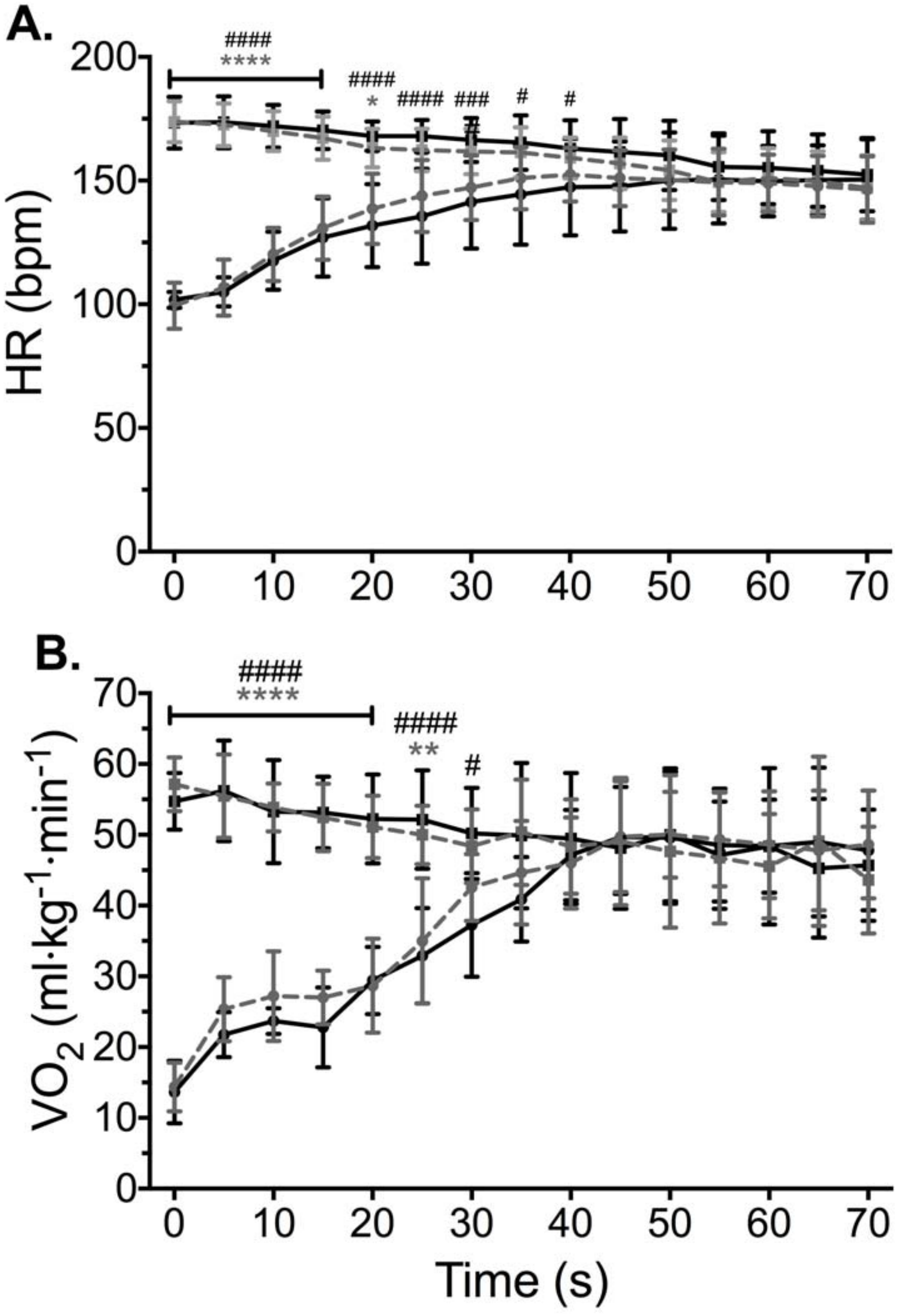


Figure 7.5: Five second average data for A. Heart rate (HR), and B. Oxygen consumption (VO2) for downhill 1 and downhill 2 for both conditions. ● signifies downhill 1 for the hardtail; ● downhill 1 for full suspension; ■ downhill 2 for hardtail; and ■ downhill 2 for full suspension.

Post-hoc differences within conditions but between downhill 1 and downhill 2: **** (p<0.0001) for hardtail; ** (P<0.01) for hardtail; ####(p<0.0001) for full suspension; ###(p<0.001) for full suspension; and # (p<0.05) for full suspension.

Tables

Table 5.1. Mean ± SD for laboratory ramp test.

Power output at maximal oxygen consumption (W)	406.4 ± 38.7
Relative power output at maximal oxygen consumption (W·kg-1)	6.43 ± 0.53
Maximal oxygen Consumption (L·min-1)	4.146 ± 0.388
Relative maximal oxygen Consumption (ml·min-1·kg-1)	65.4 ± 3.8
Heart rate maximum (bpm)	187 ± 11
Power output at ventilatory threshold (W)	256 ± 23
Power output at ventilatory threshold (W·kg-1)	4.1 ± 0.4
Heart rate at ventilatory threshold (bpm)	156 ± 10
Power output at respriatory compensation point (W)	318 ± 28
Power output at respriatory compensation point (W·kg-1)	5.0 ± 0.5
Heart rate at respriatory compensation point (bpm)	170 ± 11

CHAPTER EIGHT: SUMMARY OF FINDINGS

Overview of work

The theme of the work presented within this thesis describes the total work demand of XCO-MTB and for the first time introduces measurements associated with the proposed non-propulsive component of the sport. This extra work is quantified physiologically, and some interventions aimed at reducing non-propulsive work are tested to assess efficacy.

Study 1 (Ch.4) described the intermittent nature of propulsive work during simulated XCO-MTB race paced riding. Further, an elevated oxygen consumption and HR (reflecting increased cardiovascular demand) during periods of no propulsive work suggested a non-propulsive element to the necessary work rate in XCO-MTB. Study 2 (Ch.5) confirmed considerable impact and vibration exposure and subsequent mechanical-soft tissue damping that occurs to protect the CNS and brain during off-road riding, probably identifying the non-propulsive work. Study 3 (Ch.6) quantified this increased exposure in terms of physiological cost through comparing reduced vibration exposure and then making comparison of total work done between a smooth (on-road) and non-smooth (off-road) surface. As such, the data confirmed that significant increases in propulsive work and physiological exertion took place to enable maintenance of the same speed on (rougher) off-road terrain. Study 4 (Ch.7) aimed to cover two questions raised by the previous work. Firstly, the actual physiological cost of riding downhill in an unloaded (previously rested) state compared with loaded (previously exercised), and secondly, whether the increased demand and thus efficiency due to the non-propulsive element could be improved through the introduction of suspension systems. Study 2 also looked at technological innovation and it’s effects on performance and non-propulsive work. While not a logical step in the chronological development of the story of this thesis, the timing was apt in relation to the commercial availability of the technology; this is still the only study to have been published on the performance enhancement achieved through bigger wheel sizes.

Summary

In order to provide athletes, coaches and sports science support teams valuable performance enhancing information, a thorough understanding of the interaction between external work done and the physical and physiological consequences is required. The UCI rules dictate XCO-MTB race duration and to a certain extent the nature of the courses used. Current rules require races to entail multiple laps of 4-6 km in length, with the total race duration lasting between 60-105 minutes, age and gender dependent, and performed as a mass start. While race durations can provide a good indication of dominant energy system use or capability required, it neglects variables such as terrain profile, track surface characteristics, and positional advantage on likely work done.

The limited scientific research thus far has focussed on smoothed data (Stapelfeldt et al., 2004) and terrain averages (Gregory et al., 2007a). This lack of regard for the oscillating nature of work demand reflected by supra-maximal, short burst efforts, likely neglects changes in ratio of cadence:torque, required to negotiate the course. Current knowledge suggests that XCO-MTB athletes are not afforded the same recovery as road cyclists. This has been attributed, but not substantiated, to muscle-lung vascular transit delay pushing the short bursts of effort into recovery phases (Hurst & Atkins, 2006) and the increased energy demands of movements not associated with pedalling but course negotiation (Gregory et al., 2007a; Stapelfeldt et al., 2004). This thesis aimed to contribute to scientific literature examining physiological responses to the external work demands of XCO-MTB with specific reference to non-propulsive work in response to mechanical and soft tissue damping of vibrations. To address these aspects the thesis included a total of four original experimental investigations that involved two descriptive elements and four experimental interventions.

The descriptive demands of mechanical work and physiological responses to simulated XCO-MTB racing (Study 1, Ch.3) showed that power output, torque, and cadence constantly oscillate dependent on surface-terrain profile (uphill vs downhill) and track features such as rocks, jumps etc. Alongside a well developed aerobic capacity it was found that key movements of the sport emphasize a high demand on sporadic anaerobic energy provision. This occurred through the use of a high proportion of low velocity pedalling, entailing a large contribution of high force-low velocity muscular contractions. Therefore, signifying an important role of strength and the ability to repeatedly engage the larger motor units in performance.

Study 1 supports previous suggestions (Stapelfeldt et al., 2004) that physiological strain experienced during XCO-MTB does not parallel propulsive work done when compared with laboratory measures. The fact that there was no decrease in $\dot{V}O_2$ and an increase in HR during downhill sections associated with less work done suggests recovery was inadequate and/or extra non-propulsive work is being done. As such, it was proposed that downhill terrain could affect the sympathetic nervous system. The subsequent increased catecholamine response would increase HR beyond muscle O_2 demand. Alternate, unexplored explanations intimate that non-pedal related work (Hurst & Atkins, 2006) including terrain induced vibration damping impose significant demand on total work done. Laboratory trials into the effects of vibrations on cycling performance have shown decreased time to exhaustion by 21 % (Samuelson et al., 1989) and greater physiological demands for $\dot{V}O_2$ (50 %) and HR (35 %) (Titlestad et al., 2006b). However, neither vibration exposure during XCO-MTB nor the level of damping has been quantified from field data collection. Such knowledge could enhance athletic performance via assessing strategies to increase cycling economy in addition to reducing the risk of overuse injuries. Therefore, Study 2 (Ch.4) aimed to describe the frequency-magnitude relationship, the amplitude of accelerations and the interaction between terrain, bicycle and rider during a simulated race paced XCO-MTB lap.

The findings showed that accelerations were significantly greater at the point of interface between bike-body (Figure 8.1) compared with the lower back and head. This indicates that considerable damping ocurred, presumably to protect the axial skeleton. This effect was significantly influenced by terrain characteristics and as such acceleration exposure was much greater during descents compared to ascents except in the case of the head where it is important to limit transferance in order to maintain visual acuity, vestibular signals and decision making processes (Grether, 1971; Newell & Mansfield, 2008; Pozzo et al., 1995). While future research needs to quantify the extra physiological demands of increased vibration damping associated with XCO-MTB and the effects of decreased vibration exposure on performance. The findings here provide athletes, coaches and high performance teams useful information regarding the importance of planning specific XCO-MTB training and the use of ergonomic design features to reduce overuse injuries and enhance recovery from races or key training sessions.

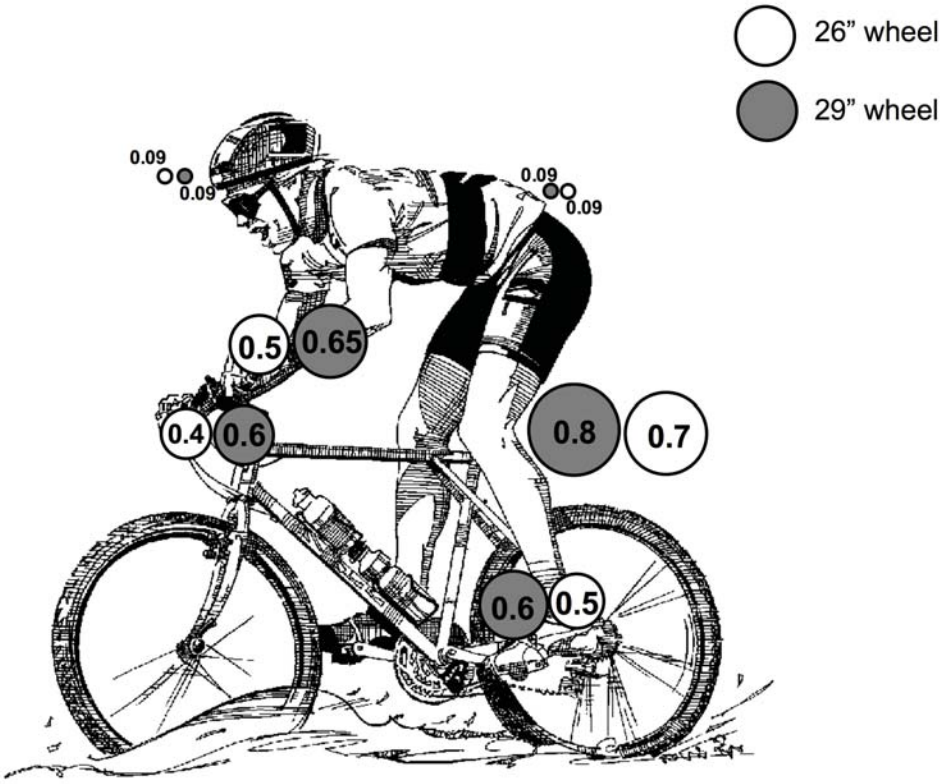


Figure 8.1: Mean vertical accelerations (g) experienced by participants during a XCO-MTB lap performed at race pace for accelerometer locations: ankle, handlebar, seatpost, wrist, lower back, and forehead. The size of the circles are in proportion.

In continuation of Study 2, Study 3 (Ch.5) tested the hypothesis that reducing terrain-surface vibrations would alter propulsive and non-propulsive work done, consequentially increasing physiological requirement with speed controlled. The main findings proved the hypothesis to be correct in that Off-Rd cycling exposed participants to significantly greater accelerations compared to Rd (Figure 8.2).

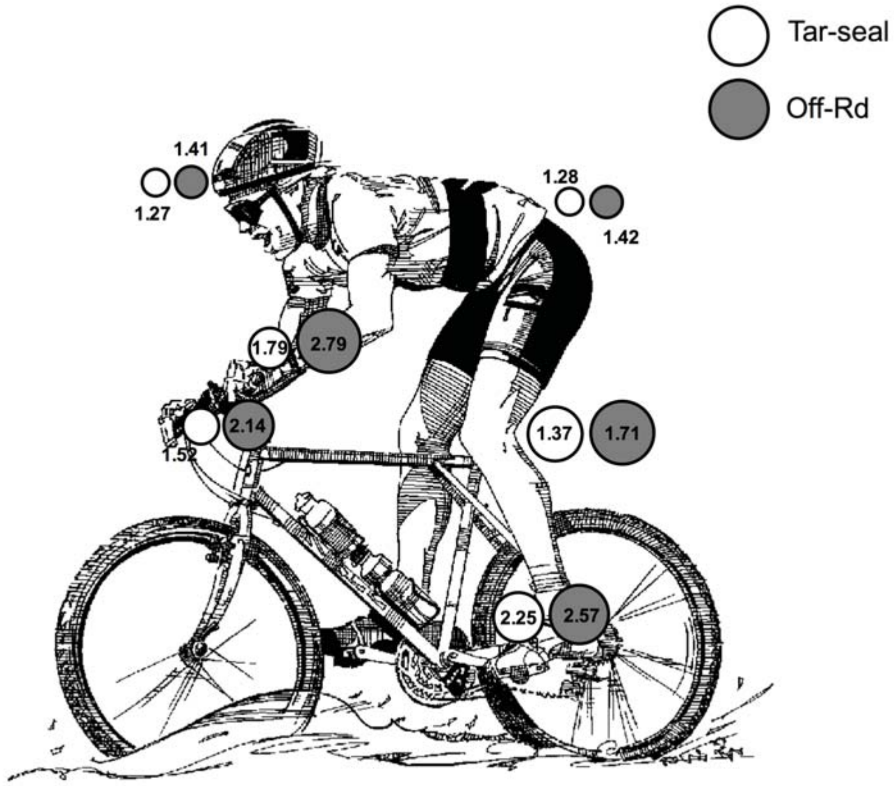


Figure 8.2: Mean total accelerations (g) experienced by participants during a climb identical in length and gradient but differing in surface (tarsealed vs off-rd) performed at the same speed with accelerations measured at: ankle, handlebar, seatpost, wrist, lower back, and forehead. The size of the circles are in proportion.

In agreement with the findings of Study 2, differences between accelerometer locations ocurred within and between conditions at the point of interface for bike-body, but not the lower back and head. Furthermore, the extra damping as a result of increased surface vibrations increased propulsive work demand from 280 ± 69 W to 312 ± 74 W for Rd and Off-Rd, respectively. Subsequently, both HR (+9 bpm) and $\dot{V}O_2$ (+2.9 $ml\cdot min^{-1}\cdot kg^{-1}$) increased significantly, reflecting a decrease in gross efficiency by 5.4 %. These results further support the assertion that technological interventions capable of reducing acceleration exposure at the bike-body interface could enhance performance through increased economy and a decrease in risk of overuse injuries. As such this theory was explored by means of altering suspension systems enabled (Study 4, Ch.6) and wheel size (Study 2, Ch.4) while riding a XCO-MTB course at race pace. Suspension systems have been available for XCO-MTB since the early 1990's with the purpose of increasing wheel-ground contact time. This would also decrease the effects of terrain surface variability on the negative effects of excursion mechanics with regards to soft tissue damping. Study 4 tested the latter through investigating the interaction between suspension systems (hardtail vs full suspension), terrain (uphill vs downhill), and accelerometer location (handlebar, wrist, ankle, seatpost, lowerback and forehead). Results presented significant main effects for total amplitude (RMS) experienced in all three aspects, plus an interaction between terrain*accelerometer location ($p<0.0001$). Post-hoc analysis identified differences in vibration exposure between the hill climb and both downhills but not between downhills. Additional analysis of acceleration direction indicated that vertical (z-axis) accelerations were also significantly reduced . This validates the capability of full suspension bicycles to decrease vibration exposure and thus additional non-propulsive work required for damping vibrations. Physiological analysis of the data for the two conditions revealed that prior uphill riding at race pace (loaded) added significant physiological stress to downhill riding when compared to unloaded downhill riding. The hypothesis presented, suggested that an intervention capable of reducing additional, non-propulsive work such as soft tissue vibration damping would reduce physiological strain or enhance subsequent downhill performance. This was unfounded when comparisons between hardtail and full suspension were made. Interestingly, there were no overall physiological differences between the hill climb and the loaded downhill. Alternatively, any benefit of reduced non-propulsive work during the downhill component was not reflected in an increased cycling economy during the uphill component following unloaded descending. However, Study 4 isolated the suspension systems being used and in a real world setting full suspension bicycles are typically ~1.2 kg heavier than hardtail equivalents. This additional weight has a negative impact on climbing performance in the region of 2.4 % or 177.1 ± 12.0 and 181.4 ± 12.3 s for hardtail and full suspension, respectively.

Limitations of Thesis

Due to the limited peer reviewed scientific literature regarding XCO-MTB performance and physiological responses the first study of this thesis set out to further understand the physiological response to the work done. While Study 1 (Ch.3) developed current understanding it lacked the competitive and physical element of an actual race. Although participants were instructed to approach the trial with the same intensity as a race, the physicality and psychological aspects of a race are known to drive physiological variables to higher levels than simulated scenarios. However, comparable comparisons with data recorded at races suggests this is not always the case . More importantly Study 1 used a laboratory derived linear relationship between power output and $\dot{V}O_2$ to determine O_2 demand for known power output values during the field trial. However, it is not understood how this relationship changes when performing repetitive bouts of high intensity exercise with an element of fatiguability as occurs during XCO-MTB. As such it is possible that anaerobic contribution was underestimated.

Study 1 confirmed the possibility of an increased non-propulsive work demand during XCO-MTB which could be presented via forced vibration as a result of transferance from the interaction of bicycle with terrain but it required quantifying.

Therefore, Study 2 explored vibration exposure and its transferance from terrain-surface to bike and body. Participants were asked to complete a lap at race pace in order to quantify the level of vibration exposure under two conditions (26” and 29”wheel sizes). While there were no significant differences for HR and power output between conditions suggesting that intensity was controlled there was significant difference for performance time favouring the 29” wheels. As such average speed was greater and although unsubstantiated, could result in an increased level of vibration exposure. Therefore, it was only possible to assess the performance value of the two wheel sizes rather than the damping capability of the wheels. Also, through controlling frame geometry in order to isolate wheelsize effect overall bicycle performance may have been compromised and the results may not reflect the true performance of a 26” and 29” XCO-MTB bicycle as a whole.

Study 3 (Ch. 5) explored the physiological cost of vibrations by changing the track surface participants cycled upon. While the study was well controlled and achieved the proposed aim it was not possible to differentiate between the work done and subsequent physiological effects of the voluntary and involuntary movements identified via accelerometry measurements. While this is potentially important to understand such capability is currently unavailable and likely unachievable given the time delay response of human physiology.

Study 4 (Ch.6) investigated the effects of decreasing vibration exposure levels through the intervention of suspension systems used. While vibration exposure was significantly altered there were no physiological differences when power output was controlled for. As such performance effects during ascent were not possible to determine for the different suspension systems tested. This could have been achieved through the addition of an extra climb where participants were required to work at maximal effort. However, it was felt that this was out of the scope of this study.

Future Directions

This thesis contributed to further understand the work demands and physiological responses to XCO-MTB with particular reference to non-propulsive work demand imparted by forced vibrations. While descriptive and intervention studies have been performed there are still numerous questions to be explored.

The initial descriptive investigation into the work demand of XCO-MTB highlighted important aspects of the sport for participants, coaches, and sports scientists. Athlete requirements revolve around the continual capability to produce high power outputs in the high force - low velocity range compared to other cycling disciplines; a high tolerance to intermittent high intensity exercise for long durations combined with a high cardiorespiratory function, already established. Therefore, traditional laboratory measures which rely on the linear relationship between power output and $\dot{V}O_2$ requires further thought in terms of how it relates to XCO-MTB field performance. Lastly and key to the remainder of this thesis is understanding non-propulsive work demand, it’s influence on gross economy, recovery, and performance.
Study 2 higlighted the significant soft-tissue damping that occurred at the point of interface between bicycle-body. These findings suggest, but requires further investigation, that off-road cyclists are susceptibility to overuse injuries at the lower back, ankles, knees, wrists, elbows and shoulders.

Through identification of vibration exposure levels during XCO-MTB (Study 2, Ch.4) the next step is to attain the extra demand of vibrations on physiological response and athlete capability with regards to propulsive and non-propulsive work done, and the relationship with speed travelled. The latter is important as any intervention designed to decrease vibration exposure would likely increase performance and therefore speed, exposing participants to the same exposure levels prior to intervention. This likely outcome was identified in the secondary aim of study 2, where 29” wheels were faster than 26” wheels for the same work done, yet vibration exposure was greater. In order to decrease risk to overuse injuries amongst recrational riders and those riding XCO-MTB style terrain for long periods of time it would be useful to determine wheelsize effect on vibration exposure level and damping in addition to specifically made bicycles performance capabilities.

Study 3 (Ch.5) determined the effect of surface terrain on work demand and cycling economy whilst cycling uphill. In finding greater exposure to >5 Hz frequencies (involuntary) on the road and a greater <5 Hz frequencies (voluntary) off-road. Further research could aim to separate voluntary and involuntary movements on measures of performance along with tyre tread pattern-surface interactions effect. The findings of Study 3 also suggests that decreases in vibration exposure and thus damping requirements leads to increased cycling economy and potentially an increase in performance. As such, interventions aimed at decreasing vibrations including frame and componentary construction, tyre volumes, tyre pressures, suspension systems and technique are all worth pursuing. Study 4 (Ch.6) added to the understanding of non-propulsive work demand and recovery during the downhill component of XCO-MTB in relation to the addition of rear suspension. In showing that a full suspension bicycle significantly decreased vibration exposure but produced only a small effect on physiological responses requires further study. Establishing the effect of this sustained decrease in vibration exposure over a complete race distance is important and may reflect significant performance enhancement not seen in short trials. In addition it would be advantageous to coaches and athletes to determine the influence of weight (functional, non-functional, and rotational) on performance. This would allow informed decision regarding the use of heavier equipment that may decrease vibration exposure levels but which is uncertain in terms of the comfort-performance balance.

Conclusion

The combined findings of this thesis indicates that the physiological stress of participating in the sport of cross-country mountain biking is primarily influenced by the geographical profile and course obstacles; superfluous to seeking positional advantage over opponents. Consequently, this results in a high oscillating work rate that is composed of a large proportion of high force-low velocity pedaling compared to other cycling disciplines. This presents itself via a high relative aerobic contribution throughout race distance with intermittent anaerobic contributions associated with obstacles and/or feature negotiation. Surface-terrain, obstacles and bicycle handling requirements do not afford the same recovery advantages of on-road cycling due to a significantly greater non-propulsive element. This is emphasized through the non-variable physiological response over a complete lap in relation to uphill and downhill cycling.

A key aspect of the investigative research component of this thesis was the exploration of vibration exposure during cross-country mountain biking and its relationship with this non-propulsive element of work done. In this regard, quantification of vibration exposure identified considerable high levels and may indeed warrant concern in regards to overuse injuries associated with extra load of off-road cycling. Accelerometer data analysis emphasizes considerable soft-tissue damping at the point of interface between bike-body compared to the lower back and forehead. While this occurred throughout all aspects of the terrain profile it was particularly high during the downhill component.

Comparison of riding at the same speed on a surface that induced greater exposure to vibrations, highlighted significant increases in work done and physiological responses. However, technological interventions aimed at reducing exposure provided equivocal findings. While a full suspension bicycle significantly reduced vibration exposure there were no effects on performance or physiological responses. It was proposed that a protocol longer in duration could identify physiological benefit worthy of consideration of using full suspension bicycles in over a complete race distance with regards to increased cycling economy. Regardless, the reduction of vibration exposure suggests athletes performing large components of off-road training should consider the use of a full suspension bicycle to decrease the risk of long term overuse injuries. Secondly, the use of larger wheels increased performance but the subsequent increase in velocity amplified the vibration response compared to smaller wheels.

As such this thesis adds practical application to the sport of cross-country mountain biking in regards to:

1. Training specificity for propulsive and non-propulsive elements.

2. Consideration of the additional load posed by greater vibration exposure associated with volume of off-road bicycling in relation to the risk of overuse injuries.

3. Implementation of technological systems to reduce vibration exposure during training but not as a means of performance enhancement.

4. The exploration of wheel size(s) and increased performance but not as a strategy for reducing vibration exposure and the subsequent injury risk

REFERENCES

Abbis, R. C., Quod, J. M., Martin, T. D., Netto, J. K., Nosaka, K., Hamilton, L., . . . Laursen, B. P. (2006). Dynamic Pacing Strategies during the Cycle Phase of an Ironman Triathlon. *Medicine & Science in Sports & Exercise, 38*(4), 726-734.

Abbiss, C. R., Ross, M. L. R., Garvican, L. A., Ross, N., Pottgiesser, T., Gregory, J., & Martin, D. T. (2013). The distribution of pace adopted by cyclists during a cross-country mountain bike World Championships. *Journal of Sports Sciences, 31*(7), 787-794. doi: 10.1080/02640414.2012.751118

Aguilar, S., Becker, P., Gonzalez, D., Kaminski, B., Knopp, N., Jankhot, C., . . . Tsosie, H. (2008). *Power Measurement for Road Bicycles: Towards a Universal Solution (Semester Unknown) IPRO 324.* Retrieved from http://216.47.136.230/bitstream/handle/10560/1677/Power Measurements for Road Bikes IPRO 324 Final Report F08.pdf?sequence=4

Aisbett, B., Rossignol, P. L., & Sparrow, W. A. (2003). The influence of pacing during 6-minute supramaximal cycle ergometer performance. *Journal of Science and Medicine in Sport, 6*(2), 187-198. doi: 10.1016/s1440-2440(03)80254-2

Allen, H. C., Andrew. (2006). *Training and racing with a power meter*. Boulder, CO: Velopress.

Atkinson, G., Peacock, O., & Law, M. (2007). Acceptability of power variation during a simulated hilly time trial. *International journal of sports medicine, 28*(2), 157-163. doi: 10.1055/s-2006-924209

Baron, R. (2001). Aerobic and anaerobic power characteristics of off-road cyclists. *Medicine and Science in Sports and Exercise, 33*(8), 1387-1393.

Barstow, T. J., & Mole, P. A. (1991). Linear and nonlinear characteristics of oxygen uptake kinetics during heavy exercise. *Journal of applied physiology, 71*(6), 2099-2106.

Beaver, W. L., Wasserman, K., & Whipp, B. J. (1986). A new method for detecting anaerobic threshold by gas exchange. *J Appl Physiol, 60*(6), 2020-2027.

Berry, M., Woodward, M., Dunn, C., Edwards, D., & Pitt-Man, C. (1993). The effects of a mountain bike suspension system on metabolic energy expenditure. *Cycling Sci, 5*, 8-14.

Bertucci, W. M., Rogier, S., & Reiser, R. F. (2013). Evaluation of aerodynamic and rolling resistances in mountain-bike field conditions. *Journal of sports sciences*, 1-8. doi: 10.1080/02640414.2013.792945

Bishop, D. (2000). Physiological predictors of flat-water kayak performance in women. *European Journal of Applied Physiology, 82*(1), 91-97. doi: 10.1007/s004210050656

Bishop, D., Bonetti, D., & Dawson, B. (2002). The influence of pacing strategy on [latin capital V with dot above]O2 and supramaximal kayak performance. *Medicine & Science in Sports & Exercise, 34*(6), 1041-1047.

Bongiovanni, L. G., Hagbarth, K. E., & Stjernberg, L. (1990). Prolonged muscle vibration reducing motor output in maximal voluntary contractions in man. *The Journal of physiology, 423*(1), 15-26.

Carr, C. E., Meyen, F., Domingues, A. R., Newman, D. J., & Jacobs, S. E. (2012). *Ryan L. Kobrick, PhD*. Paper presented at the 63rd International Astronautical Congress, Naples, Italy. http://web.mit.edu/aeroastro/www/people/dnewman/pdf2/IAC_draftOct2012_v7.pdf

Chavarren, J., & Calbet, J. A. L. (1999). Cycling efficiency and pedalling frequency in road cyclists. *European Journal of Applied Physiology and Occupational Physiology, 80*(6), 555-563. doi: 10.1007/s004210050634

Costill, D. L., Thomason, H., & Roberts, E. (1972). Fractional utilization of the aerobic capacity during distance running. *Medicine and science in sports, 5*(4), 248-252.

Coyle, E. F., Sidossis, L. S., Horowitz, J. F., & Beltz, J. D. (1992). Cycling efficiency is related to the percentage of type I muscle fibers. *Med Sci Sports Exerc, 24*(7), 782-788.

Coza, A., Nigg, B. M., & Fliri, L. (2010). Quantification of Soft-Tissue Vibrations in Running: Accelerometry Versus High-Speed Motion Capture. *Journal of applied biomechanics, 26*(3), 367-373.

Davis, J. A., Frank, M. H., Whipp, B. J., & Wasserman, K. (1979). *Anaerobic threshold alterations caused by endurance training in middle-aged men* (Vol. 46).

de Koning, J. J., Bobbert, M. F., & Foster, C. (1999). Determination of optimal pacing strategy in track cycling with an energy flow model. *Journal of Science and Medicine in Sport, 2*(3), 266-277. doi: 10.1016/s1440-2440(99)80178-9

De Lorenzo, D. S., & Hull, M. (1997). *Quantification of structural loading during off-road cycling.* University of California, Davis.

Duffield, R., Dawson, B., Pinnington, H., & Wong, P. (2004). Accuracy and reliability of a Cosmed K4b 2 portable gas analysis system. *Journal of Science and Medicine in Sport, 7*(1), 11-22.

Faiss, R., Praz, M., Meichtry, A., Gobelet, C., & Deriaz, O. (2007). The effect of mountain bike suspensions on vibrations and off-road uphill performance. *The Journal of sports medicine and physical fitness, 47*(2), 151-158.

Faria, E. W., Parker, D. L., & Faria, I. E. (2005). The Science of Cycling: Factors Affecting Performance - Part 2. *Sports medicine, 35*(4), 313-337.

Gaesser, G. A., & Brooks, G. A. (1983). Metabolic bases of excess post-exercise oxygen consumption: a review. *Medicine and Science in Sports and Exercise, 16*(1), 29-43.

Gastin, P. B. (2001). Energy system interaction and relative contribution during maximal exercise. *Sports Medicine, 31*(10), 725-741.

Gregory, J., Johns, D. P., & Walls, J. T. (2007a). Relative vs. absolute physiological measures as predictors of mountain bike cross-country race performance.

Journal of Strength and Conditioning Research, 21(1), 17-22. doi: 10.1519/R-17635.1

Gregory, J., Johns, D. P., & Walls, J. T. (2007b). Relative vs. absolute physiological measures as predictors of mountain bike cross-country race performance. *Journal of Strength and Conditioning Research, 21*(1), 17-22. doi: 10.1519/R-17635.1

Grether, W. F. (1971). Vibration and Human Performance1. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 13*(3), 203-216. doi: 10.1177/001872087101300301

Hamill, J., Derrick, T., & Holt, K. (1995). Shock attenuation and stride frequency during running. *Human Movement Science, 14*(1), 45-60.

Hamilton, L., Martin, D., Anson, J., Grundy, D., Stephens, B., Gore, C. (2007). *Power output during successful mountain bike and road cycling performances.* . Paper presented at the 12th Annual Congress of the ECSS, Jyvaskyla, Finland.

Herrick, J. E., Flohr, J. A., Wenos, D. L., & Saunders, M. J. (2011). Comparison of physiological responses and performance between mountain bicycles with differing suspension systems. *International journal of sports physiology and performance, 6*(4), 546-558.

Hines, W., O'Hara-Hines, R., & Brooke, J. (1987). A multivariate solution for cyclic data, applied in modelling locomotor forces. *Biological cybernetics, 56*(1), 1-9.

Hurst, H. T., & Atkins, S. (2006). Power output of field-based downhill mountain biking. *Journal of Sports Sciences, 24*(10), 1047-1053. doi: 10.1080/02640410500431997

Hurst, H. T., Swarén, M., Hébert-Losier, K., Ericsson, F., Sinclair, J., Atkins, S., & Holmberg, H.-C. (2012). Influence of course type on upper body muscle activity in elite Cross-Country and Downhill mountain bikers during off Road Downhill Cycling *Journal of Science and Cycling* (Vol. 1, pp. 2-9).

Impellizzeri, F., Ebert, T., Sassi, A., Menaspà, P., Rampinini, E., & Martin, D. (2008). Level ground and uphill cycling ability in elite female mountain bikers and road cyclists. *European Journal of Applied Physiology, 102*(3), 335-341. doi: 10.1007/s00421-007-0590-9

Impellizzeri, F., M, Sassi, A., Rodriguez-Alonso, M., Mognoni, P., & Marcora, S. (2002). Exercise intensity during off-road cycling competitions. *Medicine and Science in Sports and Exercise, 34*(11), 1808-1813.

Impellizzeri, F. M., & Marcora, S. M. (2007). The Physiology of Mountain Biking. *Sports medicine, 37*(1), 59-71.

Impellizzeri, F. M., Marcora, S. M., Rampinini, E., Mognoni, P., & Sassi, A. (2005). Correlations between physiological variables and performance in high level cross country off road cyclists. *British Journal of Sports Medicine, 39*(10), 747-751. doi: 10.1136/bjsm.2004.017236

Impellizzeri, F. M., Rampinini, E., Sassi, A., Mognoni, P., & Marcora, S. (2005). Physiological correlates to off-road cycling performance. *Journal of sports sciences, 23*(1), 41-47.

Ishii, T., Umerura, Y., & Kitagawa, K. (2003). Influences of mountain bike suspension systems on energy supply and performance. *Japanese Journal of Biomechanics in Sports and Exercise, 7*, 2-9.

ISO, I. O. f. S.-. (1997). Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration - Part 1 : General requirements. [Geneva].

Issurin, V. B. (2005). Vibrations and their applications in sport. A review. *The Journal of sports medicine and physical fitness, 45*(3), 324-336.

Jäncke, L., Steinmetz, H., Benilow, S., & Ziemann, U. (2004). Slowing fastest finger movements of the dominant hand with low-frequency rTMS of the hand area of the primary motor cortex. *Experimental Brain Research, 155*(2), 196-203.

Jobson, S. A., Passfield, L., Atkinson, G., Barton, G., & Scarf, P. (2009). The analysis and utilization of cycling training data. *Sports medicine, 39*(10), 833-844. doi: 10.2165/11317840-000000000-00000

Kay, B. A., Saltzman, E. L., & Kelso, J. (1991). Steady-state and perturbed rhythmical movements: A dynamical analysis. *Journal of Experimental Psychology: Human Perception and Performance, 17*(1), 183.

Laforgia, J., Withers, R., & Gore, C. (2006). Effects of exercise intensity and duration on the excess post-exercise oxygen consumption. *Journal of sports sciences, 24*(12), 1247-1264.

Lee, H., Martin, D. T., Anson, J. M., Grundy, D., & Hahn, A. G. (2002). Physiological characteristics of successful mountain bikers and professional road cyclists. *Journal of Sports Sciences, 20*(12), 1001-1008.

Levy, M., & Smith, G. (2005). Effectiveness of vibration damping with bicycle suspension systems. *Sports Engineering, 8*(2), 99-106. doi: 10.1007/bf02844008

Linnarsson, D. (1974). Dynamics of pulmonary gas exchange and heart rate changes at start and end of exercise. *Acta physiologica Scandinavica. Supplementum, 415*, 1.

Lucía, A., Hoyos, J., & Chicharro, J. L. (2001). Physiology of professional road cycling. *Sports medicine, 31*(5), 325-337.

Lucia, A., Hoyos, J., Perez, M., & Chicharro, J. L. (2000). Heart rate and performance parameters in elite cyclists: a longitudinal study. *Medicine and Science in Sports and Exercise, 32*(10), 1777-1782.

Lucia, A., Hoyos, J., Perez, M., Santalla, A., & Chicharro, J. L. (2002). Inverse relationship between VO2max and economy/efficiency in world-class cyclists. / Relation inversee entre la puissance maximale aerobie et l ' economie / rendement chez des cyclistes de niveau mondial. *Medicine & Science in Sports & Exercise, 34*(12), 2079-2084.

Macdermid, P., & Morton, R. (2012). A longitudinal analysis of start position and the outcome of World Cup cross-country mountain bike racing. *Journal of sports sciences, 30*(2), 175.

Macdermid, P. W., & Edwards, A. M. (2010). Influence of crank length on cycle ergometry performance of well-trained female cross-country mountain bike athletes. *European Journal of Applied Physiology, 108*(1), 177-182. doi: DOI 10.1007/s00421-009-1197-0

Macdermid, P. W., Fink, P. W., & Stannard, S. R. (2014a). The influence of tyre characteristics on measures of rolling performance during cross-country mountain biking. *Journal of Sports Sciences*, 1-9. doi: 10.1080/02640414.2014.942682

Macdermid, P. W., Fink, P. W., & Stannard, S. R. (2014b). Transference of 3D accelerations during cross country mountain biking. *Journal of Biomechanics, 47*(8), 1829-1837. doi: http://dx.doi.org/10.1016/j.jbiomech.2014.03.024

Macdermid, P. W., Fink, P. W., & Stannard, S. R. (2014c). Transference of 3D accelerations during cross country mountain biking. *Journal of biomechanics, 47*(8), 1829-1837.

Macdermid, P. W., & Stannard, S. (2012). Mechanical work and physiological responses to simulated cross country mountain bike racing. *Journal of sports sciences, 30*(14), 1491-1501. doi: 10.1080/02640414.2012.711487

MacDougall, J. (1977). The anaerobic threshold: its significance for the endurance athlete. *Can J Appl Sports Sci, 2*(137-140), 1977.

MacRae, H.-H., Hise, K. J., & Allen, P. J. (2000). Effects of front and dual suspension mountain bike systems on uphill cycling performance. *Medicine and science in sports and exercise, 32*(7), 1276-1280.

Matthew C Miller, P. W. M., Phil W Fink, Stephen R Stannard. (InPress). Agreement between the Powertap, Quarq, and Stages 1 powermeters for cross-country mountain biking. *Sports Technology*.

Mavrommataki, E., Bogdanis, G.C., Kaloupsis, S., Maridaki, M. (2006). Recovery of power output and heart rate kinetics during repeated bouts of rowing exercise with different rest intervals. *Journal of sports Science and medicine, 5*, 115-122.

Medbo, J. I., Mohn, A. C., Tabata, I., Bahr, R., Vaage, O., & Sejersted, O. M. (1988a). Anaerobic capacity determined by maximal accumulated O2 deficit. *Journal of Applied Physiology, 64*(1), 50-60.

Medbo, J. I., Mohn, A. C., Tabata, I., Bahr, R., Vaage, O., & Sejersted, O. M. (1988b). Anaerobic capacity determined by maximal accumulated O2 deficit. *Journal of applied physiology, 64*(1), 50-60.

Mercer, J., Bates, B., Dufek, J., & Hreljac, A. (2003). Characteristics of shock attenuation during fatigued running. *Journal of Sports Science, 21*(11), 911-919.

Mester, J., Spitzenfeil, P., Schwarzer, J., & Seifriz, F. (1999). Biological reaction to vibration - implications for sport. *Journal of Science and Medicine in Sport, 2*(3), 211-226. doi: 10.1016/s1440-2440(99)80174-1

Mitchell, J. H., Payne, F. C., Saltin, B., & Schibye, B. (1980). The role of muscle mass in the cardiovascular response to static contractions. *The Journal of Physiology, 309*(1), 45-54. doi: 10.1113/jphysiol.1980.sp013492

Newell, G. S., & Mansfield, N. J. (2008). Evaluation of reaction time performance and subjective workload during whole-body vibration exposure while seated in upright and twisted postures with and without armrests. *International Journal of Industrial Ergonomics, 38*(5–6), 499-508. doi: 10.1016/j.ergon.2007.08.018

Nigg, B. M., & Liu, W. (1999). The effect of muscle stiffness and damping on simulated impact force peaks during running. *Journal of biomechanics, 32*(8), 849-856.

Nishii, T., Umemura, Y., & Kitagawa, K. (2004). Full suspension mountain bike improves off-road cycling performance. *The Journal of sports medicine and physical fitness, 44*(4), 356-360.

Padilla, S., Mujika, I., Cuesta, G., & Goiriena, J. J. (1999). Level ground and uphill cycling ability in professional road cycling. *Medicine and science in sports and exercise, 31*(6), 878-885.

Padilla, S., Mujika, I., Orbañanos, J., & Angulo, F. (2000). Exercise intensity during competition time trials in professional road cycling. *Medicine and science in sports and exercise, 32*(4), 850-856. doi: 10.1097/00005768-200004000-00019

Padilla, S., Mujika, I., Orbañanos, J., Santisteban, J., Angulo, F., & José Goiriena, J. (2001). Exercise intensity and load during mass-start stage races in professional road cycling. *Medicine and science in sports and exercise, 33*(5), 796-802. doi: 10.1097/00005768-200105000-00019

Périard, J. D., Cramer, M. N., Chapman, P. G., Caillaud, C., & Thompson, M. W. (2011). Cardiovascular strain impairs prolonged self-paced exercise in the heat. *Experimental physiology, 96*(2), 134-144. doi: 10.1113/expphysiol.2010.054213

Pozzo, T., Levik, Y., & Berthoz, A. (1995). Head and trunk movements in the frontal plane during complex dynamic equilibrium tasks in humans. *Experimental Brain Research, 106*(2), 327-338.

Prins, L., Terblanche, E., & Myburgh, K. H. (2007). Field and laboratory correlates of performance in competitive cross-country mountain bikers. *Journal of Sports Sciences, 25*(8), 927-935. doi: 10.1080/02640410600907938

Rasmussen, K. (1982). A note on the calculation of sound propagation over impedance jumps and screens. *Journal of sound and Vibration, 84*(4), 598-602.

Redfield, R. (2005). Large motion mountain biking dynamics. *Vehicle System Dynamics, 43*(12), 845-865. doi: 10.1080/00423110412331289844

Reilly, T., & Thomas, V. (1976). A motion analysis of work-rate in different positional roles in professional football match-play. *Journal of human movement studies, 2*(2), 87-97.

Roston, W. L., Whipp, B. J., Davis, J. A., Cunningham, D. A., Effros, R. M., & Wasserman, K. (1987). Oxygen uptake kinetics and lactate concentration during exercise in humans. *American Review of Respiratory Disease, 135*(5), 1080-1084.

Samuelson, B., Jorfeldt, L., & Ahlborg, B. (1989). Influence of vibration on endurance of maximal isometric contraction. *Clinical Physiology, 9*(1), 21-26. doi: 10.1111/j.1475-097X.1989.tb00952.x

Seifert, J., Luetkemeier, M., Spencer, M., Miller, D., & Burke, E. (1997). The effects of mountain bike suspension systems on energy expenditure, physical exertion, and time trial performance during mountain bicycling. *International journal of sports medicine, 18*(3), 197-200.

Sjödin, B., & Jacobs, I. (1981). Onset of blood lactate accumulation and marathon running performance. *International journal of sports medicine, 2*(01), 23-26.

Smith, C., & Myburgh, K. (2006). Mountain bike racing-the influence of prior glycogen-inducing exercise and glutamine supplementation on selected stress and immune parameters. *South African Journal of Sports Medicine, 18*(4), 122-128.

Stannard, S., & Thompson, M. (1998). Heart rate monitors: Coaches' friend or foe. *Sports Coach, 21*(12), 36-37.

Stapelfeldt, B., Schwirtz, A., Schumacher, Y. O., & Hillebrecht, M. (2004). Workload demands in mountain bike racing. *International Journal of Sports Medicine, 25*(4), 294-300. doi: 10.1055/s-2004-819937

Stewart, A. D., & Hannan, J. (2000). Total and regional bone density in male runners, cyclists, and controls. *Medicine and science in sports and exercise, 32*(8), 1373-1377.

Titlestad, J., Fairlie-Clarke, A., Davie, M., Whittaker, A., & Grant, S. (2003). Experimental evaluation of mountain bike suspension systems. *Acta Polytechnica, 43*(5).

Titlestad, J., Fairlie-Clarke, T., Whittaker, A., Davie, M., Watt, I., & Grant, S. (2006a). Effect of suspension systems on the physiological and psychological responses to sub-maximal biking on simulated smoothand bumpy tracks. *Journal of sports sciences, 24*(2), 125-135.

Titlestad, J., Fairlie-Clarke, T., Whittaker, A., Davie, M., Watt, I., & Grant, S. (2006b). Effect of suspension systems on the physiological and psychological responses to sub-maximal biking on simulated smoothand bumpy tracks. *Journal of sports sciences, 24*(2), 125-135. doi: 10.1080/02640410500131290

Turner, A. P., Cathcart, A. J., Parker, M. E., Butterworth, C., Wilson, J., & Ward, S. A. (2006). Oxygen Uptake and Muscle Desaturation Kinetics during Intermittent Cycling. *Medicine & Science in Sports & Exercise, 38*(3), 492-503

Vibert, D., Redfield, R. C., & Rudolf, H. (2007). Benign Paroxysmal Positional Vertigo in Mountain Bikers. *Ann Otol Rhinol Laryngol, 116*, 887-890.

Wakeling, J. M., Liphardt, A.-M., & Nigg, B. M. (2003). Muscle activity reduces soft-tissue resonance at heel-strike during walking. *Journal of biomechanics, 36*(12), 1761-1769.

Wakeling, J. M., Nigg, B. M., & Rozitis, A. I. (2002). Muscle activity damps the soft tissue resonance that occurs in response to pulsed and continuous vibrations. *Journal of applied physiology, 93*(3), 1093-1103. doi: 10.1152/japplphysiol.00142.2002

Wang, E. L., & Hull, M. L. (1996). A Model for Determining Rider Induced Energy Losses in Bicycle Suspension Systems. *Vehicle System Dynamics, 25*(3), 223-246. doi: 10.1080/00423119608968966

Warner, S. E., Shaw, J. M., & Dalsky, G. P. (2002). Bone mineral density of competitive male mountain and road cyclists. *Bone, 30*(1), 281-286. doi: http://dx.doi.org/10.1016/S8756-3282(01)00704-9

Whipp, B. J., Ward, S. A., Lamarra, N., Davis, J. A., & Wasserman, K. (1982). Parameters of ventilatory and gas exchange dynamics during exercise. *Journal of applied physiology: respiratory, environmental and exercise physiology, 52*(6), 1506-1513.

Wilber, R., L., Zawadzki, K., M., Kearney, J., T., Shannon, M., P., & Disalvo, D. (1997). Physiological profiles of elite off-road and road cyclists. *Medicine and Science in Sports and Exercise, 29*(8), 1090-1094.

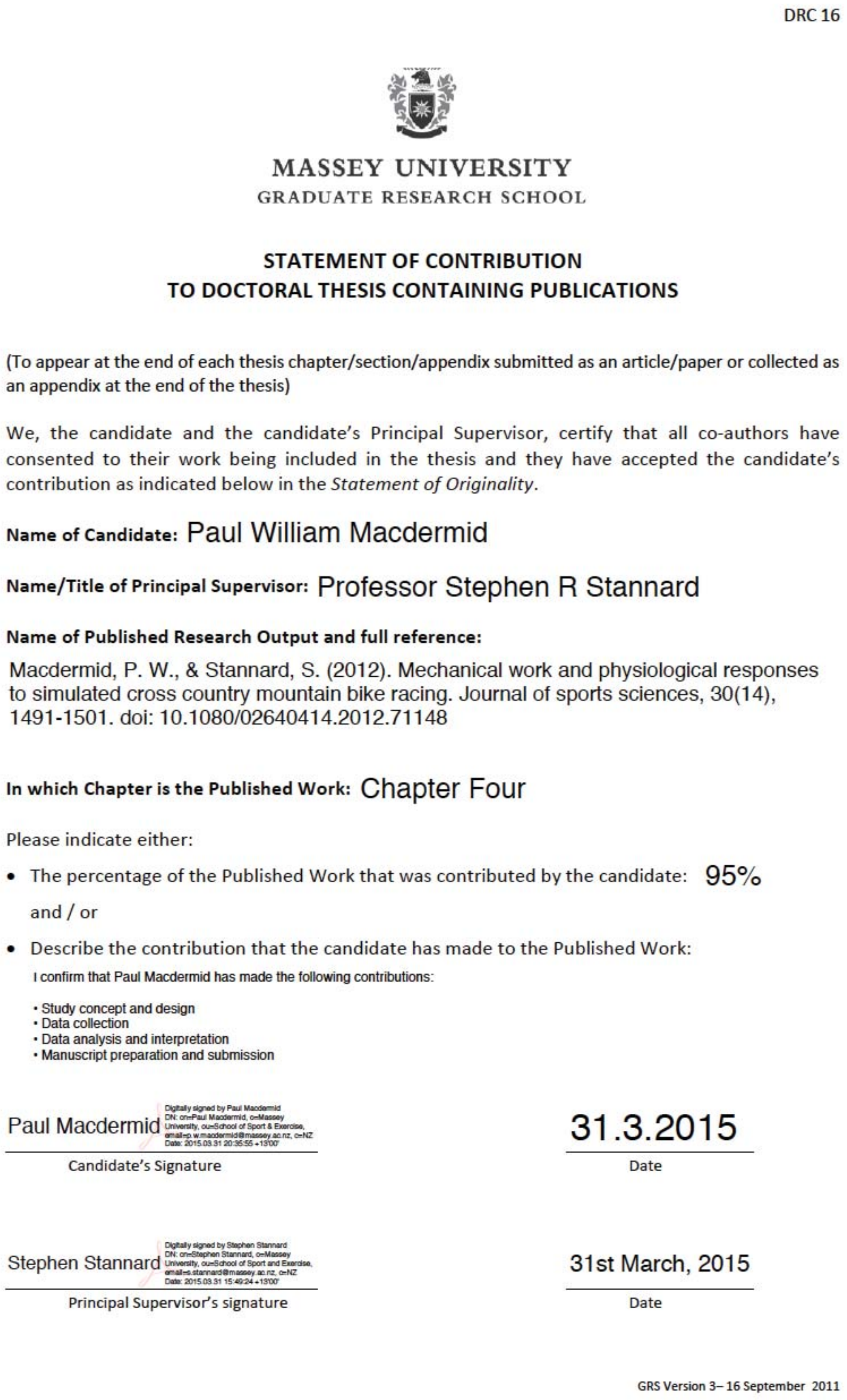
Wilczynski, H., & Hull, M. (1994). A dynamic system model for estimating surface-induced frame loads during off-road cycling. *Transactions-American Society of Mechnaical Engineers Journal of Mechanical Design, 116*, 816-816.

Wilson, D. G. (2004). *Bicycling science*: Mit Press.

Wisner, A., Donnadieu, A., & Berthoz, A. (1964). A BIOMECHANICAL MODEL OF MAN FOR THE STUDY OF VEHICLE SEAT AND SUSPENSION. *International Journal of Production Research, 3*(4), 285-315. doi: 10.1080/00207546408943063

APPENDICES

Appendix 1



DRC 16

MASSEY UNIVERSITY
GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION TO DOCTORAL THESIS CONTAINING PUBLICATIONS

(To appear at the end of each thesis chapter/section/appendix submitted as an article/paper or collected as an appendix at the end of the thesis)

We, the candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of Candidate: Paul William Macdermid

Name/Title of Principal Supervisor: Professor Stephen R Stannard

Name of Published Research Output and full reference:

Macdermid, P. W., & Stannard, S. (2012). Mechanical work and physiological responses to simulated cross country mountain bike racing. Journal of sports sciences, 30(14), 1491-1501. doi: 10.1080/02640414.2012.71148

In which Chapter is the Published Work: Chapter Four

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate: 95%

  and / or

- Describe the contribution that the candidate has made to the Published Work:

  I confirm that Paul Macdermid has made the following contributions:

  - Study concept and design
  - Data collection
  - Data analysis and interpretation
  - Manuscript preparation and submission

Paul Macdermid Digitally signed by Paul Macdermid
DN: cn=Paul Macdermid, o=Massey University, ou=School of Sport & Exercise, email=p.w.macdermid@massey.ac.nz, c=NZ
Date: 2015.03.31 20:35:55 +13'00'
Candidate's Signature

31.3.2015
Date

Stephen Stannard Digitally signed by Stephen Stannard
DN: cn=Stephen Stannard, o=Massey University, ou=School of Sport and Exercise, email=s.stannard@massey.ac.nz, c=NZ
Date: 2015.03.31 15:49:24 +13'00'
Principal Supervisor's signature

31st March, 2015
Date

GRS Version 3– 16 September 2011

Journal of Sports Sciences, October 2012; 30(14): 1491–1501

Mechanical work and physiological responses to simulated cross country mountain bike racing

PAUL WILLIAM MACDERMID & STEPHEN STANNARD

Massey University, School of Sport and Exercise, Palmerston North, New Zealand

(Accepted 9 July 2012)

Abstract

The purpose was to assess the mechanical work and physiological responses to cross country mountain bike racing. Participants ($n = 7$) cycled on a cross country track at race speed whilst $\dot{V}O_2$, power, cadence, speed, and geographical position were recorded. Mean power during the designated start section (68.5 ± 5.5 s) was 481 ± 122 W, incurring an O_2 deficit of 1.58 ± 0.67 L – min^{-1} highlighting a significant initial anaerobic (32.4 ± 10.2%) contribution. Complete lap data produced mean (243 ± 12 W) and normalised (279 ± 15 W) power outputs with 13.3 ± 6.1 and 20.7 ± 8.3% of time spent in high force-high velocity and high force-low velocity, respectively. This equated to, physiological measures for $\%\dot{V}O_{2max}$ (77 ± 5%) and % HR_{max} (93 ± 2%). Terrain (uphill vs downhill) significantly ($P < 0.05$) influenced power output (70.9 ± 7.5 vs 41.0 ± 9.2% W_{max}),the distribution of low velocity force production, $\dot{V}O_2$ (80 ± 1.7 vs 72 ± 3.7%) and cadence (76 + 2 vs 55 ± 4 rpm) but not heart rate (93.8 ± 2.3 vs 91.3 ± 0.6% HR_{max}) and led to a significant difference between anaerobic contribution and terrain (uphill, 6.4 ± 3.0 vs downhill, 3.2 ± 1.8%, respectively) but not aerobic energy contribution. Both power and cadence were highly variable through all sections resulting in one power surge every 32 s and a supra-maximal effort every 106 s. The results show that cross country mountain bike racing consists of predominantly low velocity pedalling with a large high force component and when combined with a high oscillating work rate, necessitates high aerobic energy provision, with intermittent anaerobic contribution. Additional physical stress during downhill sections affords less recovery emphasised by physiological variables remaining high throughout.

Keywords: *cycling, intermittent, field testing, oxygen deficit*

Introduction

In order to prescribe optimal training guidelines for a particular sport, a thorough understanding of the interaction between physical work done during competition and the physiological response to that work is required. Published research (Gregory, Johns, & Walls, 2007; Hamilton, Martin, Anson, Grundy, & Hahn, 2002; Impellizzeri, Marcora, Rampinini, Mognoni, & Sassi, 2005; Impellizzeri, Sassi, Rodriguez-Alonso, Mognoni, & Marcora, 2002; Stapelfeldt, Schwirtz, Schumacher, & Hillebrecht, 2004; Wilber, Zawadzki, Kearney, Shannon, & Disalvo, 1997) on the sport of Olympic format cross country mountain bike racing has concentrated on basic laboratory descriptors of endurance capabilities with relation to both absolute and relative workload(s) in the field. Such measures might not directly relate to cross country mountain bike race performance (Baron, 2001; Gregory et al., 2007; Prins, Terblanche, & Myburgh, 2007) and may mislead coaches to prescribe ineffective training.

The geographical profile of a cross country mountain bike course varies dramatically. The nature of the sport means positional advantage at the start of the race is vital (Macdermid & Morton, 2011). The result is an explosive pace off the start followed by intermittent bursts for 1.5–1.75 h (Stapelfeldt et al., 2004).

The limited research thus far on cross country mountain bike racing has focused on smoothed data (Stapelfeldt et al., 2004) and terrain (uphill, flat, downhill) averages (Gregory et al., 2007) with little regard for the oscillating nature of the work demand, particularly the changing ratio of cadence to torque in producing the requisite power. Supramaximal efforts in short bursts or short rest periods, as required in cross country mountain biking in order to save time, are not detected if data is smoothed or data collection rates are slow. If this occurs there may be a training over-emphasis on constant intensity work and aerobic capacity. Yet in

Correspondence: Paul William Macdermid, Massey University, School of Sport and Exercise, Palmerston North, New Zealand. E-mail: P.W.Macdermid@massey.ac.nz

ISSN 0264-0414 print/ISSN 1466-447X online © 2012 Taylor & Francis
http://dx.doi.org/10.1080/02640414.2012.711487

terms of muscle fibre recruitment and the physiological differences, periods of supra-maximal and constant intensity work are important, especially when specificity of stimulus is required for training purposes.

There is a dearth of scientific research regarding the nature of work demand during cross country mountain bike racing with specific reference to the true physiological/physical requirements of the sport. This thus limits the effectiveness of both the sport scientist and coach in being able to develop and prescribe effective training strategies. Therefore, the aim of this study was to assess the intermittent work demand of a simulated cross country mountain bike lap performed at race pace in the field with reference to physical and physiological requirements.

We hypothesise that, unlike the consistent work protocols administered in the laboratory to test mountain bikers, in the field, a highly varied work requirement will include significant periods of low cadence, high force during uphill sections and higher cadence low force periods during temporally shorter downhill sections. For this reason, we further hypothesise that a much greater intermittent anaerobic contribution is required during cross country mountain bike racing than during more traditional cycling disciplines including the first few minutes.

Methods

Participants

Seven male nationally competitive cross country mountain bike cyclists (mean ± *s*: age 23 ± 9 years, height 176 ± 4 cm, mass 66.9 ± 7.7 kg, $\dot{V}O_{2max}$ (maximum oxygen uptake) 67.6 ± 5.3 ml – kg^{-1} – min^{-1}) were recruited to perform in this study. Prior to participation, all participants provided written consent in accordance with the NZ Central Regional Ethics Committee. Although all participants were well-trained cross country mountain bike athletes they had no prior experience of the specific tests conducted and as a result undertook a familiarisation period one month prior to testing. Familiarisation entailed riding on a treadmill (TechnoGym, Italy) until comfortable at the different speeds and gradients and riding the cross country mountain bike course whilst wearing an automated, breath by breath portable gas analyser (Cortex Metamax 3B, Cortex, Biophysik, Leipzig Germany). Time taken to become familiar with treadmill riding was participant dependent but was deemed successful when they could ride as per normal. One participant (not included in any data analysis) pulled out of the study because they were unable to complete this part of the trial.

Laboratory tests

On the initial visit to the laboratory participants were weighed (with and without cycle clothing and the portable gas analyser plus mountain bike with the powermeter (PowerTap, USA) to be used during the trial) and measured (cm). Participants used their own cross country mountain bikes but all used the same set of wheels (Stans Alpine rims, ZTR front hub and PowerTap rear hub) and tyres (Continental Race King, supersonic 2.2, Ger.). Tyre pressure was adjusted to that preferred by the rider in the field (SmartGauge, TOPEAK, Ger.).They were then allowed a warm-up period (5 min at 15 km – h^{-1} and 5 min at 20 km – h^{-1} with the treadmill set at 0% gradient) which also acted as a re-familiarisation with the test equipment, followed by a sub-maximal test on the treadmill in order to obtain the Power: $\dot{V}O_2$ relationship (Medbo et al., 1988). This test consisted of three incremental bouts of exercise of 5 min duration at a constant speed of 20 km – h^{-1} whilst treadmill gradient was set at 1, 3, and 5%. Power output and $\dot{V}O_2$ data was logged every second throughout the trial and averaged along with $\dot{V}O_2$ data over the final two minutes of each stage (Medbo et al., 1988). This enabled an individual power: $\dot{V}O_2$ relationship to be formed whilst riding their own cross country mountain bike, which could then be extrapolated to predict O_2 demand (Gastin, 2001; Medbo et al., 1988) during the field test. Following a 30 min active recovery period a ramp test (starting on 100 W and increasing by 25 W every minute) to exhaustion (Lucia, Hoyos, Perez, & Chicharro, 2000) was performed. During the test, expired gas data were collected continuously, logged every second and averaged over 60 s periods to enable the calculation of $\dot{V}O_{2max}$ and respiratory compensation point (Macdermid & Edwards, 2010).

Field test trials

Two days after the laboratory trial, participants attended a day at a purpose-built mountain bike course (Pukeora MTB Park, Central Hawkes Bay, NZ) where they completed a re-familiarisation of the cross country mountain bike course. All participants had previously ridden the course on at least three separate occasions. The course was broken down into sections based on terrain (ascent or descent) of which the characteristics are provided (Figure 1). Data taken from the Garmin Edge 705, during the trials showed the course length was 7977 ± 68 m in length (Coefficient of Variation (CV) = 0.85%) had an ascent of 265.2 ± 3.6 (CV = 1.34%) and descent of 250.4 ± 3.4 (CV = 1.34%) showing good reliability of the Garmin device.

After a 2-h break (including a light carbohydrate based meal and drink), and following a warm-up enables the separation of force-velocity into quadrants and was calculated based on the following equations:

$$\begin{aligned}&\mathit{Average\ effective\ pedal\ force}(N)\\&\quad= (\mathit{power\ output}\ (W) * 60)/\\&\qquad(\mathit{cadence}\ (\mathit{rpm}) * 2 * \mathit{Pi} * \mathit{crank\ length}(m))\end{aligned} \tag{2}$$

$$\begin{aligned}&\mathit{Circumferential\ pedal\ velocity}\left(m\ \cdot s^{-1}\right)\\&\quad= (\mathit{cadence} * \mathit{cranklength} * 2 * \mathit{Pi}/60)\end{aligned} \tag{3}$$

Each participant's corresponding values for the respiratory compensation point (Macdermid & Edwards, 2010) taken from the laboratory trial was used to separate the force and velocity scatterplot into quadrants (Figure 4B) reflecting force-velocity characteristics used during the activity (I: high force-high velocity; II: high force-low velocity; III: low force-low velocity; IV: low force-high velocity).

Physiological variables continuously sampled and logged every second included $\dot{V}O_2$ (L – min^{-1}) and Heart Rate (HR) (bpm) which, along with power output (W) were analysed with regards to the terrain sections (Figure 1).

The $\dot{V}O_2$ and power output data, averaged for each 5 s period of the field test and in conjunction with the linear relationship data established via the laboratory test, were used to estimate O_2 deficit and subsequently energy system contribution to exercise based on the following calculations:

$$O_2\ \mathit{demand} = mx + b \tag{4}$$

where, m is the slope and b is y-intercept of the power: $\dot{V}O_2$ relationship determined in the laboratory test, and x is the 5 s smoothed average of power output measured during the field test.

$$O_2\ \mathit{deficit} = O_2\ \mathit{demand} - \mathit{Actual}\ \dot{V}O_2 \tag{5}$$

It was expected that wheel revolutions would vary greatly whereas breathing frequencies would mostly be high. In the PowerTap, power is a function of torque * wheel (hub radial velocity) speed, and so power readings, recorded each breath through the Garmin, would be calculated from quite varied work times. For consistency therefore, and to be able to manage the large amount of data, a five second averaging was employed for all dependent variables.

Statistical analyses

Data recorded throughout the laboratory and field trials were transmitted to a conventional personal computer and processed with the Garmin Training Centre, Saris PowerAgent and Metamax 3B software provided with the relevant hardware. Descriptive data (mean, standard deviation (*s*)) were calculated for all dependant variables using GraphPad Prism (version 5.0). A two-way repeated-measures analysis of variance (ANOVA), with two within-subject variables (terrain and order) were used to test differences between mechanical and physiological responses while a two-way ANOVA was used to assess the effect of terrain on the force-velocity relationship for quadrant analysis. Where an overall significant difference was found the main effect was analysed using Bonferroni post-hoc testing for pairwise comparisons, significance set at $P < 0.05$.

Results

Laboratory tests

Table I shows the participants' responses to the sub-maximal and maximal laboratory tests used in the analysis of field data. Manual calibration of the treadmill for this test meant that 'real' speed during the three-stage sub-maximal test was actually 19 km · h^{-1}.

Field tests

The starting straight consisted of a fast tarmac surface of 500 m in length with an average gradient of 2.5% before feeding into a single track off road surface. The time taken to complete this section was 68.5 ± 5.5 s, relating to a mean ± *s* power output from a standing start of

Table I. Laboratory test characteristics of the participants ($n = 7$) for the sub-maximal treadmill test and the maximal ergometer test. Where results are given per kg this refers to total weight of the individual participant's clothing, bike plus powermeter and the portable gas analyser.

	19 km – h^{-1} @ 1%	19 km – h^{-1} @ 3 %	19 km – h^{-1} @ 5 %	Max data were applicable
Power Output (W)	92.3 ± 8.5	173.1 ± 13.7	249.1 ± 20.3	405.5 ± 31.3
Power Output (W – $\sum$kg^{-1})	1.16 ± 0.08	2.20 ± 0.03	3.14 ± 0.06	5.26 ± 0.27
Cadence (rpm)	73 ± 5	76 ± 4	78 ± 5	N/A
$\dot{V}O_2$ (L – min^{-1})	1.52 ± 0.15	2.39 ± 0.23	3.25 ± 0.30	4.39 ± 0.59
$\dot{V}O_2$ (ml – $\sum$kg^{-1} – min^{-1})	19.4 ± 1.0	30.4 ± 0.9	41.4 ± 0.8	56.8 ± 6.0
HR (bpm)	111 ± 8	134 ± 12	156 ± 11	188 ± 4

481 ± 122 W, 5.9 ± 1.8 W – $\sum \text{kg}^{-1}$, or 6.63 ± 1.34 W – kg^{-1}. The mean total O_2 deficit incurred during this period equalled 1.58 ± 0.67 L – min^{-1} and resulted in an estimated aerobic (67.6 ± 10.2%) and anaerobic (32.4 ± 10.2%) contribution to the work done over the start. Quadratic analysis showed that 82.4 ± 2.6% of the time during the allocated period was high force of which 86.6 ± 12.1% was high force-high velocity. Figure 2 highlights the nature of the aforementioned variables during this short period reflecting a cross country mountain bike race start.

Over the whole lap the average time equalled 1701 ± 50 s which was characterised by a mean power output of 243 ± 12 W; 3.00 ± 0.14 W · kg^{-1}; or 3.62 ± 0.18 W · kg^{-1}, a normalised power output of 279 ± 15 W; 3.5 ± 0.2 W · $\sum \text{kg}^{-1}$; or 4.1 ± 0.3 W · kg^{-1}, and a cadence of 67 ± 5 rpm. Mean distribution of the quadrant analysis of the average effective pedal force and circumferential pedal velocity shows that 57.2% of time was spent at low velocity (including 20.7 ± 8.3 and 36.5 ± 5.4% for high force-low velocity and low force-low velocity, respectively) while 42.8% was spent at high velocity (including 13.3 ± 6.1 and 29.5 ± 8.2% for high force-high velocity and low force-high velocity, respectively) with a high force contribution of 34% compared to 66% low force during cross country mountain bike racing. An individual participant's quadrant analysis is provided in Figure 4B.

Absolute $\dot{V}O_2$ for the same periods was 3.45 ± 0.22 L · min^{-1} (77 ± 5%$\dot{V}O_{2\text{max}}$), while heart rate was 175 ± 6 bpm (93 ± 2% of HR_{max}). Figure 3 shows how physiological and work variables were distributed (percentage of time) during the field test, highlighting the dissociation of variance between power output and physiological measures over the duration of the trial. This is further highlighted in Figure 4A, showing five-second averages for one participant over the entire field test duration.

Comparison between physiological measures during laboratory treadmill cycling (19 km · h^{-1} @ 5% gradient) and cross country mountain biking in the field (using exactly the same equipment) provided no statistical difference in mean absolute power output

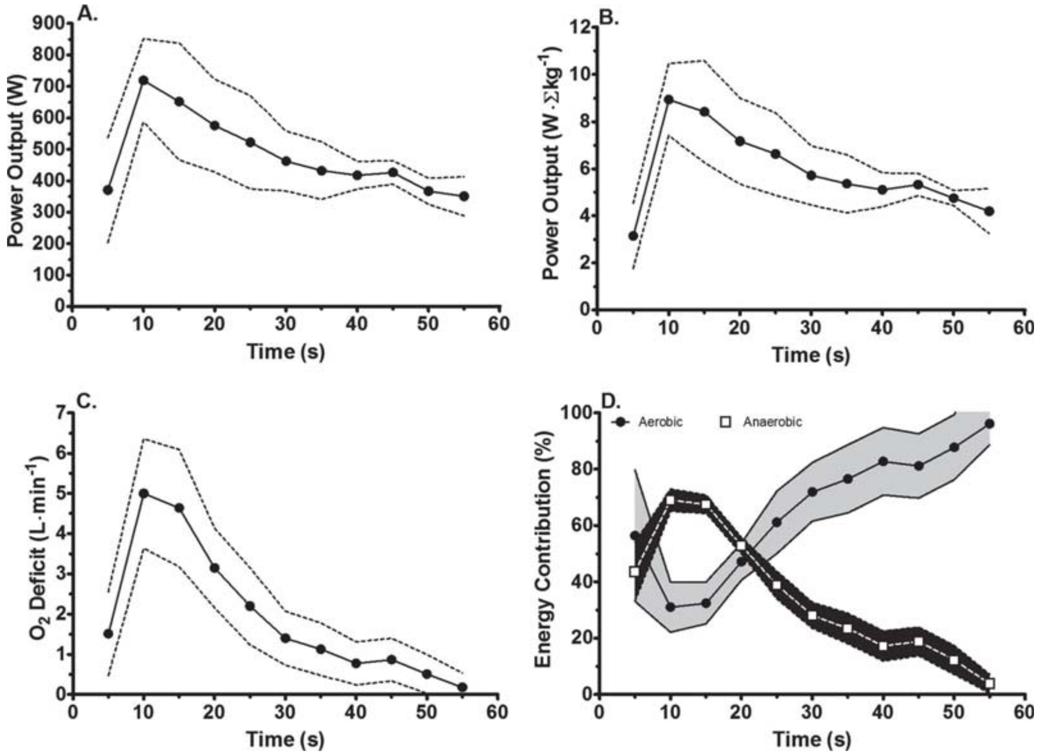


Figure 2. Data recorded (Mean ± *s*) over the start straight and averaged every 5 s. A. Power output profile (W), B. Power output profile (W · $\sum \text{kg}^{-1}$), C. Oxygen deficit (L · min^{-1}), and D. Estimated aerobic and anaerobic contribution to work done (%).

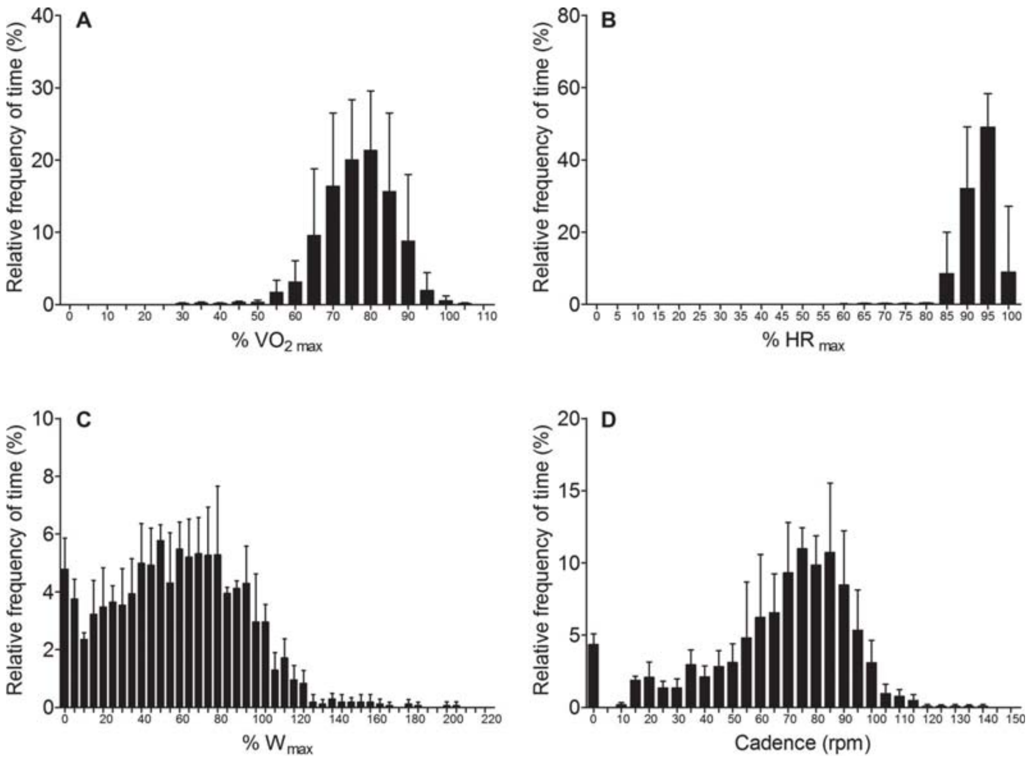


Figure 3. Frequency distribution (mean ± *s*) for physiological variables during the field test represented as percentages of maximum from laboratory tests for A. % $\dot{V}O_{2max}$; B. % HR_{max}; and work variables C. % W_{max}; and D. Cadence (rpm).

($P = 0.117$, 249 ± 20 vs 243 ± 12 W) or relative $\dot{V}O_2$ ($P = 0.331$), yet HR (161 ± 6 vs 175 ± 6 bpm, respectively) was significantly different ($P = 0.004$).

The lap (Figure 1) was composed of eight distinguishable sections which were predominantly ascent (range 127–281 s) or descent (range 62–293 s). Two-way repeated-measures ANOVA analysis of section specific data (Figure 1, Table II) highlights the difference between terrain with regard to order within the lap. As expected there is a significant interaction between terrain and order for all variables measured. Further analysis of power data for terrain indicated that mean distribution of the quadrant analysis of the average effective pedal force and circumferential pedal velocity whilst ascending indicated that greater time was spent in high force-low velocity (29.2 ± 12.2%) compared with high force-high velocity (16.3 ± 9.3%) but with more overall time spent in the low force-low velocity and low force-high velocity (25.1 ± 8.4 vs 29.5 ± 11.4%) respectively. Conversely, the distribution of time for descending showed the majority of time was spent in low force pedalling (low force-low velocity (49.3 ± 4.7%) and low force-high velocity (35.4 ± 6.0%)), while high force pedalling made-up 10.4 ± 4.9 and 11.5 ± 6.8% for high force-high velocity and high force-low velocity, respectively. Two-way ANOVA indicates an overall interaction between quadrant and terrain ($P < 0.001$) with no overall effect of terrain ($P = 0.353$) but an effect of quadrant ($P = 0.002$). Post-hoc analysis only showed significant differences for terrain for high force-low velocity (29.2 ± 12.2 vs 11.5 ± 6.8%, $P < 0.05$) and low force-low velocity (25.1 ± 8.4 vs 49.3 ± 4.7%, $P < 0.001$).

Terrain is not only defined by a change in gradient but can also include negotiation of corners and/or obstacles. Such occurrences are often met with decelerations and accelerations, resulting in surges of power output. Figure 5 shows the mean ± *s* number of surges that occurred during the simulated lap at race pace. This equated to a mean total for all participants of 53 ± 5 surges (three consecutive readings). Due to the nature of the terrain it is hard to surmise the regularity of such efforts required by cross country mountain bike athletes but it does relate to one surge every 32 s and 1 supra-maximal effort every 106 s.

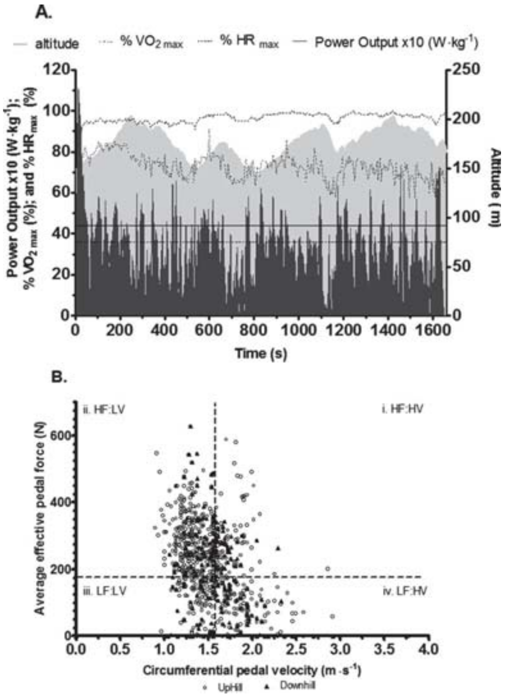


Figure 4. An individual participant's data over the whole lap for: A. Altitude (m), power output ($W \cdot kg^{-1}$), % $\dot{V}O_{2max}$, and % HR_{max} averaged over 5 s periods for the whole field test duration, with the average power (horizontal dashed line) and normalised power (horizontal solid line); B. Quadrant analysis separated by the mean effective pedal force and circumferential velocity of that participant, at respiratory compensation point from laboratory test and indicating the difference between hill and downhill sections.

With such an intermittent nature to the sport, estimated energy system contribution via oxygen deficit indicates a mean $\pm$ *s* of 94.0 $\pm$ 1.2 and 6.0 $\pm$ 1.2%, $P < 0.001$ for aerobic and anaerobic contribution to work done. Analysis of terrain data indicates no difference ($P > 0.05$) between aerobic contribution for ascending (93.7 $\pm$ 3.0%) and descending (96.0 $\pm$ 2.4%), while a significant difference was found between anaerobic contribution ($P < 0.05$) for ascending (6.4 $\pm$ 3.0%) and descending (3.2 $\pm$ 1.8%).

Discussion

This investigation set out to assess the mechanical work and physiological responses to a simulated cross country mountain bike, race paced lap. The main findings were: (a) power output and cadence constantly oscillate during cross country mountain bike racing, predetermined by terrain; (b) low velocity pedalling constitutes the majority of cross country mountain bike racing with a large contribution of high force-low velocity muscular contraction; (c) cross country mountain biking is predominated by the requirement of a well-developed aerobic capacity but key movements of the sport emphasise a high demand on anaerobic energy provision; (d) cross country mountain bike courses have distinguishable sections in terrain profile but athletes are not afforded the same nature of recovery as road cyclists, emphasised by physiological variables remaining high.

In setting out to simulate a race start, all participants were asked to approach the designated starting straight with an effort similar to that which they would make in a race. Although impossible to simulate the physical drive for positional advantage, it was felt due to the supra-maximal power outputs obtained (Figure 2 A–B), that all athletes approached this section as requested. Consequently, work completed over the first minute of the field test produced supra-maximal power outputs (greater than the power output associated with $\dot{V}O_{2max}$) by way of high force-high velocity muscular contraction, resulting in a large anaerobic energy contribution. Figure 2 (C–D) profiles the physiological implications of the simulated start. The mean energy system contributions over this comparatively short time period agreed with previous findings with regard to one off, all-out efforts and time scales (Gastin, 2001). However, in the sport of cross country mountain bike racing, athletes are required to continue for at least a further 90 min making the sport unique in events of this duration.

Investigations into optimal pacing strategies for performance in events lasting less than 2 minutes indicate that an all-out strategy produces the best performances (Bishop, Bonetti, & Dawson, 2002; De Koning, Bobbert, & Foster, 1999) with slightly longer events (4000 m pursuit cycling) following a pattern of all-out effort for the first 12 seconds followed by an even pace thereafter as per Figure 2A (Aisbett, Rossignol, & Sparrow, 2003; De Koning et al., 1999). Even short (800 kJ) time trials have supported a constant pacing strategy (Atkinson, Peacock, & Law, 2007), and as a result it would be easy to suggest that such strategies employed by cross country mountain bikers (Stapelfeldt et al., 2004) and used in this study could be detrimental to performance. However, our analysis of male competitors ($n = 79$) during the 2010 World Championship showed that even though this strategy is used, mean individual CV $\pm$ 95% CI of lap times amongst well trained athletes was 1.93 $\pm$ 1.43%. It must also be remembered that in this instance we are investigating a race not a time trial, and the rules which confine the sport mean that positional advantage from the start could outweigh the negative effects from initially working too hard (Macdermid & Morton, 2011). Data reported in Table II reveals that although participants engaged supra-maximal effort from the start (to gain positional advantage into the single track, Figure 2), a more sustainable effort ensued.

Taking the whole lap average data into consideration, absolute power output data (243 ± 12 W) and % HR_{max} data (93 ± 2%) are very similar to those previously reported (Impellizzeri et al., 2002; Stapelfeldt et al., 2004) in elite national athletes during a number of complete cross country mountain bike races. However, this study did produce slightly lower (77 ± 5%) values than the estimations of % $\dot{V}O_{2max}$ (84 ± 3%) made previously (Impellizzeri et al., 2002). Such small discrepancies could easily be due to course characteristics which might affect the ability of the participants to maintain work rate during sections of the course. Also, the previously reported data was taken from actual races which may have an additive (psychological) effect on slightly higher physiological values derived from HR. The very low standard deviations around the means for the aerobic and anaerobic contribution to the complete lap indicate homogeneity for the demands of this particular course and form of racing.

When the raw power outputs are converted to normalised power, data from this study is similar to criterion road race data and is subsequently similar to the constant power output of a flat time-trial. Such data agrees with the use of normalised power rather than mean power to make cross comparisons between cycling disciplines or training sessions (Jobson et al., 2009). However, the manner in which the work was completed could be of the upmost importance and will determine the specificity of stimulus for training requirements. An example of this that requires further investigation is the quadrant analysis data. These data highlight a large component of high force-low velocity muscle contraction suggesting strength maybe more important for cross-country mountain bike athletes in order to negotiate terrain compared to other cycling disciplines.

Figure 3 C–D emphasises the large variation in both power output and cadence over the course of a cross-country mountain bike lap which is underlined by the spread of the mean distribution of the quadrant analysis of the average effective pedal force and circumferential pedal velocity (individually represented, Figure 4B). In contrast, % HR_{max} and to a lesser extent % $\dot{V}O_{2max}$ show much less variation (Figure 3 A–B). An explanation for such a difference between mechanical and physiological variation can be explained partly, due to a muscle-lung vascular transit delay pushing the rising phases of short bursts of effort into recovery phases or in this

Table II. Mean ± *s* for performance, mechanical and physiological measures sampled throughout the field trial and separated based on terrain (hill (H) and downhill (DH)) and order as depicted in Figure 1.

	Hill 1	DH 1	Hill 2	DH 2	Hill 3	DH3	Hill 4	DH 4	Two-Way ANOVA
Time (s)	262.0 ± 11.5	293.0 ± 11.0	127.0 ± 14.4	155.0 ± 18.4	281.0 ± 17.1	62.0 ± 14.0	253.0 ± 22.5	241.0 ± 9.6	***; ###;†††
Power (%W_{max})	81.0 ± 4.2	48.4 ± (1.7)	72.0 ± 6.7	37.4 ± 3.2	66.2 ± 4.2	25.6 ± 2.9	64.2 ± 2.9	48.4 ± 3.6	**; ###; ns
Cadence (rpm)	75.4 ± 5.5	58.4 ± 3.7	74.6 ± 6.5	54.8 ± 5.0	78.2 ± 5.9	48.6 ± 7.6	74.0 ± 7.5	57.2 ± 6.1	*; ###; ns
% $\dot{V}O_{2\ max}$	80.7 ± 3.5	76.6 ± 4.4	81.7 ± 6.1	71.2 ± 4.9	79.4 ± 7.1	67.6 ± 7.3	77.8 ± 7.5	72.2 ± 6.7	**; ns; †††
% HR_{max}	90.4 ± 3.2	90.8 ± 3.0	94.4 ± 2.2	91.0 ± 2.9	95.4 ± 1.7	91.2 ± 3.0	94.8 ± 1.8	92.2 ± 2.8	***; ###;†††

***($P < 0.001$); **($P < 0.01$); *($P < 0.05$) the interaction between the terrain (hill or downhill) and the order (1–4). ($P < 0.001$); ns ($P > 0.05$) signifies whether the occurrence of terrain with the lap affects the result. ††† ($P < 0.001$); ns ($P > 0.05$) tests the difference between the terrain (hill vs downhill).

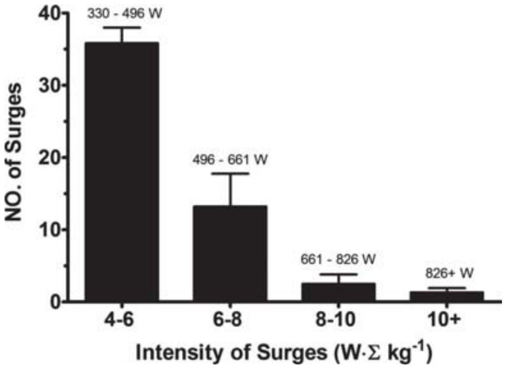


Figure 5. Mean *s* surge analysis for participants ($n = 7$) over the whole lap and based on total weight of participant, bike and gas analyser.

case blunting the response of lower power output bouts (Hurst & Atkins, 2006; Turner et al., 2006). The effects of downhill cross country mountain biking on the dissociation between power output and HR have been attributed to increased energy demands of movements not associated with pedalling but rather negotiating the course (Gregory et al., 2007; Stapelfeldt et al., 2004). The separation of the data into terrain sections (Figure 1) identifies a significant difference between the start phase of the lap (hill 1) with hills 2, 3 and 4. Overall, power output decreased in subsequent climbs, which is not unexpected considering the quest to gain positional advantage from the start. However, HR increased while $\dot{V}O_2$ remained relatively unchanged following hill 1.

Laboratory studies regarding constant power outputs (>lactate threshold) and O_2 kinetics have showed consistently that there is no achievement of an early steady state after 3 minutes with $\dot{V}O_2$ continuing to rise until exercise is terminated or exhaustion supervenes (Barstow & Mole, 1991; Roston et al., 1987). In the case of this field study it is possible to suggest that participants arrived at the pinnacle of the first climb prior to exhaustion, allowing them to continue at a pace that would enable completion of race distance (1.5–1.75 h).

The fact that there was no decrease in $\dot{V}O_2$ but an increase in HR suggests that recovery was inadequate adding to the reduced oscillatory effect of power on heart rate and to a lesser extent $\dot{V}O_2$. This is supported by previous studies into repeated bouts of high intensity rowing and HR kinetics (Mavrommataki, Bodganis, Kaloupsis, & Maridaki, 2006) where 1.5 and 3 minutes recovery was not deemed sufficient in order to maintain power output over 1000 m bouts of rowing. Whereas, laboratory studies have used constant load tests to demonstrate the slow component $\dot{V}O_2$, the data presented here shows dissociation between a declining power output, $\dot{V}O_2$, and heart rate, and thus mimics the inverse of such trials. While the changes in both HR and $\dot{V}O_2$ are minor it does suggest either a probable reduction in stroke volume, or in oxygen extraction at the muscle but the latter is unlikely. Feasible explanations for such occurrences could also be linked to the effect downhill terrain could have on the sympathetic nervous system. It is possible that increased catecholamine responses could drive HR above what is necessary in terms of oxygen delivery. Alternatively, increased thermal load may drive up cardiac output to increase skin blood flow, producing a HR above that which is necessary in terms of O_2 delivery to the working muscles (Périard, Cramer, Chapman, Caillaud, & Thompson, 2011).

In addition the explanation is compounded by the course characteristics used in this study and potentially all cross-country mountain bike courses. Figure 1 highlights some of the potential issues regarding the classification of sections with regard to length, overall ascent and descent, mean gradient and the number of directional changes. Visual inspection of the data indicates that sections 1–2 and 7–finish are downhill overall but also contain a large number of directional changes along with a proportionally high gain in altitude when compared with the hill sections. Such characteristics will influence the interpretation of overall terrain characteristics and the associated impact on physiological measures. Likewise, exercising at a power output shown to elicit 60% $\dot{V}O_{2max}$ or reporting such a mean power output does not reflect the intermittent demands of cross country mountain bike racing or the capabilities of athletes taking part. Gear selection and cadence are almost certainly influenced by the gradient of slope, changes in direction, and overcoming obstacles, and thus consequently cause large fluctuations in torque (Gregory et al., 2007) and work rate. The course used in this study (Figure 1) had equal ascent and descent and thus time spent climbing was greater. Interestingly, the total number of changes in direction of 127 was not split evenly as there were 53 changes in direction ascending and 74 descending. This could have led to fewer power surges (Figure 5) as determined by the software (PowerAgent, Cycle Ops, USA) which determines a surge in power as a value lasting >3 s. Again, even with the use of such software there is the potential to underestimate the erratic nature of the sport which seems to have more in common with game sports than road race cycling. Participation in elite cross country mountain bike racing, like such sports may be dependent on a high aerobic capability of the athlete (Impellizzeri et al., 2005) but it is likely that supra-maximal intensities and all-out surges are critical in deciding the result. The sport of cross country mountain bike racing may be dominated by the aerobic energy system but it is potentially not the defining aspect of performance.

The use of estimating energy system contribution to exercise via oxygen deficit has previously been used in single bout exercise periods (Bishop, 2000; Gastin, 2001). However, issues regarding the changing linear relationships between power and $\dot{V}O_2$ for repetitive bouts of maximal exercise are unknown. Changes in the slope and Y-intercept of such a relationship with fatigue could potentially lead to a minor underestimation of anaerobic contribution to subsequent bouts. Even so, Figure 5 highlights the fact that there is a greater emphasis of anaerobic energy utilisation during sections of the course that are predominantly ascending compared with descending as would be expected.

Conclusion

The results of the present study illustrate that the mechanical work performed and the physiological responses of cross country mountain bike racing are discontinuous as a result of changes in terrain and course features. As a result cross country mountain bike racing is predominated by high force-low velocity pedalling during ascent and combined with a high oscillating work rate necessitates high aerobic energy provision, with intermittent anaerobic contribution. Additional stress during downhill sections affords less recovery than seen in other cycling disciplines, emphasised by non-variable physiological values in relation to terrain.

Practical implications

The following are practical recommendations for athletes and coaches working with cross country mountain bike athletes:

- Training prescription should consider the importance of the interaction of energy system(s) development to a high level. A high aerobic capacity is essential but will almost certainly need to be trained in a different manner to the current practices of road cyclists taking into account the force-velocity relationship.
- Athletes must be accustomed to climbing for extended periods at intensities greater than 90% $\dot{V}O_{2max}$ with supra-maximal surges and immediately be able to negotiate technical descents at high speed while under physiological stress.
- Cross country mountain biking requires a large strength component compared to other cycling disciplines. For that reason athletes and coaches should be conscious of the need to perform short duration, high intensity efforts with cadences below 80 rpm.

References

Abbiss, C.R., Quod, M.J., Martin, D.T., Netto, K.J., Nosaka, K., Lee, H., … Laursen, P.B. (2006). Dynamic pacing strategies during the cycle phase of an Ironman triathlon. *Medicine & Science in Sports & Exercise*, *38*(4), 726–734.

Aisbett, B., Rossignol, P.L., & Sparrow, W.A. (2003). The influence of pacing during 6-minute supramaximal cycle ergometer performance. *Journal of Science and Medicine in Sport*, *6*(2), 187–198.

Atkinson, G., Peacock, O., & Law, M. (2007). Acceptability of power variation during a simulated hilly time trial. *International Journal of Sports Medicine*, *28*(2), 157–163.

Baron, R. (2001). Aerobic and anaerobic power characteristics of off-road cyclists. *Medicine and Science in Sports and Exercise*, *33*(8), 1387–1393.

Barstow, T.J., & Mole, P.A. (1991). Linear and nonlinear characteristics of oxygen uptake kinetics during heavy exercise. *Journal of Applied Physiology*, *71*(6), 2099–2106.

Bishop, D. (2000). Physiological predictors of flat-water kayak performance in women. *European Journal of Applied Physiology*, *82*(1), 91–97.

Bishop, D., Bonetti, D., & Dawson, B. (2002). The influence of pacing strategy on $\dot{V}O2$ and supramaximal kayak performance. *Medicine and Science in Sports and Exercise*, *34*(6), 1041–1047.

De Koning, J.J., Bobbert, M.F., & Foster, C. (1999). Determination of optimal pacing strategy in track cycling with an energy flow model. *Journal of Science and Medicine in Sport*, *2*(3), 266–277.

Gastin, P.B. (2001). Energy system interaction and relative contribution during maximal exercise. *Sports Medicine*, *31*(10), 725–741.

Gregory, J., Johns, D.P., & Walls, J.T. (2007). Relative vs. absolute physiological measures as predictors of mountain bike cross-country race performance. *Journal of Strength and Conditioning Research*, *21*(1), 17–22.

Hamilton, L., Martin, D.T., Anson, J.M., Grundy, D., & Hahn, A.G. (2002). Physiological characteristics of successful mountain bikers and professional road cyclists. *Journal of Sports Sciences*, *20*(12), 1001–1008.

Hurst, H.T., & Atkins, S. (2006). Power output of field-based downhill mountain biking. *Journal of Sports Sciences*, *24*(10), 1047–1053.

Impellizzeri, F.M., Marcora, S.M., Rampinini, E., Mognoni, P., & Sassi, A. (2005). Correlations between physiological variables and performance in high level cross country off road cyclists. *British Journal of Sports Medicine*, *39*(10), 747–751.

Impellizzeri, F.M, Sassi, A., Rodriguez-Alonso, M., Mognoni, P., & Marcora, S. (2002). Exercise intensity during off-road cycling competitions. *Medicine and Science in Sports and Exercise*, *34*(11), 1808–1813.

Jobson, S.A., Passfield, L., Atkinson, G., Barton, G., & Scarf, P. (2009). The analysis and utilization of cycling training data. *Sports medicine*, *39*(10), 833–844.

Lucia, A., Hoyos, J., Perez, M., & Chicharro, J.L. (2000). Heart rate and performance parameters in elite cyclists: A longitudinal study. *Medicine and Science in Sports and Exercise*, *32*(10), 1777–1782.

Macdermid, P.W., & Edwards, A.M. (2010). Influence of crank length on cycle ergometry performance of well-trained female cross-country mountain bike athletes. *European Journal of Applied Physiology*, *108*(1), 177–182.

Macdermid, P.W., & Morton, R.H. (2011). A longitudinal analysis of start position and the outcome of World Cup cross-country mountain bike racing. *Journal of Sports Sciences*, *30*(2), 175–182.

Mavrommataki, E., Bogdanis, G.C., Kaloupsis, S., & Maridaki, M. (2006). Recovery of power output and heart rate kinetics during repeated bouts of rowing exercise with different rest intervals. *Journal of Sports Science and Medicine*, *5*, 115–122.

Medbo, J.I., Mohn, A.C., Tabata, I., Bahr, R., Vaage, O., & Sejersted, O.M. (1988). Anaerobic capacity determined by maximal accumulated O2 deficit. *Journal of Applied Physiology*, *64*(1), 50–60.

Périard, J.D., Cramer, M.N., Chapman, P.G., Caillaud, C., & Thompson, M.W. (2011). Cardiovascular strain impairs prolonged self-paced exercise in the heat. *Experimental physiology*, *96*(2), 134–144.

Prins, L., Terblanche, E., & Myburgh, K.H. (2007). Field and laboratory correlates of performance in competitive cross-country mountain bikers. *Journal of Sports Sciences*, *25*(8), 927–935.

Roston, W.L., Whipp, B.J., Davis, J.A., Cunningham, D.A., Effros, R.M., & Wasserman, K. (1987). Oxygen uptake kinetics and lactate concentration during exercise in humans. *American Review of Respiratory Disease*, *135*(5), 1080–1084.

Stapelfeldt, B., Schwirtz, A., Schumacher, Y.O., & Hillebrecht, M. (2004). Workload demands in mountain bike racing. *International Journal of Sports Medicine*, *25*(4), 294–300.

Turner, A.P., Cathcart, A.J., Parker, M.E., Butterworth, C., Wilson, J., & Ward, S.A. (2006). Oxygen uptake and muscle desaturation kinetics during intermittent cycling. *Medicine and Science in Sports and Exercise*, *38*(3), 492–503.

Wilber, R.L., Zawadzki, K.M., Kearney, J.T., Shannon, M.P., & Disalvo, D. (1997). Physiological profiles of elite off-road and road cyclists. *Medicine and Science in Sports and Exercise*, *29*(8), 1090–1094.

Appendix 2

This article was downloaded by: [paul macdermid]
On: 31 July 2014, At: 06:20
Publisher: Routledge
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK

Journal of Sports Sciences
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/rjsp20

The influence of tyre characteristics on measures of rolling performance during cross-country mountain biking

Paul William Macdermid[a], Philip W. Fink[ab] & Stephen R. Stannard[a]
[a] School of Sport & Exercise, Massey University, Palmerston North, New Zealand
[b] School of Sport & Exercise, Massey University, Wellington, New Zealand

Published online: 29 Jul 2014.

To cite this article: Paul William Macdermid, Philip W. Fink & Stephen R. Stannard (2014): The influence of tyre characteristics on measures of rolling performance during cross-country mountain biking, Journal of Sports Sciences, DOI: 10.1080/02640414.2014.942682

To link to this article: http://dx.doi.org/10.1080/02640414.2014.942682

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the “Content”) contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

Journal of Sports Sciences, 2014
http://dx.doi.org/10.1080/02640414.2014.942682

The influence of tyre characteristics on measures of rolling performance during cross-country mountain biking

PAUL WILLIAM MACDERMID[1], PHILIP W. FINK[1,2] & STEPHEN R. STANNARD[1]

[1]*School of Sport & Exercise, Massey University, Palmerston North, New Zealand and* [2]*School of Sport & Exercise, Massey University, Wellington, New Zealand*

(*Accepted 27 June 2014*)

Abstract
This investigation sets out to assess the effect of five different models of mountain bike tyre on rolling performance over hard-pack mud. Independent characteristics included total weight, volume, tread surface area and tread depth. One male cyclist performed multiple (30) trials of a deceleration field test to assess reliability. Further tests performed on a separate occasion included multiple (15) trials of the deceleration test and six fixed power output hill climb tests for each tyre. The deceleration test proved to be reliable as a means of assessing rolling performance via differences in initial and final speed (coefficient of variation (CV) = 4.52%). Overall differences between tyre performance for both deceleration test ($P = 0.014$) and hill climb ($P = 0.032$) were found, enabling significant ($P < 0.0001$ and $P = 0.049$) models to be generated, allowing tyre performance prediction based on tyre characteristics. The ideal tyre for rolling and climbing performance on hard-pack surfaces would be to decrease tyre weight by way of reductions in tread surface area and tread depth while keeping volume high.

Keywords: *mountain biking, tyres, rolling resistance, performance, field testing*

Introduction

Rolling resistance, or resistance arising from the interaction of a bicycle tyre and the ground, plays an important role in cycling performance. Labelled the second most important component of drag (Wilson, Papadopoulos, & Whitt, 2004), it is paramount to performance (Capelli et al., 1998; Grappe et al., 1999) in a sport where small advantages can make the difference between winning and losing. Rolling resistance has been studied during road and track cycling (Di Prampero, Cortili, Mognoni, & Saibene, 1979; Faria, Parker, & Faria, 2005), but little research has been performed on mountain biking. Better knowledge on the performance of tyres is especially important as tyre choice in relation to tread pattern is a critical strategic decision often made only through guesswork and prior experience for a given course condition.

Rolling resistance arises from hysteric losses in the tyre–ground interaction (Faria et al., 2005) and is generally modelled as equal to the product of the coefficient of rolling resistance and the vertical loading on the wheel (Candau et al., 1999; Martin, Gardner, Barras, & Martin, 2006; Martin, Milliken, Cobb, Mcfadden, & Coggan, 1998). The vertical loading is largely determined by the weight of the cycle plus rider, while the coefficient of rolling resistance is a product of many things. These include wheel size, type of tyre, tread configuration and inflation pressure of the tyres (Bertucci, Duc, Villerius, Pernin, & Grappe, 2005; Bertucci, Rogier, & Reiser, 2013; Di Prampero, 2000; Grappe et al., 1999). Unlike air resistance, the other major resistance component during cycling, rolling resistance is independent of speed, although this has been disputed (Kyle, 1988). The bulk of the research, however, has shown that the rolling resistance force is independent of speed, and that is how it will be modelled in this article.

Although independent of speed, the contribution of rolling resistance to total resistance increases as speed decreases (Faria et al., 2005), with reductions in speed of 50% from 14 to 7 m s^{-1} being attributed to a threefold increase in rolling resistance contribution to total resistance (Grappe et al., 1999). This would suggest that in a cycling discipline such as cross-country mountain biking where the average speeds are relatively low compared to other cycling discipline (Gregory, Johns, & Walls, 2007; Impellizzeri, Sassi, Rodriguez-Alonso, Mognoni, &

Correspondence: Paul William Macdermid, School of Sport & Exercise, Massey University, Palmerston North, New Zealand. E-mail: P.W.Macdermid@massey.ac.nz

Marcora, 2002; Macdermid & Stannard, 2012) and terrain is more variable, it is feasible that rolling resistance could play a crucial part in determining performance through its contribution to drag (Bertucci et al., 2005, 2013).

Cross-country mountain bicycles have been shown to have greater resistance than road bicycle tyres (Di Prampero, 2000). Aside from recent variations, effective wheel size due to different rim diameter and tyre size causing a larger contact patch, the lower tyre inflation pressure used (Faria & Cavanagh, 1978; Wilson et al., 2004) and the terrain they are designed to roll over (Whitt, 1971) all will affect rolling resistance. Additionally, tyre properties such as fabric and weave used, the thread count and the strength of the tyre all interact with the aforementioned circumstances to produce overall rolling resistance (Wilson et al., 2004).

This poses some difficult decisions for most cross-country mountain bike athletes, as a critical aspect of racing is to achieve optimum traction and maintain optimum efficiency whilst reducing the chances of mechanical failure through punctures, debeading tyres or loss of traction. As such, improving performance is not as simple as minimising straight-line rolling resistance. Nevertheless, an improved knowledge of how tyre volume, weight and tread characteristics affect rolling performance would be useful when making tyre choices. Traditionally, cross-country mountain bike tyres have been of small volume (1.9″) and recommended inflation pressures have been between 30 and 50 psi (Overend & Pavelka, 1999) in order to increase rolling efficiency. Issues arising from such high tyre pressures would be a decrease in tyre deformation causing a loss of grip but also increasing transference of vibrations from terrain to rider. Such vibrations could negatively affect cycling efficiency via increased work done (Hurst et al., 2012) as a result of vibration damping. Manufacturer recommendations typically provide a maximum inflation pressure of 65 psi which is contrary to recent trends amongst high-level cross-country mountain bike athletes who run tyres >2.0″ width (minimal tread pattern), with inflation pressures between 15 and 30 psi or 0.3 psi kg Σweight (rider + bike). Theoretically, the latter would increase the tyre contact print (Wilson et al., 2004), providing increased grip for technical manoeuvring (cornering) but negatively increasing the coefficient of rolling resistance component.

The main purpose of this study therefore was to investigate the effect of identically constructed cross-country mountain bike tyres, but differing in tread pattern and volume, on the resistance to roll on hard-pack single track using a deceleration test and during a climb typical of a cross-country mountain bike race. In addition, a secondary aim was to try and use an existing model (Candau et al., 1999) in determining the coefficient of rolling resistance for cross-country mountain bike tyres in a field environment.

Method

One trained male cyclist (age 38 years, body mass 61.5 kg, height 1.72 m, $\dot{V}O_{2\,max}$ 72 ml kg^{-1} min^{-1}) participated in two field tests performed on separate occasions, separated by 7 days, incorporating a coasting deceleration test (Candau et al., 1999; Grappe et al., 1999) and a fixed power output hill climb. All tests were performed on the same mountain bike (GT Zaskar Team 26″ hard tail, Optimized Force Constructed Carbon, Santa Ana, CA, USA) weighing 8.74 kg, fitted with a rear hub powermeter (PowerTap, CycleOps, Madison, WI, USA) and one pair of five identically constructed, different tread patterned tyres (Continental, Supersonic, GER (Table I)). Tyre inflation pressure was set at 0.3 psi per total weight (bike + fully clothed and helmeted cyclist), which is within the range used by expert cross-country mountain bike athletes.

Coasting deceleration test

In an attempt to consider the terrain surface–wheel interaction, this test was performed on a hard-packed soil track (0.8 m × 100 m) typical of cross-country mountain bike single track and sheltered

Table I. Characteristics of the tyres used during the study.

Tyre model	ΣT_{wt} (g)	ISO/ETRTO (mm)	T_{vol} (cm^3)	TSA (mm^2 unit area)	Tr_D (mm)	Classification
1. Twister	760	559/55	3303	12.8	1.52	Slick
2. RaceKing	1000	559/55	4583	23.6	3.32	Slick
3. X-King	1050	559/47	4583	19.0	2.95	Intermediate
4. Speed-King	850	559/55	4159	9.0	6.18	Mud
5. MountainKing	1030	559/52.5	4583	12.2	4.33	Mud

Notes: Measures for tyre volume are industry standards and provided in inches. Tread volume is quantified as a standard area per tyre and taken as a mean of the whole tyre contact patch area. T_{wt} = weight (g) of both tyres on the bicycle; ISO/ETRTO refers to international standard for measure tyre developed by the European Tyre and Rim Technical Organisation; T_{vol} = estimated volume of tyre; TSA = tread surface area per standardised unit; Tr_D = mean tread depth of the tyre.

from the prevailing wind. While the track was hard-packed, it was checked for conformity between trials and rolled with a steel lawn roller to ensure consistency. All testing was performed on one occasion, on the same day, where outdoor environmental conditions were temperature 16°C (iROX HT78, iROX, Bern, Switzerland), air pressure 100.1 kPa and wind speed <1.0 m s^{-1} (TurboMeter, Davis Instruments, Hayward, CA, USA) in a WNW direction. Timing was performed via a single beam system with microprocessor functionality to reduce error (SmartSpeed, Fitness Technology, Fusion Sport, Brisbane, QLD, Australia). This system measures in milliseconds and has a typical error (CV (%)) of <1% for 20 m running (Earp & Newton, 2012).

This test involved the rider accelerating from a standstill over a 67 m distance in an attempt to reach a predetermined speed of 35 km h^{-1} which is a realistic speed attained by cross-country mountain bike athletes when sprinting for position at the start of a race and during descending (Macdermid & Morton, 2012; Macdermid & Stannard, 2012). This was identified by the participant through the use of a bicycle computer (Garmin, Edge 705, Olathe, KS, USA) with a compatible speed sensor (GSC + 10, Garmin). On reaching the end of this strip, the participant changed to a gear of 2.0 m development (34 tooth chainring, 36 tooth sprocket) allowing the participant to continue pedalling without transmitting propulsive force to the rear wheel, whereupon they coasted across two timing beams 1 m apart in order to determine initial speed; the participant remained in a standardised position on the bike (determined by the saddle height, position on saddle and position of hands on the handlebars) whilst pedalling without transmitting propulsive force for a further 20 m (70–90 m) where overall time was recorded; final speed was measured as per the time taken to cross two timing beams, 1 m apart (between 89–90 m). Data recorded included time (s) and mean power (W) over the initial 70 m; initial speed (km h^{-1}), final speed (km h^{-1}) and during the 20 m coasting period. Change in speed was determined by subtracting the final speed from the initial speed and is presented as a percentage of initial speed and/or speed difference.

Although the reproducibility and sensitivity of this method has been previously reported (Candau et al., 1999), it has not been performed with mountain bikes or outside on a level hard-pack soil environment. Therefore, the first task was to establish the reliability and sensitivity. For this test, the participant performed 30 trials using the RaceKing model of tyre (Table I, Figure 1, tyre 2) with inflation set at 21 psi (0.3 psi per total weight).

To determine the differences between tyres, the participant performed 15 trials per tyre, where those falling outside an initial speed of 34–36 km h^{-1} were excluded in order to obtain a more reliable outcome measure. Differences between tyres were quantified with the percentage loss in speed from the first meter to the twentieth meter. To estimate the relative losses due to aerodynamic drag and rolling resistance, a variation of the method of Candau et al. (1999) was used. The acceleration of the bicycle and rider was assumed to be:

$$a(t) = -C_r g - \frac{1}{2m}\rho AC_d v(t)^2$$

where C_r is the coefficient of rolling resistance, AC_d is the effective frontal area, g is the gravitational constant and ρ is the air density. Making the assumption that

$$\alpha = -C_r g$$

and

$$\beta = \frac{1}{2m}\rho AC_{d,}$$

this differential equation can be integrated twice to give the equation for displacement at time T of

Figure 1. Pictorial image of the five tyres used for this study.

$$D(T) = \frac{1}{2\beta}\ln\left[1 + \tan^2(2\alpha\beta + K_1)\right] - \frac{1}{2\beta}\ln\left[1 + \tan^2(K_1)\right]$$

(see Candau et al., 1999 for derivation of the equations). The sum of error squared across the distances (E) of the last three timing gates (which gives the time at set distances) was used to assess the fit. E was calculated as

$$E = \sum_{i=2}^{4}\left(D_i(T_i) - D_{pi}\right)^2$$

where D_i is the distance calculated at time T_i and D_{pi} is the actual distance (1, 19 and 20 meters). The constants α, β and K_1 were fit to the data for each trial using a minimum least-squares method in Matlab (Mathworks, Natick, MA, USA), where E was minimised with α and β constrained to be greater than or equal to zero. The coefficient of rolling resistance was derived from α using

$$C_r = -\frac{\alpha}{g}$$

and the effective frontal area (EFA) was calculated from β using

$$AC_d = -\frac{2\beta M}{\rho}$$

Hill climb test

The purpose of this test was to try and quantify tyre performance in a realistic setting. The test involved the participant completing a climb (600 m distance; average gradient 9.7% on a surface of hard-packed mud) at a fixed work output (3.5 W Σkg^{-1} (bike + rider weight)) on nine occasions for each of the five tyre models (Table I). The test was initiated from a standing start, and the participant was instructed to maintain a fixed power output for the whole climb as displayed on the on-bike computer display. The PowerTap has been reported as suitably valid and reliable for power output measurements during trials of this nature (Bertucci et al., 2005) as has the Garmin edge 500 (Macdermid & Stannard, 2012). The participant was blind to all measures other than real time power and average lap power.

Statistical analyses

Data are presented using descriptive statistics of mean and SD, while measurement-error statistics were calculated for reliability of the coasting test including the 95% confidence limits for the above random error statistics, the CV and Pearson's correlation coefficient to assess reliability of final speed with initial speed (Atkinson & Nevill, 1998).

A repeated-measures analysis of variance (ANOVA) with one variable (tyres) was used to test the differences in outcome measurements for both the coasting and hill climb. Where an overall significant difference was found, the main effect was analysed using Bonferroni post-hoc testing for pairwise comparisons.

Multiple linear regression (enter method) was performed for dependent variables, speed difference (km h^{-1}) for the deceleration test and separately for hill climb performance time. Predictors (independent variables) for both tests included tyre weight (g) total for front and back (ΣT_{wt}), estimated tyre volume based on ISO/ETRTO measurements (Van Der Plas, 1991) and Pappus's centroid theorem for calculating volume of a torus (cm^3), the tread surface area (cm^2) per standardised unit area and the average tyre tread depth (mm) calculated as the total tread volume per standardised unit divided by tread surface area. Diagrammatic representation of the measures used for tyre characteristics is provided in Figure 2. In addition to tyre characteristic predictors, initial speed and mean power output were used for the deceleration and hill climb regressions, respectively.

All statistical analyses were performed using IBM SPSS statistics 20, significance set at $P < 0.05$.

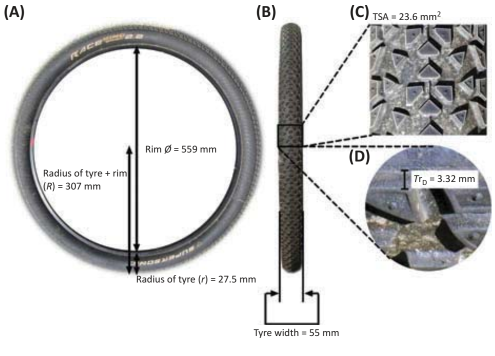


Figure 2. Diagrammatic presentation of tyre characteristic variables. The example provided is for the RaceKing model (Table I, Figure 2),

where, ISO/ETRTO measures are shown as (A) wheel rim diameter (Ø) and (B) tyre width; (C) tread surface area (TSA), calculated per standardised unit area with tread knobs highlighted in white used for this example; (D) mean tread depth (Tr_{D}), calculated as the mean depth for all tread knobs per standardised unit area.

Results

Reliability

In order to assess the reliability of the coasting deceleration test, the participant completed 30 trials under one condition on a separate occasion to the main trial. The mean time (s) to complete the initial 70 m was 10.95, s = 0.198 (95% CI 10.87–11.02) with a CV 1.81%; the initial speed was 24.32, s = 1.03 km h^{-1} (95% CI 23.91–24.72), CV 4.22%; time to complete the coasting section was 3.101, s = 0.146 s (95% CI 3.043–3.158), CV 4.70%; the final speed was 17.56, s = 0.79 km h^{-1} (95% CI 17.24–17.87), CV 4.52%. Pearson's correlation between the initial speed and final speed was r = 0.8536 ($P < 0.0001$).

Coasting deceleration test

Although the mean speed (km h^{-1}) over the acceleration period (70 m) was significantly different ($F_{(4,14)}$ = 27.05; $P < 0.0001$) between tyres, speed at the onset of the coasting period (initial speed) for each tyre was not significantly different ($F_{(4,14)}$ = 1.745; P = 0.1529), indicating that the initial speed was controlled. As a result, tyre performance can be judged based on the final speed or the percentage difference between initial speed and final speed. First, the final speed revealed significant differences between tyres ($F_{(4,14)}$ = 1.055; P = 0.0001), with post-hoc test analysis establishing that the Twister, RaceKing and X-King were travelling at greater speeds ($P < 0.05$) than the MountainKing tyre. As a result the speed difference (%) exposes rolling performance differences between tyres ($F_{(4,14)}$ = 0.8871; P = 0.0141) with post-hoc analysis showing the X-King tyres reduction in speed to be significantly less ($P < 0.05$) than for the MountainKing (Figure 3). Data for the deceleration test variables is displayed in Table II.

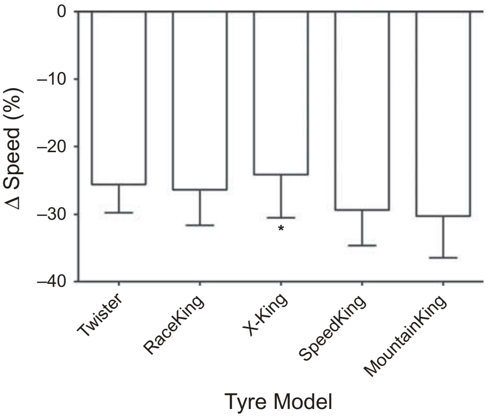


Figure 3. Mean ± s data taken from the coasting deceleration test for the percentage change in velocity (km h^{-1}) between the initial velocity and final velocity during the coasting deceleration test for the five tyres used.

*signifies $P < 0.05$ for Bonferroni post-hoc testing when compared with the MountainKing tyre model.

Multiple regression analysis with speed difference (S_{diff}) as the dependent variable produced a significant model ($F_{5,69}$ = 39.654; $P < 0.0005$; adjusted R^2 = 0.723). Significant predictor variables included total tyre weight (B = 0.179, P = 0.012), estimated tread volume (B = −0.440, P = 0.013), tread surface area (B = 1.184, P = 0.027), tyre tread depth (B = 9.194, P = 0.015) and initial speed (B = 0.795, $P < 0.0001$) and could be characterised by the following regression equation:

$$S_{\text{diff}} = -52.931 + \left(0.179 \times \sum T_{\text{wt}}\right) - (0.440 \times T_{\text{vol}}) + (1.184 \times \text{TSA}) + (9.194 \times Tr_{\text{D}}) + (0.795 \times s_{\text{i}})$$

where S_{diff} is the difference between initial speed and final speed (%), ΣT_{wt} is the total tyre weight (front and back), T_{vol} is the estimated tyre volume, TSA is the tread surface area, Tr_{D} is the tyre tread depth and s_{i} is the initial speed.

Modelling C_r

Data used from the deceleration test and applied to the model of Candau et al. (1999) are presented

Table II. Mean ± s performance results for the different variables measured during the deceleration test.

	Tyre model				
	Twister	RaceKing	X-King	Speed-King	MountainKing
$\bar{s}$70 (km h^{-1})	26.8 ± 0.5	26.3 ± 0.4	25.2 ± 0.8	26.4 ± 0.4	26.1 ± 0.4
S_{I} (km h^{-1})	35.7 ± 2.5	35.4 ± 2.5	33.9 ± 2.9	35.7 ± 1.8	34.5 ± 2.7
S_{F} (km h^{-1})	26.5 ± 2.4	25.9 ± 0.9	25.6 ± 1.0	25.3 ± 1.5	24.0 ± 1.9
S_{diff} (km h^{-1})	9.2 ± 1.9	9.4 ± 2.4	8.1 ± 2.6	10.5 ± 2.1	10.5 ± 2.7

Note: $\bar{s}$70 = mean speed over the 70 m acceleration period; S_{I} = initial speed; S_{F} = final speed; S_{diff} = difference between S_{I} and S_{F}.

Table III. Attempted model for coefficient of rolling resistance (C_r), effective frontal area (EFA) and total error (E) for XCO-MTB tyres based on the work of Candau et al. (1999).

Tyre model	C_r	EFA	E (m^2)
Twister	0.000490 ± 0.000222	2.184 ± 0.032	0.0937 ± 0.0108
RaceKing	0.000527 ± 0.000222	2.206 ± 0.036	0.095 ± 0.0192
X-King	0.000580 ± 0.000223	2.225 ± 0.036	0.0912 ± 0.0178
SpeedKing	0.000492 ± 0.000198	2.225 ± 0.037	0.1065 ± 0.0256
MountainKing	0.000222 ± 0.000149	2.223 ± 0.048	0.1267 ± 0.0362

in Table III. The error presented in Table III is the sum of the error in distance squared across all three timing gates used in the data fitting. While the calculated coefficient of rolling resistance is low and EFA is high, the total values for error are very small, further emphasising the reliability of the data from the deceleration test.

Hill climb test

The participant was asked to complete the climb six times under five conditions (tyre model, Table I) at a power output relating to 3.5 W kg of Σ weight^{-1} which equated to a relative power output of 4.4 W kg^{-1} or absolute power output of 250 W. Repeated-measures ANOVA showed there were no significant differences found for mean power output ($F_{(4,5)}$ = 12.300; P = 0.1945) between conditions (249 ± 3; 249 ± 6; 250 ± 3; 248 ± 6 and 250 ± 4 W for Twister, RaceKing, X-King, SpeedKing and MountainKing, respectively); yet there was an overall significance ($F_{(4,5)}$ = 1.937; P = 0.0317) in time to reach the top (Figure 4(A)). Mean ± s times were 198.5, s = 2.8, 198.5, s = 2.4, 197.3, s = 1.2, 200.2, s = 3.6 and 201.5, s = 1.1 s for Twister, RaceKing, X-King, SpeedKing and MountainKing, respectively. Post-hoc testing indicated that pairwise comparison was only significant between X-King and MountainKing. When average speed per work done per total weight was assessed as a measure of performance efficiency interaction of tyre, bike and rider, no overall difference ($F_{(4,5)}$ = 3.460; P = 0.0835) was found (Figure 4(B)).

Multiple regression analysis with time (s) to complete the hill climb as the dependent variable provided a significant model ($F_{4,25}$ = 2.771; P = 0.049; adjusted R^2 = 0.196). Significant variables included total tyre weight ($\sum T_{wt}$) (B = 0.481, P = 0.026), estimated tread volume (T_{vol}) (B = −0.121, P = 0.026), tread surface area (TSA) (B = 3.417, P = 0.035) and tyre tread depth (Tr_D) (B = 25.346, P = 0.027) and are characterised by the following regression equation:

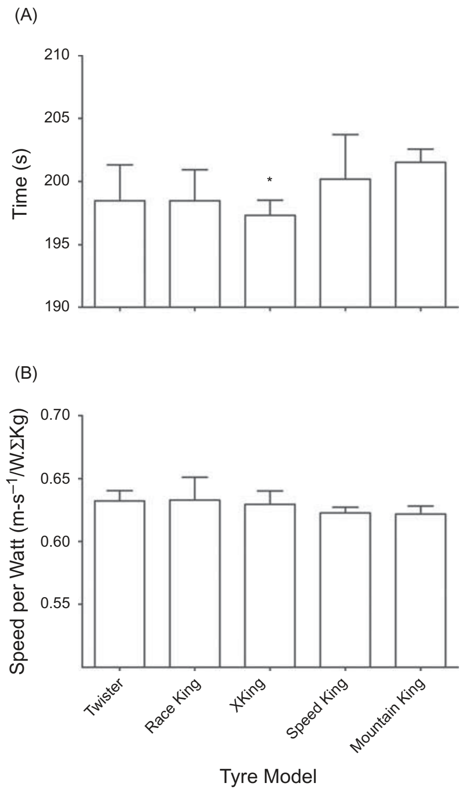


Figure 4. Mean ± s data for (A) time taken to complete the climb and (B) average speed (m s^{-1}) per Watt.

$$\begin{aligned}\text{Hill climb time (s)} = {} & 106.334 + (0.481 \times \sum T_{wt}) \\ & - (0.121 \times T_{vol}) \\ & + (3.417 \times \text{TSA}) \\ & + (25.346 \times Tr_D)\end{aligned}$$

where $\sum T_{wt}$ is the total tyre weight (front and back), T_{vol} is the estimated tyre volume, TSA is the tread surface area and Tr_D is the tyre tread depth.

Mean power output (W) was excluded from the model due to a non-statistical significance (B = 0.334, P = 0.223).

Discussion

This investigation sets out to assess the effect of identically constructed cross-country mountain bike tyres, differing in tread characteristics and volume, on the resistance to roll on hard-pack single track using a deceleration test and during a climb typical of a cross-country mountain bike race. The main findings were: (a) the deceleration test is a reliable method of determining the rolling performance of a cross-country mountain bike tyre; (b) previous models of determining rolling resistance of road tyres are not applicable for cross-country mountain bikes; (c) while cross-country mountain bike tyres have many facets that can influence overall performance, results suggest that the best option for performance, tyre reliability considered, would be to decrease weight by way of a reduction in both tread surface area and tread depth; (d) the intermediate tyre (X-King) tested (Table I) provides the rider with the best option for racing in conditions tested.

In setting out to assess the rolling performance of cross-country mountain bike tyres, two field based tests were performed under controlled conditions. The coasting deceleration test has been validated (Candau et al., 1999) to assess resistive forces of cycling and used to identify the effects of tyre pressure and load on rolling resistance of road bicycles in an indoor environment (Grappe et al., 1999). This is the first time it has been used outdoors on a surface typical of cross-country mountain biking. As a result, the preliminary trial was performed to quantify the reliability of such a test in an authentic environment to the sport of cross-country mountain bike racing. While data analysis showed some variation (~ 1 km h^{-1}) for initial speed (determined by single beam, microprocessor functionality timing device), this is within the range of reliability for the Garmin GPS device used (Macdermid & Stannard, 2012) to attain the pre-coasting speed of 25 km h^{-1}. Comparisons of CV between initial speed and final speed highlight the small variability amongst the two data points measured and is further supported by the small error of 10 cm over the 20 m unloaded cycling reported in the modelled data of Table III. As such, the coasting deceleration test can be confirmed reliable for assessing the rolling performance of cross-country mountain bike tyres in a true-to-life setting, with standardised conditions.

Data taken from the deceleration test for the tyres were used to try and model the coefficient of rolling resistance as per previous studies using road bikes indoors (Candau et al., 1999; Grappe et al., 1999). While the fit of the model was good, as can be seen in Table III, the resulting coefficient of rolling resistance and estimated frontal area were improbable: the reported coefficients of rolling resistance were far lower than for road bike (Candau et al., 1999; Wilson et al., 2004) even though previous research has indicated that the rolling resistance is larger for mountain bikes (Di Prampero, 2000) and that the lower pressures typically used in mountain biking should result in higher rolling resistance (Bertucci & Rogier, 2012; Bertucci et al., 2013). Meanwhile, the EFAs were around four times larger than those reported for road cycling (Candau et al., 1999; Martin, Harney, & Berry, 1998) which is not likely. It seems probable that some of the resistance due to the tyres is being attributed to air resistance, most likely as a result of rolling resistance not being independent of speed. As such, a different model of resistance is necessary for mountain biking and should be explored in future research.

The main aim of using the coasting deceleration test was to assess the tyre rolling performance hinged on standardisation of initial speed between conditions (tyres). Although the reliability trial showed this to be possible, it is still important to identify this within the main trial as increases in initial speed would cause an increased air resistance contribution to total resistance and could possibly be misinterpreted as an increase in rolling resistance (Di Prampero et al., 1979). Confirmation of this control measure is emphasised by the non-significant difference and allows rolling performance to be assessed based on the final speed and more precisely the Δ speed. Discrepancies between these two output measures are seen with regard to interpretation of best tyres where the order of performance was Twister, RaceKing, X-King, SpeedKing and MountainKing. However, small non-significant difference in initial speed has potentially affected the final speed which is accounted for in Figure 3 where the order of best performance becomes X-King, Twister, RaceKing, SpeedKing and MountainKing. These findings are interesting as they reflect those of the hill climb test (Figure 4), suggesting that the rolling performance as determined from the deceleration test (expressed Δ speed) is good enough to indicate performance over a hill climb on different terrain where tyre compression properties would be greater due to the uphill gradient.

While this study sets out to assess the rolling performance of a range of tyres of the same construction but different tread patterns, it was impossible to control other aspects such as tyre volume. Both the SpeedKing and Twister were unavailable in a 26 × 2.2″ size (Table I), and although the width difference between these and the other tyres tested only amounted to 2.5 mm and 7.5 mm, respectively, there could be a performance disadvantage (Nilges, 2010) related to a narrower but longer contact patch and thus a greater retardation force to overcome. While the work of Nilges highlighted a difference on grass but not on gravel, the two smaller volume tyres used in our study showed performance to be consistent across both tests on two different surfaces. Interestingly, the two lower volume tyres in this study performed quite differently while having two quite distinct characteristics relating to tread surface area and tread depth (Table I). The Twister is low volume, lightweight and has minimal tread, is classified as a slick, yet has a high tread surface area per standardised unit and a low tread depth compared to the SpeedKing, classified as a mud tyre, which is lightweight and has a more aggressive tread configuration by way of a low tread surface area and a high tread depth. Both tyres are considerably lighter than the others tested; yet tread characteristics seem to be the defining component with regard to performance in these tests. However, while intimating preference for minimal tread, it is important to highlight the fact that the best overall performing tyre was in fact the heaviest tyre tested, with the equal greatest tyre volume, and had an intermediary value for tread surface area and tread depth (Table I). Combining these values through the multiregression equation provides the best performance option for rolling – climbing. Again, the only difference between the X-King, RaceKing and MountainKing other than 25 g per tyre, maximum, is the tread characteristics (Table I).

A limitation of this study with regard to performance over a cross-country mountain bike race course is the linearity of the testing methods used. Cross-country mountain biking involves negotiating a large number of corners (Macdermid & Stannard, 2012), and although unsubstantiated it is likely that a more aggressive tread pattern and tyre volume would provide increased confidence and greater performance during cornering and unstable sections of a course. Yet more time and emphasis is spent climbing (Gregory et al., 2007; Macrae, Hise, & Allen, 2000) as it is easier to gain or lose time on this part of a course. As such, it could be argued that by choosing a tyre that allows the rider to climb well will provide the best competitive advantage. To this end, the data provided within this study identify the best performing tyre as not being the lightest or the slickest but one with a well-designed tread configuration (optimal weight to tread surface area and tread depth), a tyre for all terrain and most conditions.

Conclusion

We have shown that a simple deceleration test is easily administered and reliable for testing tyre rolling performance in the field on a flat surface specific to cross-country mountain bike racing. Traditionally, cross-country mountain bike athletes or team managers have chosen the lightest tyres in order to improve performance. The findings of this study show that the ideal tyre for performance on hard-pack surfaces, tyre reliability considered, would be to decrease weight by way of a reduction in both tread surface area and tread depth. Future research should concentrate on developing a model to calculate rolling resistance and air resistance during cross-country mountain bike riding.

References

Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. [Review]. *Sports Medicine*, *26*(4), 217–238.

Bertucci, W., Duc, S., Villerius, V., Pernin, J.-N., & Grappe, F. (2005). Validity and reliability of the powertap mobile cycling powermeter when compared with the srm device. *International Journal of Sports Medicine*, *26*(10), 868–873.

Bertucci, W., & Rogier, S. (2012). Effects of different types of tyres and surfaces on the power output in the mountain bike field conditions: A preliminary study. *Computer Methods in Biomechanics and Biomedical Engineering*, *15*(suppl 1), 234–236.

Bertucci, W. M., Rogier, S., & Reiser, R. F.(2013). Evaluation of aerodynamic and rolling resistances in mountain-bike field conditions. *Journal of Sports Sciences*, *31*, 1–8.

Candau, R. B., Grappe, F., Menard, M., Barbier, B., Millet, G. Y., Hoffman, M. D., … Rouillon, J. D. (1999). Simplified deceleration method for assessment of resistive forces in cycling. *Medicine and Science in Sports and Exercise*, *31*(10), 1441–1447.

Capelli, C., Schena, F., Zamparo, P., Dal Monte, A. D., Faina, M., & Di Prampero, P. E. (1998). Energetics of best performances in track cycling. *Medicine & Science in Sports & Exercise*, *30*, 614–624.

Di Prampero, P., Cortili, G., Mognoni, P., & Saibene, F. (1979). Equation of motion of a cyclist. *Journal of Applied Physiology*, *47* (1), 201–206.

Di Prampero, P. E. (2000). Cycling on earth, in space, on the moon. *European Journal of Applied Physiology*, *82*, 345–360.

Earp, J. E., & Newton, R. U. (2012). Advances in electronic timing systems: Considerations for selecting an appropriate timing system. *The Journal of Strength & Conditioning Research*, *26*(5), 1245–1248.

Faria, E. W., Parker, D. L., & Faria, I. E. (2005). The science of cycling: Factors affecting performance – part 2. *Sports Medicine*, *35*(4), 313–337.

Faria, I. E., & Cavanagh, P. R. (1978). *The physiology and biomechanics of cycling*. New York, NY: John Wiley & Sons.

Grappe, F., Candau, R., Barbier, B., Hoffman, M., Belli, A., & Rouillon, J.-D. (1999). Influence of tyre pressure and vertical load on coefficient of rolling resistance and simulated cycling performance. *Ergonomics*, *42*(10), 1361–1371.

Gregory, J., Johns, D. P., & Walls, J. T. (2007). Relative vs. absolute physiological measures as predictors of mountain bike cross-country race performance. *Journal of Strength and Conditioning Research*, *21*(1), 17–22.

Hurst, H. T., Swarén, M., Hébert-Losier, K., Ericsson, F., Sinclair, J., Atkins, S., & Holmberg, H.-C. (2012). Influence of course type on upper body muscle activity in elite cross-country and downhill mountain bikers during off road downhill cycling. *Journal of Science and Cycling*, *1*, 2–9.

Impellizzeri, F., Sassi, A., Rodriguez-Alonso, M., Mognoni, P., & Marcora, S. (2002). Exercise intensity during off-road cycling competitions. *Medicine & Science in Sports & Exercise*, *34*(11), 1808–1813.

Kyle, C. R. (1988). The mechanics and aerodynamics of cycling. In E. R. Burke (Ed.), *Medical and scientific aspects of cycling* (pp. 235–251). Champaign, IL: Human Kinetics.

Macdermid, P. W., & Morton, R. H. (2012). A longitudinal analysis of start position and the outcome of world cup cross-country mountain bike racing. *Journal of Sports Sciences*, *30*(2), 175–182.

Macdermid, P. W., & Stannard, S. (2012). Mechanical work and physiological responses to simulated cross country mountain bike racing. *Journal of Sports Sciences*, *30*(14), 1491–1501.

Macrae, H.-H., Hise, K. J., & Allen, P. J. (2000). Effects of front and dual suspension mountain bike systems on uphill cycling performance. *Medicine and Science in Sports and Exercise*, *32*(7), 1276–1280.

Martin, G. W., 3rd, Harney, J. W., & Berry, M. J. (1998). Functionality of mutations at conserved nucleotides in eukaryotic secis elements is determined by the identity of a single non-conserved nucleotide. [Research Support, U.S. Gov't, Non-P. H.S. Research Support, U.S. Gov't, P. H.S.] *RNA*, *4*(1), 65–73.

Martin, J. C., Gardner, A. S., Barras, M., & Martin, D. T. (2006). Modeling sprint cycling using field-derived parameters and forward integration. *Medicine and Science in Sports and Exercise*, *38*(3), 592–597.

Martin, J. C., Milliken, D. L., Cobb, J. E., Mcfadden, K. L., & Coggan, A. R. (1998). Validation of a mathematical model for road cycling power. *Journal of Applied Biomechanics*, *14*, 276–291.

Nilges, P. (2010). How to increase your speed: All about rolling resistance. Retrieved June 28, 2013, from http://www.google.co.nz/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CB0QFjAA&url=http%3A%2F%2Fwww.mtbonline.co.za%2Fdownloads%2FRolling_Resistance_Eng_illustrated.pdf&ei=4R3JU7baDejy7AbyrIBw&usg=AFQjCNFWiKfFyzd_pVVWGpgqNpUdDLawLw&sig2=Fg0xuBsURQoG59GSXq9_zw&bvm=bv.71198958,d.ZGU

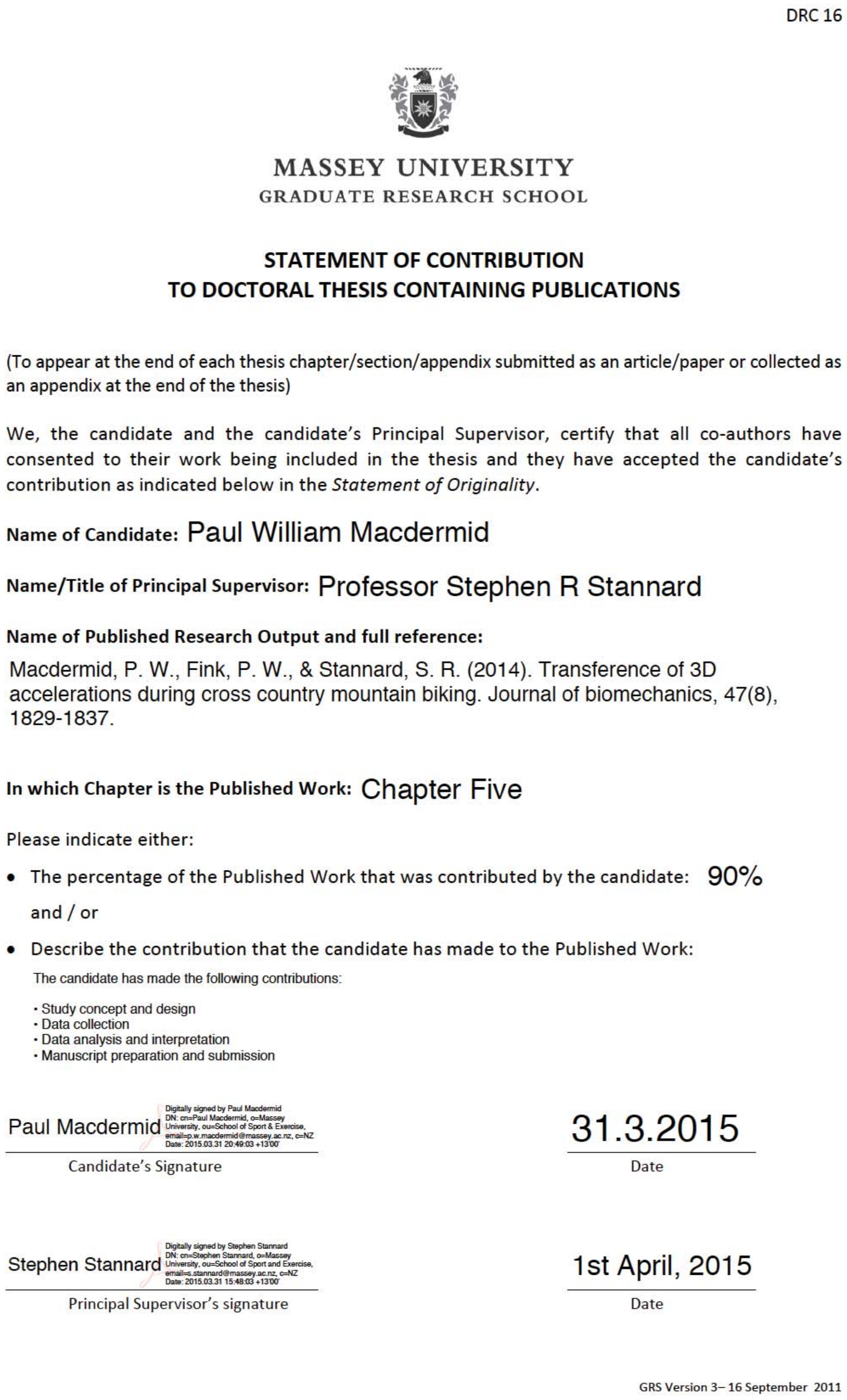
Overend, N., & Pavelka, E. (1999). *Ned overend: Mountain bike like a champion, master the techniques of America's greatest rider*. Emmaus, PA: Rodale Press.

Van Der Plas, R. (1991). *Bicycle technology: Understanding, selecting, and maintaining the modern bicycle and its components*. San Francisco, CA: Bicycle Books.

Whitt, F. R. (1971). A note on the estimation of the energy expenditure of sporting cyclists. *Ergonomics*, *14*(3), 419–424.

Wilson, D. G., Papadopoulos, J., & Whitt, F. R. (2004). *Bicycling science*. Cambridge, MA: MIT Press.

Appendix 3



DRC 16

MASSEY UNIVERSITY
GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
TO DOCTORAL THESIS CONTAINING PUBLICATIONS

(To appear at the end of each thesis chapter/section/appendix submitted as an article/paper or collected as an appendix at the end of the thesis)

We, the candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of Candidate: Paul William Macdermid

Name/Title of Principal Supervisor: Professor Stephen R Stannard

Name of Published Research Output and full reference:

Macdermid, P. W., Fink, P. W., & Stannard, S. R. (2014). Transference of 3D accelerations during cross country mountain biking. Journal of biomechanics, 47(8), 1829-1837.

In which Chapter is the Published Work: Chapter Five

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate: 90%

  and / or

- Describe the contribution that the candidate has made to the Published Work:

  The candidate has made the following contributions:

  - Study concept and design
  - Data collection
  - Data analysis and interpretation
  - Manuscript preparation and submission

Paul Macdermid
Digitally signed by Paul Macdermid
DN: cn=Paul Macdermid, o=Massey University, ou=School of Sport & Exercise, email=p.w.macdermid@massey.ac.nz, c=NZ
Date: 2015.03.31 20:49:03 +13'00'

Candidate's Signature

31.3.2015

Date

Stephen Stannard
Digitally signed by Stephen Stannard
DN: cn=Stephen Stannard, o=Massey University, ou=School of Sport and Exercise, email=s.stannard@massey.ac.nz, c=NZ
Date: 2015.03.31 15:48:03 +13'00'

Principal Supervisor's signature

1st April, 2015

Date

GRS Version 3– 16 September 2011

Journal of Biomechanics 47 (2014) 1829–1837

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Transference of 3D accelerations during cross country mountain biking

Paul W. Macdermid [*], Philip W. Fink, Stephen R. Stannard

Massey University, College of Health, School of Sport & Exercise, Private Bag 11-222, Palmerston North 4474, New Zealand

ARTICLE INFO

Article history:
Accepted 11 March 2014

Keywords:
Mountain biking
Accelerations
Vibrations
Damping
Field testing

ABSTRACT

Investigations into the work demands of Olympic format cross country mountain biking suggest an incongruent relationship between work done and physiological strain experienced by participants. A likely but unsubstantiated cause is the extra work demand of muscle damping of terrain/surface induced vibrations. The purpose of this study was to describe the relationship between vibration mechanics and their interaction with terrain, bicycle and rider during a race pace effort on a cross country mountain bike track, on both 26″ and 29″ wheels. Participants completed one lap of a cross country track using 26″ and 29″ wheels, at race pace. Power, cadence, speed, heart rate and geographical position were sampled and logged every second for control purposes. Tri-axial accelerometers located on the bicycle and rider, recorded accelerations (128 Hz) and were used to quantify vibrations experienced during the whole lap and over terrain sections (uphill and downhill). While there were no differences in power output ($p=0.3062$) and heart rate ($p=0.8423$), time to complete the lap was significantly ($p=0.0061$) faster on the 29″ wheels despite increased vibrations in the larger wheels ($p=0.0020$). Overall accelerometer data (RMS) showed location differences ($p<0.0001$), specifically between the point of interface of bike–body compared to those experienced at the lower back and head. The reduction in accelerations at both the lower back and head are imperative for injury prevention and demonstrates an additional non-propulsive, muscular, challenge to riding. Stress was greatest during downhill sections as acceleration differences between locations were greater when compared to uphill sections, and thus possibly prevent the recovery processes that may occur during non-propulsive load.

1. Introduction

Work demand during Olympic format cross country mountain biking (XCO-MTB) does not reflect the physiological strain experienced by participants (Stapelfeldt et al., 2004). Explanations focus on non-pedal related work (Hurst and Atkins, 2006), which could include terrain induced vibration damping.

Bicycling is considered a non-impact sport (Stewart and Hannan, 2000) yet mountain bikes are subjected to vibrations (De Lorenzo and Hull, 1997; Faiss et al., 2007; Levy and Smith, 2005) which the bicycle–body must dissipate before the accelerations reach the central nervous system (CNS) (Samuelson et al., 1989). As such, XCO-MTB has shown to provide a significant osteogenic effect compared to road cycling (Warner et al., 2002) but non-pedal related work such as that required to dampen energy from vibrations in XCO-MTB is not yet well quantified and could indirectly influence the total work done and thus performance in a race situation.

The majority of load components occurring at the bicycle level during off-road cycling have been shown to occur at <50 Hz (De Lorenzo and Hull, 1997; Levy and Smith, 2005). Higher frequencies have been found at the wheel itself, but these frequencies were not present at the interface with the rider (Levy and Smith, 2005). The high frequency vibrations (25–25,000 Hz) are associated with wheel rotations and tread configuration and are absorbed by the bicycle (Levy and Smith, 2005), and soft tissue at the point of interface (Issurin, 2005). Although this may occur in XCO-MTB it is likely that there will be many rapid and variable changes in track surface adding to the work required of the bike–body damping mechanisms. Alternatively, low frequency vibrations (<25 Hz) are less likely to be dealt with the bicycle and are more difficult for the body to deal with as the frequency which propagates through contracted or stretched muscle is within the range of resonance reported for whole body (Mester et al., 1999) and individual muscles directly related to propulsion during cycling (Wakeling et al., 2002). Such vibrations are reported to increase muscle activity, a result of dampening, and increase motor unit involvement for a given production of muscle force (Mester et al., 1999) and thus decrease overall efficiency. Laboratory work placing cycle ergometers on vibration platforms (20 Hz, amplitude of 1.8 mm)

---

[*] Corresponding author. Tel.: +64 6 356 9099x81748.
E-mail address: p.w.macdermid@massey.ac.nz (P.W. Macdermid).

http://dx.doi.org/10.1016/j.jbiomech.2014.03.024
0021-9290/© 2014 Elsevier Ltd. All rights reserved.

decreased time to exhaustion by 21% (Samuelson et al., 1989) while a novel study involving a bump simulator (bumps were 30 and 70 mm) for mountain bikes (Titlestad et al., 2003) showed that at frequencies of 2.9–4.0 Hz oxygen cost and heart rate increased by 50% and 35%, respectively (Titlestad et al., 2006). The addition of bumps in such trials, whether realistic or not, highlights the increased work demand as a result of vibration or shocks in XCO-MTB. These findings are supported by the addition of suspension systems to bikes with regards to comfort, economy, and performance (Nishii et al., 2004), with subsequent decreases in vibrations or shocks at the saddle level (Faiss et al., 2007). Even with these technological improvements, it is has been shown that the rider's upper body will perform significant work (Hurst et al., 2012), potentially due to bike handling and the damping of vibrations. Nevertheless, there is little empirical description of the transference of energy from the terrain surface to bike to human during XCO-MTB.

While traditionally XCO-MTB have used 26″ wheels, the last few years have seen the introduction of 29″ and 27.5″ wheels. At the 2012 Olympic Games wheel size distribution amongst the top 10 males and females combined, equated to 70; 25; and 5% for 29″, 26″ and 27.5″ wheels respectively. It has been suggested that wheel diameter reduces vibration in any format (Wilson, 2004). A statement endorsed by industry led promotions claiming greater performance and a smoother ride and thus overall performance gain.

The primary aim of this study is to describe the frequency–magnitude relationship, the amplitude of accelerations and the interaction between the terrain, bicycle and rider during a typical XCO-MTB race lap whilst using 26″ and 29″ wheels. We hypothesised that accelerations experienced at the head and lower back will be significantly less than those at the bicycle and limbs, that the accelerations will be different for uphill and downhill riding, and that 29″ wheels will dampen vibrations to a greater extent than 26″ wheels.

2. Methods

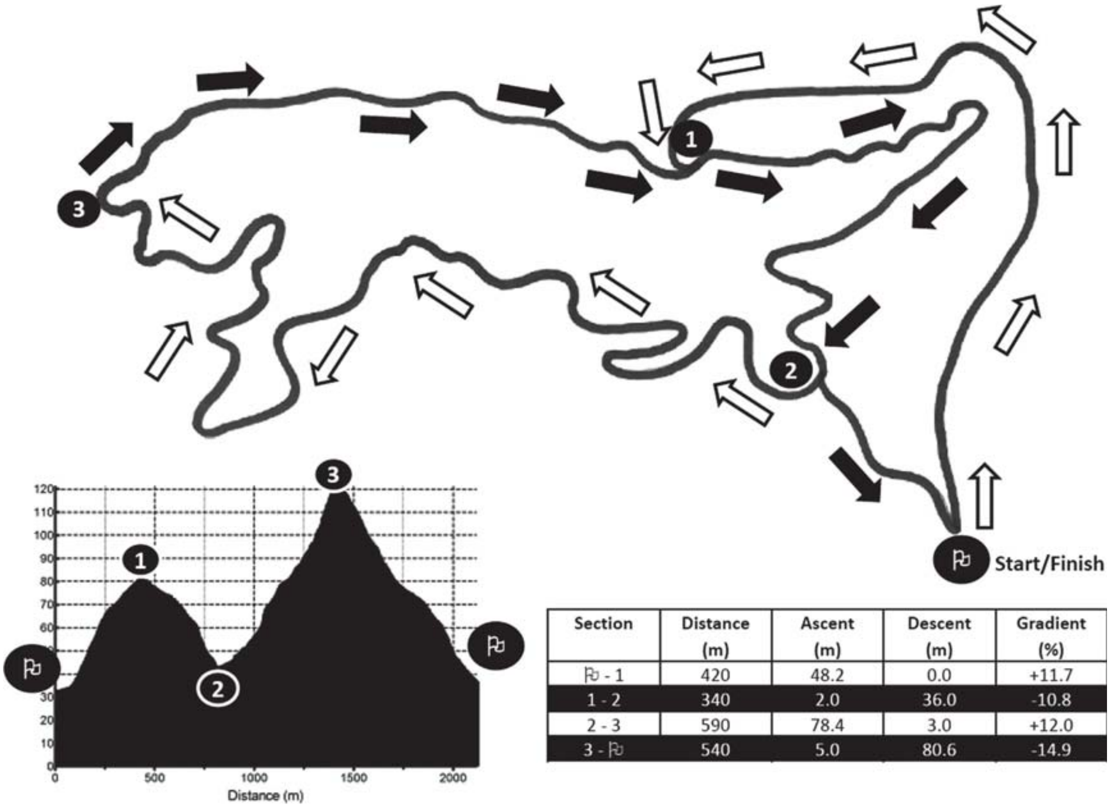
2.1. Participants

Eight nationally competitive XCO-MTB athletes (mean ± s: age 25 ± 11 years, height 178 ± 12 cm, mass 63.0 ± 9.0 kg) performed a laboratory ramp style test commencing at 100 W and increasing by 25 W per minute (W_{max} 419 ± 68 W or 6.6 ± 0.2 W kg^{-1}, HR_{max} 197 ± 8 bpm) until volitional fatigue. All participants provided written informed consent in accordance with the Declaration of Helsinki.

2.2. Field test trials

Participants attended a day at a purpose-built mountain bike course (Kohitere Forest, Levin, NZ) completing a re-familiarisation of the XCO-MTB course to be used. The course was broken down into sections based on terrain (Fig. 1).

Participants were required to perform one lap of the course under two conditions (26″ and 29″ wheels), separated by 15 min to allow full recovery. Because we wanted to quantify the accelerations during realistic conditions, participants were instructed to ride at race pace which has been previously reported at about 90% HR_{max} (Impellizzeri et al., 2002). Each condition involved participants riding the same bicycle (GT Zaskar elite 29″ hard tail, Optimised Force



Section	Distance (m)	Ascent (m)	Descent (m)	Gradient (%)
⚐ - 1	420	48.2	0.0	+11.7
1 - 2	340	2.0	36.0	-10.8
2 - 3	590	78.4	3.0	+12.0
3 - ⚐	540	5.0	80.6	-14.9

Fig. 1. Course outline for the XCO-MTB lap used during the study. Where ⚐ indicates start and finish, ⇨ refers to a climb and ➔signifies a descent. Numbers encircled 1–3 on the map are related to climbs or descents highlighted on the schematic profile of the course. Section characteristics are provided in the table to the right of the schematic profile.

Constructed Carbon, USA), adjusted to personal requirements prior to the trial, and thus controlling posture, but fitted with either 26″ or 29″ wheels (X430 and X470, 32H, DT Swiss, CH.). By using the same frame built for 29″ wheels the bike handling properties could have been compromised. However, mechanical trail, seen as a major determinant of a bicycles handling properties (Wilson, 2004), only differed by 10 mm and was unnoticed by participants. Conditions were performed in a counter balanced order to prevent any order effect on the dependent variables of interest.

2.3. *Outcome measures*

Power output (*W*), cadence (rpm), speed (km h^{-1}), and heart rate (bpm) were continuously sampled and logged every second (SRAM QUARK S2275 MTB Power Metre, USA; Garmin, Edge 500, USA) in order to make comparisons between conditions for work done and physiological strain when comparing performance time (*s*). This powermeter system has a reported accuracy ± 1.5% (Aguilar et al., 2008). Data recorded from the power metre, heart rate monitor transceiver and GPS device were transmitted to a conventional PC for processing.

Wireless, tri-axial accelerometer, magnetometers and gyroscope with a reported accuracy 0.0012 $m\ s^2 \cdot \sqrt{Hz}^{-1}$ (Emerald, APDM, OR, USA), were used in a synchronised data logging mode to measure accelerations in accordance with the International Standards (ISO 2631-1) for measuring vibrations (ISO, 1997). Use of accelerometers to measure vibrations on the human has been validated (Coza et al., 2010) and the Emerald accelerometers have been validated as a method for measuring vibrations (Carr et al., 2012).

The accelerometers were placed on the handlebar centre; lower left arm (frontal distal position); left lower leg (frontal, distal position); seat post (within 10 cm of saddle-rider contact area); lumbar region of lower back; and medial forehead (Fig. 2). Based upon the positioning of accelerometers and the understanding that all excitations at the bike–body interface occurs at < 50 Hz for off-road cycling (De Lorenzo and Hull, 1997; Faiss et al., 2007; Levy and Smith, 2005; Wilczynski and Hull, 1994) accelerometers were sampled at 128 Hz, logged, transmitted to PC, converted to h5 file and processed using MATLAB R2011b.

All data were analysed for total (*XYZ*), vertical (*Z*-axis), and horizontal (*X*- and *Y*- axes) accelerations. Root mean squares of accelerations were calculated to quantify the amount of vibration the participants experienced (ISO, 1997). A spectral analysis was also performed using a fast Fourier transform to examine the frequency of vibrations, and five measures were used for statistical analysis: (1) half frequency, the frequency at which half the total power was below the frequency, which quantified whether the accelerations were high or low frequency; (2) maximum frequency, the frequency at which the maximum amplitude was observed; and (3) maximum magnitude, the magnitude at that frequency. To separate the voluntary movements of the body or bicycle from the vibrations, maximum frequency and maximum magnitude were analysed at low frequency (< 5 Hz), which contains the voluntary movements (in addition to vibrations), and high frequency (> 5 Hz), which contains vibrations and physiological tremor. These values were chosen because previous research has indicated that 5 Hz is an upper limit for voluntary movements (Hines et al., 1987; Jäncke et al., 2004; Kay et al., 1991). This cut-off would also preserve the first two harmonics for a cyclist pedalling at 150 rpm, which was faster than the maximum cadence for any of the participants. Thus, the high frequency represents vibrations, while the lower frequency contains both vibrations and voluntary movement (e.g., pedalling).

2.4. *Statistical analysis*

Descriptive data (mean and standard deviation) were calculated for all dependent variables and compared by paired Student's *t*-tests. A two-way repeated-measures analysis of variance (ANOVA), with two within-subject variables (terrain and wheel size) was used to test differences between time (*s*), power output (*W*), cadence (rpm) and heart rate (bpm) in order to assess performance variations between trials.

Accelerometer data comparisons were made via univariate analysis of variance (three-way ANOVA), including within-subject variables, wheel size, terrain and accelerometer location, tested for main effects and interactions (wheel size × Terrain × Location; wheel size × terrain; wheel size × accelerometer location; and terrain × accelerometer location) for variables maximum frequency and maximum magnitude for < 5 Hz and > 5 Hz.

Analysis of RMS included separate three-way ANOVA analysis, within-subject variables: wheel size, accelerometer location and axis (vertical and horizontal), tested for main effects and interactions (wheel size × Terrain × Location; wheel size × axis; wheel size × accelerometer location; and axis × accelerometer location).

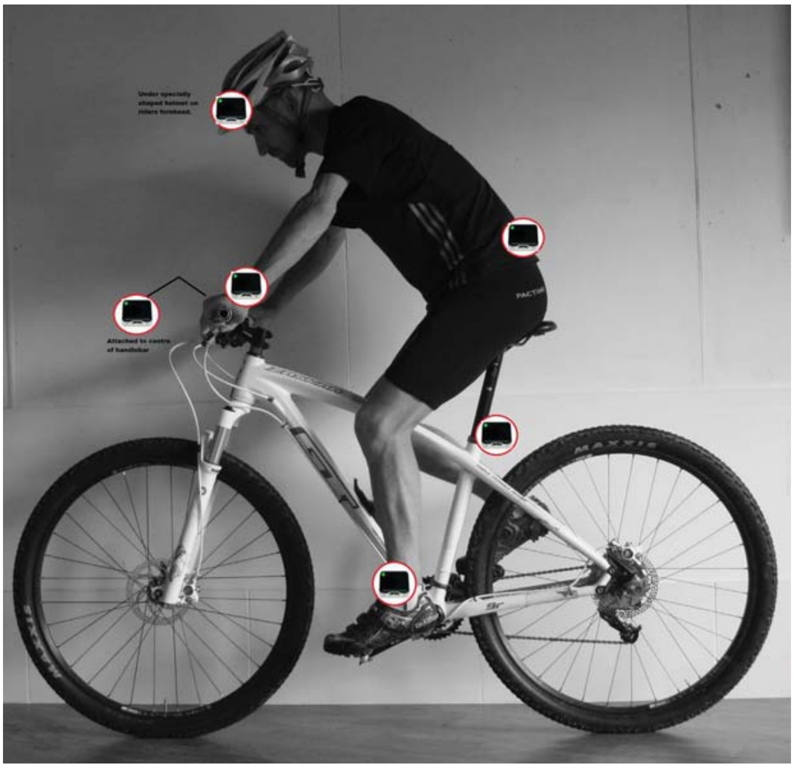


Fig. 2. A photograph depicting accelerometer locations during the trial.

Where an overall significant difference was found the main effect was analysed using Bonferroni post-hoc testing for pairwise comparisons. All statistical analyses were performed using IBM SPSS Statistics 20, significance set at $P < 0.05$.

3. Results

3.1. Performance analysis

Participants were asked to complete a lap of the XCO-MTB course under two conditions (26″ and 29″ wheels) at race pace (self-determined). Although, paired Student's *t*-tests showed no significant differences for overall power output (245 ± 31 and 244 ± 38 W, $p=0.3062$) and heart rate (165 ± 11 and 165 ± 10 bpm, $p=0.8423$), overall time proved to be significantly slower on the 26″ compared to the 29″ wheels (635.4 ± 41.5 vs 616.6 ± 49.2 s, $p=0.0061$), respectively. Terrain categorisation data (Table 1) showed no interactions for wheel size × terrain ($p=0.9202$; $p=0.8899$; $p=0.9090$) for time, power and heart rate respectively. As expected there were significant differences for within-subject variable, terrain, when comparing time ($p < 0.0001$), power output ($p < 0.0001$), and heart rate ($p=0.0477$) but not for wheel size ($P > 0.05$).

3.2. Accelerometer data

Three-way ANOVA analysis of total acceleration amplitude (RMS) showed that there was a significant main effect for wheel size ($F_{(1,168)}=10.079$; $P=0.0020$), axis ($F_{(1,84)}=1308.191$; $P < 0.0001$) and accelerometer location ($F_{(5,56)}=301.72$; $P < 0.0001$) plus an interaction ($F_{(1,168)}=67.121$; $P < 0.0001$) between axis (vertical and horizontal) and accelerometer location (Fig. 3). Fig. 4A–F shows the terrain effect on accelerations for total, vertical and horizontal axis for each accelerometer location. Three-way ANOVA showed significant differences ($P < 0.001$) for the total, vertical and horizontal accelerations for the main effects of terrain and accelerometer locations. There was also a significant terrain × location interaction ($P < 0.001$). Post-hoc analysis identified differences between downhill sections, between uphill and downhill section but not between uphills.

Power spectra for all six accelerometer locations for a single participant using 26″ wheels are shown in Fig. 5. Overall, the power was much higher, particularly at high frequencies, in the downhill sections. Only the head and back locations showed accelerations similar to that seen in uphill riding, indicating that the vibrations entering the bicycle were damped before reaching these parts of the bodies. In the uphill sections there is a low frequency (< 2 Hz) spike in the leg acceleration, which was caused by the pedalling motion. Power spectra for all seven participants can be found in the Supplementary material.

Results for vertical accelerations of frequency bandwidths (< 5 Hz and > 5 Hz) for wheel size, accelerometer location, and terrain section, expressed as mean ± SD, for maximum frequency, magnitude at maximum frequency are shown in Tables 2 and 3. Table 4 includes half frequency data (non-frequency banded) for wheel size, terrain and accelerometer location. Fig. 5 illustrates an individual subject spectral analysis for vertical acceleration of each accelerometer location, and separated for terrain.

There were significant main effects for wheel size ($F_{(1,168)}=4.378$, $P=0.037$ for < 5 Hz frequency band but not > 5 Hz, $F_{(1,168)}=1.412$, $P=0.234$), accelerometer location ($F_{(5,56)}=84.738$, $P < 0.001$; $F_{(5,56)}=95.221$, $P < 0.001$) and terrain ($F_{(3,84)}=54.498$, $P < 0.001$; $F_{(3,84)}=5.475$, $P=0.001$), plus terrain × location interaction ($F_{(15,56)}=5.368$, $P < 0.001$; $F_{(15,56)}=8.279$, $P < 0.001$) for maximum frequency (Table 2) at the frequency bands of < 5 Hz and > 5 Hz, respectively. Key findings from post-hoc analysis showed that there were overall significant differences ($P < 0.05$) between hill 1 and hill 2, and between the uphill's and downhill's, but not between the two downhill's. Multiple comparisons between the accelerometer locations were significantly different ($P < 0.05$) except handlebar–left arm, handlebar–eat post, left arm–seat post, lower back–head and handlebar–left leg, lower back–head for frequency bands < 5 Hz and > 0035 Hz, where $P > 0.05$.

Significant main effects of magnitude at maximum frequency for vertical accelerations were present for accelerometer location ($F_{(5,56)}=90.784$, $P < 0.001$; $F_{(5,56)}=109.744$, $P < 0.001$) and terrain ($F_{(3,84)}=126.711$, $P < 0.001$; $F_{(3,84)}=482.101$, $P < 0.001$), with a significant terrain × location interaction ($F_{(15,56)}=19.720$, $P < 0.001$; $F_{(15,56)}=41.628$, $p < 0.001$) for both frequency bands. Post-hoc analysis showed significant difference between all pair combinations of comparison between uphill and downhill's for the frequency band > 5 Hz while all multiple comparisons showed significant differences for the frequency band < 5 Hz. Multiple comparisons between the accelerometer locations were significantly different ($P < 0.05$) for all accelerometer positions except the lower back and head, for both frequency bands.

Analysis of half frequency data (Table 4) highlighted significant differences ($F_{(1,168)}=4.126$, $P=0.043$; $F_{(3,84)}=4.126$, $P < 0.001$; $F_{(5,56)}=409.394$, $P < 0.000$) between main effects wheel size, terrain and accelerometer locations, respectively, but with no interactions other than terrain × location ($F_{(15,56)}=11.886$, $P < 0.001$).

4. Discussion

The primary aim of this study was to quantify the vibrations from the bicycle during a typical XCO-MTB race lap, and to determine how these accelerations were dampened in the body whilst using 26″ and 29″ wheels. The main findings were: (a) variables of acceleration were significantly greater at the bike–body interface compared with the lower back and head; (b) terrain affected all locations by increasing measures associated with vibrations on downhill sections except in the case of the head

Table 1
Mean ± SD for performance variables measured throughout the field trial and separated based on terrain (Hill (H) and downhill (DH)) for the depicted order.

	Wheel Size (inches)	Uphill 1	Downhill 1	Uphill 2	Downhill 2	Two-way ANOVA
Time (s)	26	129 ± 9	88 ± 7	290 ± 23	128 ± 10	WS $P=0.242$ Terr $P < 0.001$
	29	126 ± 15	86 ± 8	280 ± 24	125 ± 12	WS × Terr $P=0.920$
Power (W)	26	362 ± 48	93 ± 57	304 ± 33	65 ± 36	WS $P=0.984$ Terr $P < 0.001$
	29	352 ± 58	81 ± 31	317 ± 38	74 ± 40	WS × Terr $P=0.846$
Heart rate (bpm)	26	165 ± 11	162 ± 13	170 ± 11	159 ± 12	WS $P=0.821$ Terr $P=0.048$
	29	163 ± 13	158 ± 9	171 ± 9	161 ± 10	WS × Terr $P=0.909$

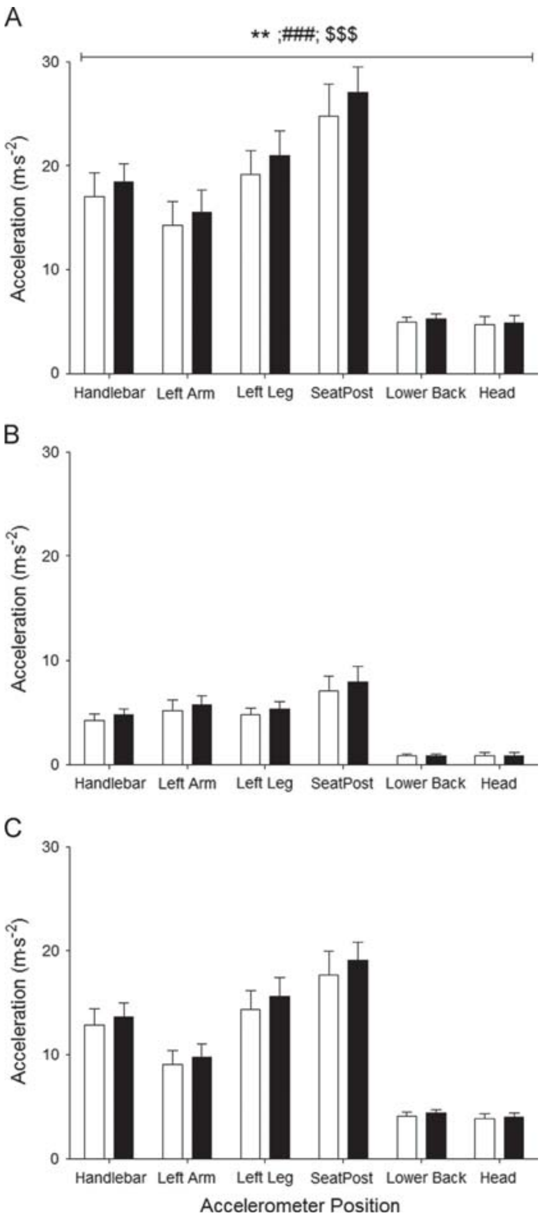


Fig. 3. Mean ± s amplitude (RMS) for (A) total; (B) vertical; and (C) horizontal components of acceleration over the whole lap. □ signifies 26″ wheel trial while ■ signifies 29″ wheels. **($P<0.01$) main effect of wheel size; $^{\#\#\#}$($P<0.001$) main effect of accelerometer location; $^{\$\$\$}$($P<0.001$) axis × accelerometer location.

where variables remained constant; (c) overall, 29″ wheels were faster than 26″ wheels; and (d) 29″ wheels increased acceleration overall both in the vertical and horizontal planes when compared to 26″ wheels.

Participants were asked to complete the laps at race pace, and the validity of the tests depended on their effort during the task. Participants were able to provide reliable efforts, as evidenced by the non-significant difference between wheel sizes in terms of heart rate or power (Table 1). Moreover, measures of workload and intensity are comparable with previous work on XCO-MTB race intensities (Stapelfeldt et al., 2004), indicating that the tests were valid measures of accelerations during race conditions.

In showing that there is a difference between the accelerations experienced at the bike–body interface compared with those of the lower back and head during XCO-MTB racing we have confirmed that a large amount of soft tissue damping occurs in order to protect the body via stabilisation (Figs. 3 and 4). This damping was similar to that seen in locomotion (Hamill et al., 1995; Mercer et al., 2003), where high frequency accelerations were greatly reduced at the head. Whilst we made no measure of muscle tension or stiffness in the current study, based on previous research (Hurst et al., 2012; Mester et al., 1999; Wakeling et al., 2003) it is probable that the muscles played a key role in removing the acceleration. In addition, soft tissue acts as a wobbling mass that vibrates in a direct response to mechanical excitation (Nigg and Liu, 1999; Wakeling et al., 2002) and such additional work detracts from the force generating capability of the muscles (Issurin, 2005) as there is a greater demand on motor units for a given force production (Mester et al., 1999). Such a response would be detrimental to forward propulsion of the XCO-MTB athlete.

Laboratory-based studies (Samuelson et al., 1989) investigating cycling and the effects of vibration show that accelerations of 20 m s^{-1} at the foot are damped to 2 m s^{-1} at the head with a subsequent decrease in submaximal time to exhaustion of 21% compared with cycling under normal (no vibrations) conditions. The accelerations previously reported at the head during laboratory cycling (Samuelson et al., 1989) are comparable to the field data for XCO-MTB presented (Fig. 3). Whatever the level of vibration experienced at the bike–body interface, it appears that muscular work is done to limit transference to the CNS in order to maintain optimal visual acuity, vestibular signals and decision making processes (Grether, 1971; Newell and Mansfield, 2008; Pozzo et al., 1995). This would necessarily be reflected in a decreased gross efficiency compared to ergometer or road cycling at the same absolute workload. Maintenance of optimal CNS function is essential to optimise performance and maintain safety while negotiating technical and synonymously bumpy XCO-MTB courses.

While Fig. 3 provides an overview of vibration severity at different accelerometer positions. Fig. 4 supplies us with more detail regarding the nature of the course in relation to possibilities of energy expenditure for muscle damping of vibrations. The significant interaction between terrain × accelerometer location emphasises that energy expenditure for dissipating vibrations is much smaller ascending compared to descending (Fig. 4 and Tables 2 and 4). However, it must be stressed that terrain is not just about ascent or descent as post-hoc analysis showed differences between the two climbs (Hill 1 and Hill 2). Hill 1 was a hard packed forest road which is relatively smooth with minimal steering requirements and performed at a relatively constant pace, while hill 2 was a single track climb consisting of multiple switch back corners, tree roots and obstacles with fluctuating pace changes. An interesting observation was the greater proportion of horizontal accelerations during climbing compared to descending as part of overall acceleration. This would be reflected in the fact that there would be greater resistance to forwards movement as a result of irregular gradient, track directions and surface terrain changes (Bertucci et al., 2013), but also the transference of effort from the upper body into force applied at the pedals. As reported in a previous study (Macdermid and Stannard, 2012) the torque applied during ascent in XCO-MTB is very high and requires a strength element not often seen in road cycling.

Comparisons of main effect for accelerometer location demonstrate that differences only occurred at the locations interfacing

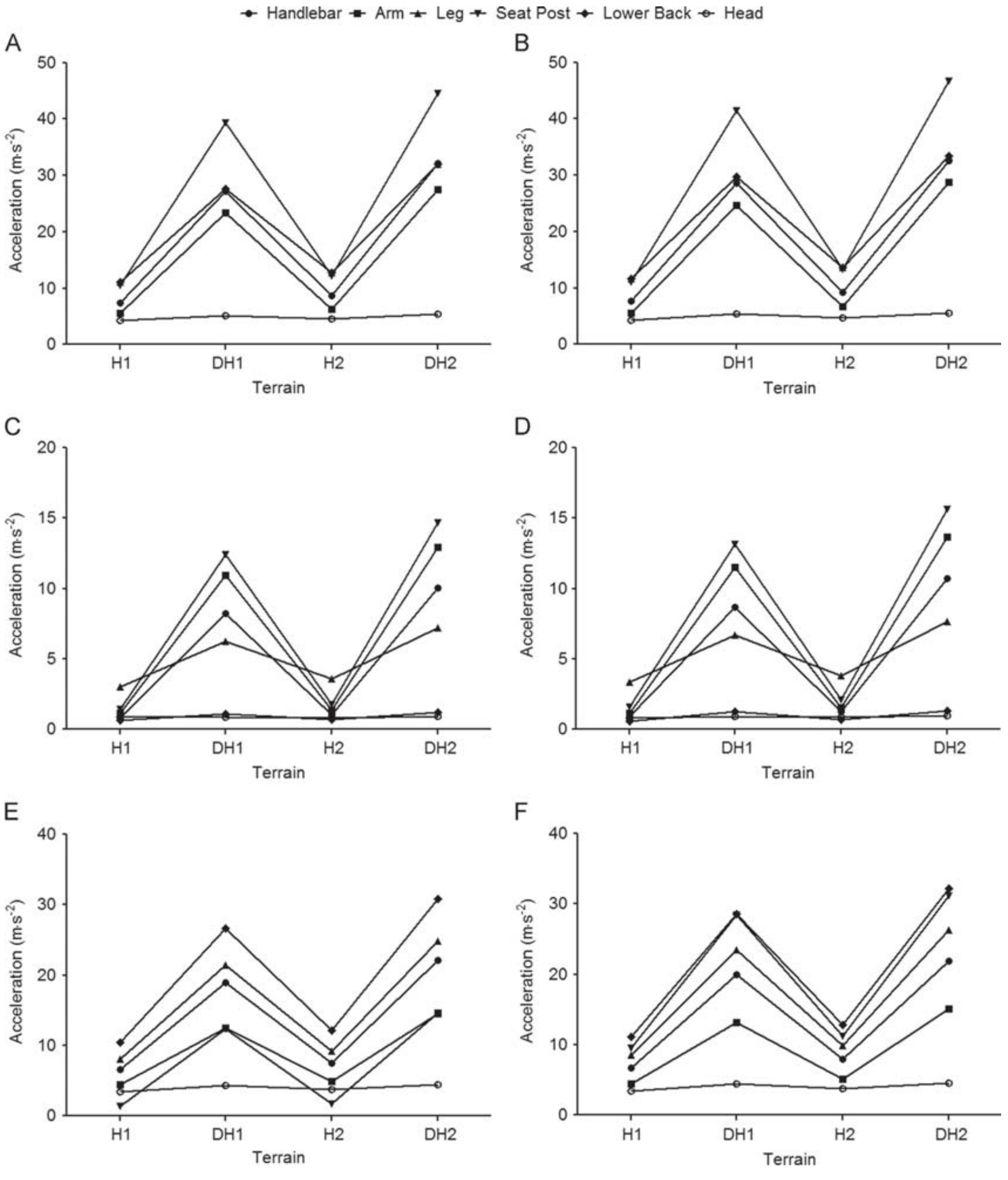


Fig. 4. Mean acceleration expressed as RMS for accelerometer locations for different terrain segments as described in fig. 1 (H1 = Uphill 1; DH1 = Downhill 2; H2 = Uphill 2; DH2 = Downhill 2). (A) Total acceleration for 26″ wheels; (B) total acceleration for 29″ wheels; (C)vertical acceleration for 26″ wheels; (D) vertical acceleration for 29″ wheels; (E) horizontal acceleration for 26″ wheels; and (F) horizontal acceleration for 26″ wheels.

bike–body, further consolidating the increased demand of energy expenditure for muscles in a damping role. Combined with the knowledge that more time is spent climbing than descending (66% vs 34% in this study) during XCO-MTB racing (MacRae et al., 2000) and the difficulties of passing when descending in race conditions (Macdermid and Morton, 2011), it is not surprising that the majority of international XCO-MTB athletes use a hard tail designed bike as opposed to a heavier full suspension design. This is contrary to peer reviewed literature suggesting that full suspension designs provide a more efficient ride over bumpy terrain

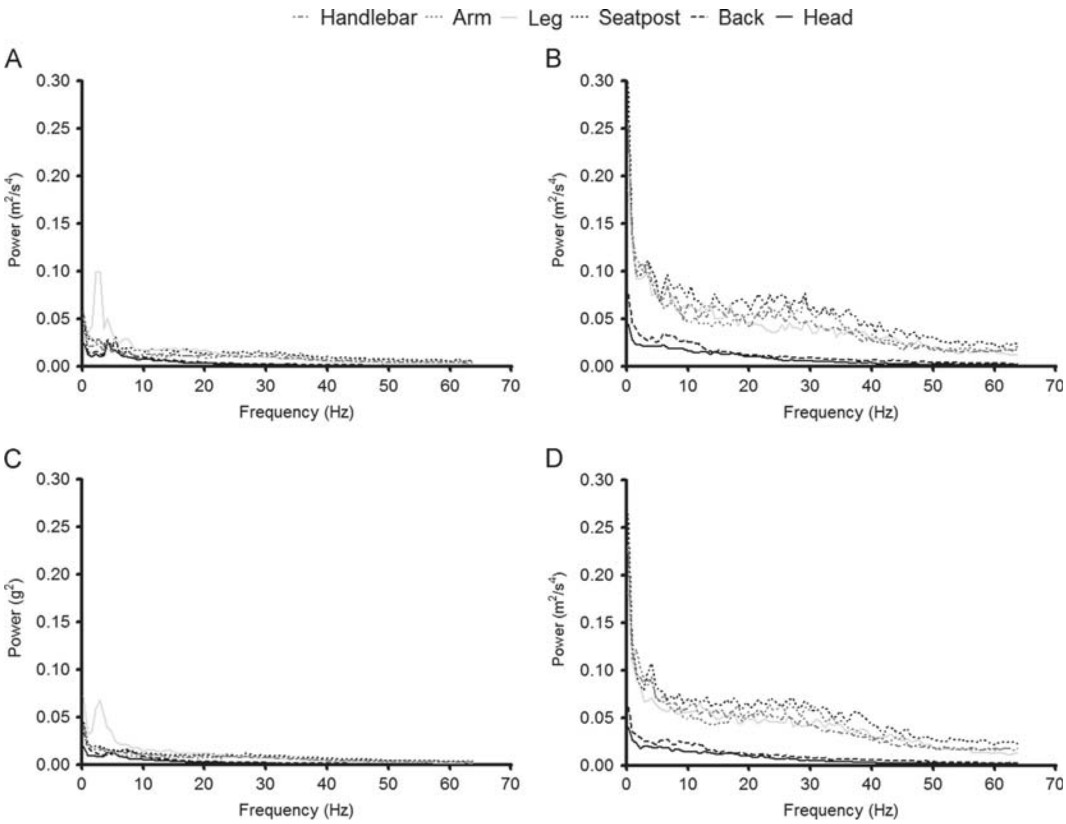


Fig. 5. Spectral analysis of vertical accelerations for subject 3 during different sections of the course where, (A) is uphill 1; (B) is downhill1; (C) is uphill 2; and (D) is downhill 2.

Table 2
Mean ± SD for maximum frequency (Hz) of accelerations at points of contact between bike– body during a XCO-MTB lap, and separated for terrain, frequency banding and wheel size.

Accelerometer location	**26″Wheels**				**29″ Wheels**			
	Uphill 1	*Downhill* 1	*Uphill* 2	*Downhill* 2	*Uphill* 1	*Downhill* 1	*Uphill* 2	*Downhill* 2
Frequency band **(< 5 Hz)**								
Handlebar	2.5886 ± 0.5836	4.2049 ± 0.3865	2.5649 ± 0.4408	4.3362 ± 0.4772	2.7128 ± 0.8429	4.1202 ± 0.6685	3.0253 ± 0.6821	4.0563 ± 0.4443
Left arm	2.2872 ± 0.2906	3.8030 ± 1.1836	2.7508 ± 0.4038	3.5787 ± 1.3051	2.3720 ± 0.6737	4.4542 ± 0.4506	3.0361 ± 0.5719	4.0525 ± 0.5563
Left leg	1.2100 ± 0.1643	1.5214 ± 0.1981	1.3790 ± 0.1190	1.8739 ± 0.4691	1.2467 ± 0.1784	1.4736 ± 0.2567	1.3872 ± 0.1609	1.7862 ± 0.2609
Seatpost	2.5839 ± 0.5664	4.1348 ± 0.3727	2.6636 ± 0.4313	3.9023 ± 0.9578	2.7275 ± 0.8689	4.1398 ± 0.7566	2.6695 ± 0.4213	4.0876 ± 0.5080
Lower back	2.1906 ± 0.3439	2.5000 ± 0.6107	2.4408 ± 0.7278	2.5287 ± 1.0570	2.4063 ± 0.4803	3.0003 ± 0.8713	2.6686 ± 0.6146	2.6604 ± 0.9820
Head	2.2085 ± 0.1610	2.3810 ± 0.5833	2.3559 ± 0.2798	2.6429 ± 0.8873	2.3446 ± 0.7609	2.4625 ± 0.4605	2.3227 ± 0.2796	2.7956 ± 0.9635
Frequency band **(> 5 Hz)**								
Handlebar	11.5479 ± 3.6624	8.0184 ± 0.4146	8.3838 ± 3.1137	7.7079 ± 0.8894	12.9508 ± 4.6860	9.4889 ± 3.4710	8.9032 ± 2.3627	7.4205 ± 1.0044
Left arm	15.0403 ± 2.0706	12.0810 ± 2.4787	13.9667 ± 2.7886	13.830 ± 2.7830	15.5842 ± 2.6019	14.3738 ± 3.3495	13.5840 ± 1.3101	13.1108 ± 2.8850
Left leg	7.4420 ± 4.1788	13.4708 ± 2.4782	6.4915 ± 3.0441	11.4479 ± 4.2789	7.2764 ± 2.8482	13.1381 ± 4.8928	5.2644 ± 0.2734	13.0820 ± 3.0109
Seatpost	14.0130 ± 1.405	10.0799 ± 2.5423	12.6914 ± 2.4115	10.2124 ± 2.8376	14.4374 ± 3.7298	11.2226 ± 3.6646	11.9687 ± 2.6532	13.5728 ± 3.1709
Lower back	5.6440 ± 0.7655	6.0253 ± 0.5550	5.1746 ± 0.1138	6.4741 ± 1.1317	5.6311 ± 0.7367	6.5419 ± 1.1428	5.6208 ± 0.3654	6.1394 ± 0.9143
Head	5.7459 ± 0.8424	6.8482 ± 1.3518	5.6552 ± 0.5066	6.5939 ± 1.7374	5.4094 ± 0.4349	6.4482 ± 1.7284	5.8718 ± 0.6557	6.0834 ± 1.3503

(Titlestad et al., 2006) but agreeing with a more recent study showing that the hard tail designed bikes are more efficient whilst climbing and consequentially faster over a race lap (Herrick et al., 2011), albeit using a somewhat outdated suspension system. In an attempt to gain performance advantages there has been a rise in popularity in the use of 29″ wheels (compared to traditional 26″ wheels), hard tail designed bikes, with an unsubstantiated reported capability of reducing the impact of terrain induced vibrations.

Our hypothesis that 29″ wheels would dampen vibrations and thus decrease the non-propulsive work was unfounded as 29″ wheels, on this course at least, were faster than 26″ wheels. The non-significant difference in mean power output and the highly

Table 3
Mean ± SD for magnitude (g^2) at maximum frequency of accelerations at points of contact between bike–body during a XCO-MTB lap, and separated for terrain, frequency banding and wheel size.

Accelerometer location	**26″ Wheels**				**29″ Wheels**			
	Uphill 1	*Downhill* 1	*Uphill* 2	*Downhill* 2	*Uphill* 1	*Downhill* 1	*Uphill* 2	*Downhill* 2
Frequency band (<5 Hz)								
Handlebar	0.4131 ± 0.1398	1.1653 ± 0.1623	0.3231 ± 0.1133	1.4079 ± 0.3269	0.4443 ± 0.1273	1.2272 ± 0.2127	0.3985 ± 0.1657	1.5901 ± 0.5990
Left arm	0.5903 ± 0.1581	1.3938 ± 0.1914	0.4447 ± 0.1795	1.8298 ± 0.5919	0.5850 ± 0.1603	1.5127 ± 0.4041	0.5276 ± 0.2481	1.9365 ± 0.8383
Left leg	0.8230 ± 0.3917	0.8055 ± 0.1828	0.4725 ± 0.0769	0.9601 ± 0.2391	0.9077 ± 0.3667	0.8686 ± 0.2077	0.4834 ± 0.0874	0.9904 ± 0.2474
Seatpost	0.6591 ± 0.2110	1.5352 ± 0.0891	0.4562 ± 0.1216	1.8255 ± 0.5691	0.6791 ± 0.2216	1.6120 ± 0.4049	0.5225 ± 0.2068	2.1895 ± 0.8327
Lower back	0.5962 ± 0.2382	0.3810 ± 0.1339	0.2422 ± 0.0498	0.3722 ± 0.0907	0.5457 ± 0.1806	0.3550 ± 0.0946	0.2326 ± 0.0564	0.3517 ± 0.1117
Head	0.3131 ± 0.2179	0.2679 ± 0.0475	0.2098 ± 0.0766	0.2790 ± 0.0633	0.3084 ± 0.1557	0.3067 ± 0.0770	0.2039 ± 0.0803	0.2805 ± 0.0607
Frequency band (>5 Hz)								
Handlebar	0.0741 ± 0.0131	0.3086 ± 0.0437	0.0675 ± ± 0.0129	0.3061 ± 0.0304	0.0852 ± 0.0201	0.3238 ± 0.0341	0.0731 ± 0.0146	0.3087 ± 0.0357
Left arm	0.0813 ± 0.0312	0.3669 ± 0.0664	0.0708 ± 0.0218	0.3846 ± 0.0885	0.0785 ± 0.0292	0.3788 ± 0.1062	0.0748 ± 0.0209	0.3553 ± 0.0724
Left leg	0.1287 ± 0.0270	0.2703 ± 0.0480	0.1178 ± 0.0217	0.2704 ± 0.0655	0.1402 ± 0.0136	0.2886 ± 0.0429	0.1289 ± 0.0207	0.2621 ± 0.0432
Seatpost	0.0959 ± 0.0152	0.4142 ± 0.0664	0.0843 ± 0.0192	0.3860 ± 0.0415	0.1053 ± 0.0142	0.4108 ± 0.0720	0.0878 ± 0.0353	0.4084 ± 0.0724
Lower back	0.0910 ± 0.0282	0.1361 ± 0.0243	0.0717 ± 0.0120	0.1206 ± 0.0134	0.1074 ± 0.0632	0.1494 ± 0.0207	0.0708 ± 0.0110	0.1285 ± 0.0162
Head	0.1031 ± 0.0336	0.1109 ± 0.0231	0.0879 ± 0.0408	0.1081 ± 0.0251	0.1250 ± 0.0674	0.1296 ± 0.0253	0.0848 ± ± 0.0329	0.1101 ± 0.0284

Table 4
Mean ± SD for half frequency of accelerations at points of contact between bike–body during a XCO-MTB lap, and separated for terrain, frequency banding and wheel size.

Accelerometer location	**26″ Wheels**				**29″ Wheels**			
	Uphill 1	*Downhill* 1	*Uphill* 2	*Downhill* 2	*Uphill* 1	*Downhill* 1	*Uphill* 2	*Downhill* 2
Handlebar	15.8624 ± 1.0477	14.5918 ± 1.0240	14.1362 ± 0.9059	14.6793 ± 1.1576	16.5617 ± 1.4037	15.3782 ± 1.5753	14.9690 ± 1.0991	15.6064 ± 1.5506
Left arm	17.3421 ± 0.7197	15.3079 ± 1.2644	15.4967 ± 0.9427	15.3220 ± 1.2542	17.9721 ± 1.2566	15.7504 ± 1.2666	15.7387 ± 0.4797	15.6458 ± 1.1853
Left leg	10.0112 ± 2.4305	15.6915 ± 2.8369	9.7534 ± 2.6260	16.2162 ± 2.7882	10.9057 ± 2.5868	14.9042 ± 4.5278	11.1205 ± 2.7368	15.2911 ± 5.0433
Seatpost	16.8318 ± 1.4104	15.9063 ± 0.6317	15.4923 ± 1.1290	15.9806 ± 0.6732	17.3226 ± 0.8898	16.3659 ± 0.6833	15.9265 ± 0.8271	16.3350 ± 0.6041
Lower back	4.6051 ± 1.0238	8.0323 ± 1.3014	5.6807 ± 1.1265	8.5386 ± 1.0915	5.5449 ± 1.5778	8.2586 ± 0.8061	5.8891 ± 1.0114	8.5927 ± 1.4153
Head	3.7280 ± 1.1997	7.5154 ± 1.4194	4.0316 ± 1.1196	8.3477 ± 1.2322	3.8560 ± 1.3861	7.5236 ± 1.0461	4.2690 ± 1.2837	8.5165 ± 1.6393

significant difference in overall time make this a very important finding, equating to 167–186 s over a typical race distance. Table 1 shows there was no significant difference between wheel size and performance over terrain sections, reflecting variance in the small number of subjects used, as mean times were between 2.3% and 3.5% quicker on all sections. The source of the increase in velocity per unit power output is likely owing in part to a combination of decreased rolling resistance and aerodynamic drag. A reduction in rolling resistance would be attributable to less deformation and therefore reduced energy loss of the 29″ tyres as a result of their greater volume. Secondly, smaller fluctuations in speed would lead to less aerodynamic drag, but if this were true the low frequency component of the acceleration should favour the 29″ wheels (Table 3); which it does not.

The angle between the wheel axle and the point of impact is greater in a larger wheel and has been implicated in greater momentum and reduced vibrations (Wilson, 2004) yet our data clearly show that vibrations were greater in both the vertical and horizontal directions with the 29″ wheels. This increased vibration may simply be a result of the higher velocities with the 29″ wheels making comparison of wheel size and their ability to attenuate vibration transference between bike and body difficult. It is also important to acknowledge the fact that this study compared 29″ with 26″ wheels sitting in the same (29″ frame), so might not represent a true comparison of actual 26″ and 29″ bikes where frame/fork geometry differences may affect performance. However, by using the same frame we isolated the wheel diameter effect by controlling for geometric measures associated with bike handling (head tube angle and mechanical trail (Wilson, 2004)). A further study could aim to make comparisons between complete 26″ and 29″ bikes.

Practical applications of this research can be found in the supplementary material.

Conflict of interests statement

The authors have no financial or personal relationships with other people or organisations that could have inappropriately influenced this work.

Appendix A. Supplementary materials

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jbiomech.2014.03.024.

References

Aguilar, S., Becker, P., Gonzalez, D., Kaminski, B., Knopp, N., Jankhot, C., Marcellis, B., Poli, D., Ruidera, R., Tsosie, H., 2008. Power Measurement for Road Bicycles: Towards a Universal Solution (Semester Unknown). IPRO p. 324

Bertucci, W.M., Rogier, S., Reiser, R.F., 2013. Evaluation of aerodynamic and rolling resistances in mountain-bike field conditions. J. Sports Sci., 1–8

Carr, C.E., Meyen, F., Domingues, A.R., Newman, D.J., Jacobs, S.E., Ryan, L. Kobrick, 2012. Proceedings of the 63rd International Astronautical Congress. International Astronautical Federation. Naples, Italy.

Coza, A., Nigg, B.M., Fliri, L., 2010. Quantification of soft-tissue vibrations in running: accelerometry versus high-speed motion capture. J. Appl. Biomech. 26, 367–373.

De Lorenzo, D.S., Hull, M., 1997. Quantification of Structural Loading During off-Road Cycling. University of California, Davis

Faiss, R., Praz, M., Meichtry, A., Gobelet, C., Deriaz, O., 2007. The effect of mountain bike suspensions on vibrations and off-road uphill performance. J. Sports Med. Phys. Fit. 47, 151–158.

Grether, W.F., 1971. Vibration and human performance1. Hum. Factors: J. Hum. Factors Ergon. Soc. 13, 203–216.

Hamill, J., Derrick, T., Holt, K., 1995. Shock attenuation and stride frequency during running. Hum. Mov. Sci. 14, 45–60.

Herrick, J.E., Flohr, J.A., Wenos, D.L., Saunders, M.J., 2011. Comparison of physiological responses and performance between mountain bicycles with differing suspension systems. Int. J. Sports Physiol. Perform. 6, 546–558.

Hines, W., O'Hara-Hines, R., Brooke, J., 1987. A multivariate solution for cyclic data, applied in modelling locomotor forces. Biol. Cybern. 56, 1–9.

Hurst, H.T., Atkins, S., 2006. Power output of field-based downhill mountain biking. J. Sports Sci. 24, 1047–1053.

Hurst, H.T., Swarén, M., Hébert-Losier, K., Ericsson, F., Sinclair, J., Atkins, S., Holmberg, H.-C., 2012. Influence of course type on upper body muscle activity in elite cross-country and downhill mountain bikers during off road downhill cycling. J. Sci. Cycl. 1, 2–9.

Impellizzeri, F., Sassi, A., Rodriguez-Alonso, M., Mognoni, P., Marcora, S., 2002. Exercise intensity during off-road cycling competitions. Med. Sci. Sports Exerc 34, 1808–1813.

ISO—International Organization for Standardization. 1997. Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration – Part 1: General Requirements. Geneva.

Issurin, V.B., 2005. Vibrations and their applications in sport. A review. J. Sports Med. Phys. Fit. 45, 324–336.

Jäncke, L., Steinmetz, H., Benilow, S., Ziemann, U., 2004. Slowing fastest finger movements of the dominant hand with low-frequency rTMS of the hand area of the primary motor cortex. Exp. Brain Res. 155, 196–203.

Kay, B.A., Saltzman, E.L., Kelso, J., 1991. Steady-state and perturbed rhythmical movements: a dynamical analysis. J. Exp. Psychol.: Hum. Percept Perform 17, 183.

Levy, M., Smith, G., 2005. Effectiveness of vibration damping with bicycle suspension systems. Sports Eng. 8, 99–106.

Macdermid, P.W., Morton, R.H., 2011. A longitudinal analysis of start position and the outcome of World Cup cross-country mountain bike racing. J. Sports Sci. 30, 175–182.

Macdermid, P.W., Stannard, S., 2012. Mechanical work and physiological responses to simulated cross country mountain bike racing. J. Sports Sci. 30, 1491–1501.

MacRae, H.-H., Hise, K.J., Allen, P.J., 2000. Effects of front and dual suspension mountain bike systems on uphill cycling performance. Med. Sci. Sports Exerc. 32, 1276–1280.

Mercer, J., Bates, B., Dufek, J., Hreljac, A., 2003. Characteristics of shock attenuation during fatigued running. J. Sports Sci. 21, 911–919.

Mester, J., Spitzenfeil, P., Schwarzer, J., Seifriz, F., 1999. Biological reaction to vibration – implications for sport. J. Sci. Med. Sport 2, 211–226.

Newell, G.S., Mansfield, N.J., 2008. Evaluation of reaction time performance and subjective workload during whole-body vibration exposure while seated in upright and twisted postures with and without armrests. Int. J. Ind. Ergon. 38, 499–508.

Nigg, B.M., Liu, W., 1999. The effect of muscle stiffness and damping on simulated impact force peaks during running. J. Biomech. 32, 849–856.

Nishii, T., Umemura, Y., Kitagawa, K., 2004. Full suspension mountain bike improves off-road cycling performance. J. Sports Med. Phys. Fit. 44, 356–360.

Pozzo, T., Levik, Y., Berthoz, A., 1995. Head and trunk movements in the frontal plane during complex dynamic equilibrium tasks in humans. Exp. Brain Res. 106, 327–338.

Samuelson, B., Jorfeldt, L., Ahlborg, B., 1989. Influence of vibration on endurance of maximal isometric contraction. Clin. Physiol. 9, 21–26.

Stapelfeldt, B., Schwirtz, A., Schumacher, Y.O., Hillebrecht, M., 2004. Workload demands in mountain bike racing. Int. J. Sports Med. 25, 294–300.

Stewart, A.D., Hannan, J., 2000. Total and regional bone density in male runners, cyclists, and controls. Med. Sci. Sports Exerc. 32, 1373–1377.

Titlestad, J., Fairlie-Clarke, A., Davie, M., Whittaker, A., Grant, S., 2003. Experimental evaluation of mountain bike suspension systems. Acta Polytech., 43

Titlestad, J., Fairlie-Clarke, T., Whittaker, A., Davie, M., Watt, I., Grant, S., 2006. Effect of suspension systems on the physiological and psychological responses to submaximal biking on simulated smoothand bumpy tracks. J. Sports Sci. 24, 125–135.

Wakeling, J.M., Liphardt, A.-M., Nigg, B.M., 2003. Muscle activity reduces soft-tissue resonance at heel-strike during walking. J. Biomech. 36, 1761–1769.

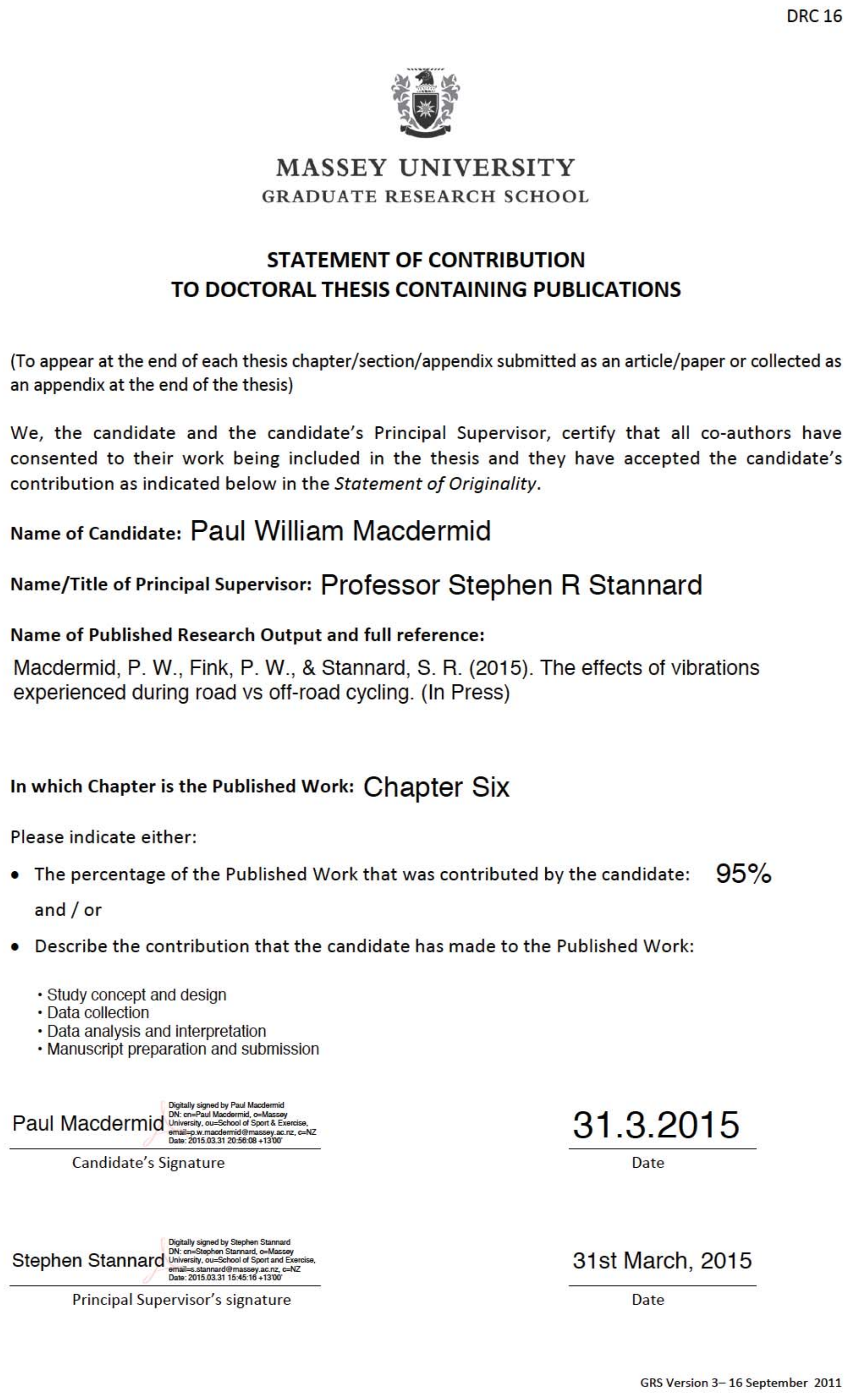
Wakeling, J.M., Nigg, B.M., Rozitis, A.I., 2002. Muscle activity damps the soft tissue resonance that occurs in response to pulsed and continuous vibrations. J. Appl. Physiol. 93, 1093–1103.

Warner, S.E., Shaw, J.M., Dalsky, G.P., 2002. Bone mineral density of competitive male mountain and road cyclists. Bone 30, 281–286.

Wilczynski, H., Hull, M., 1994. A dynamic system model for estimating surface-induced frame loads during off-road cycling. Trans.—-Am. Soc. Mech. Eng. J. Mech. Des. 116, 816 (816).

Wilson, D.G., 2004. Bicycling Science. Mit Press

Appendix 4



DRC 16

MASSEY UNIVERSITY
GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION TO DOCTORAL THESIS CONTAINING PUBLICATIONS

(To appear at the end of each thesis chapter/section/appendix submitted as an article/paper or collected as an appendix at the end of the thesis)

We, the candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of Candidate: Paul William Macdermid

Name/Title of Principal Supervisor: Professor Stephen R Stannard

Name of Published Research Output and full reference:

Macdermid, P. W., Fink, P. W., & Stannard, S. R. (2015). The effects of vibrations experienced during road vs off-road cycling. (In Press)

In which Chapter is the Published Work: Chapter Six

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate: 95%

  and / or

- Describe the contribution that the candidate has made to the Published Work:

  - Study concept and design
  - Data collection
  - Data analysis and interpretation
  - Manuscript preparation and submission

Paul Macdermid
Digitally signed by Paul Macdermid
DN: cn=Paul Macdermid, o=Massey University, ou=School of Sport & Exercise, email=p.w.macdermid@massey.ac.nz, c=NZ
Date: 2015.03.31 20:56:08 +13'00'

Candidate's Signature

31.3.2015

Date

Stephen Stannard
Digitally signed by Stephen Stannard
DN: cn=Stephen Stannard, o=Massey University, ou=School of Sport and Exercise, email=s.stannard@massey.ac.nz, c=NZ
Date: 2015.03.31 15:45:16 +13'00'

Principal Supervisor's signature

31st March, 2015

Date

GRS Version 3– 16 September 2011

IJSM/4444/7.1.2015/MPS

Physiology & Biochemistry 1

The Effects of Vibrations Experienced during Road vs. Off-road Cycling

Authors P. W. Macdermid, P. W. Fink, S. R. Stannard

Affiliations School of Sport & Exercise, Massey University, Palmerston North, New Zealand

Key words
- mountain biking
- accelerometers
- rolling resistance
- cycling economy
- performance

Abstract

The purpose of this investigation was to compare the effects of vibrations experienced during off-road and road cycling. It was hypothesised that additional damping will be expressed through a greater work demand and increased physiological markers when travelling at the same speed over an identical terrain profile. Participants ascended a tar-sealed road climb and a single-track off-road climb at a predetermined speed. Time, speed, power, cadence, heart rate and $\dot{V}O_2$ were sampled and logged every second while tri-axial accelerometers recorded accelerations (128 Hz) to quantify vibrations experienced. Statistical analysis indicated accelerations to be greater during the off-road condition ($p<0.0001$) with post-hoc analysis exposing differences ($p<0.001$) for handlebar, arm, leg and seat post but not the lower back or head. The increased accelerations during off-road riding are associated with the increased vibrations and rolling resistance experienced. This led to increases in the work done (road: 280±69 vs. off-road: 312±74 W, $p=0.0003$) and, consequentially, a significant increase in the physiological markers $\dot{V}O_2$ (road: 48.5±7.5 off-road 51.4±7.3 $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$, $p=0.0033$) and heart rate (road: 161±10 off-road 170±10 bpm, $p=0.0001$) during the off-road condition. Such physiological differences and their causes are important to understand in order to provide suitable training recommendations or technological interventions for improving competitive performance or recreational enjoyment.

Introduction

It is important to understand the factors affecting performance in any sport if enhancements of technical, mechanical, and training methods are to be achieved. Recent investigations [6,19] suggest that the work demand and therefore physiological stresses for Olympic format cross-country mountain biking (XCO-MTB) differ from that of road racing. Power and cadence data reported for XCO-MTB races [25] and simulated race pace efforts [19] highlight large, possibly terrain-induced, variability with considerable emphasis on low-velocity high force, and pedal mechanics [19]. The accompanying metabolic response suggests reduced economy while riding XCO-MTB, explanations for which have centred on non-propulsive dissipation by skeletal muscle of terrain-induced vibrations to improve comfort and performance [12,15,24,28], but ultimately to protect the central nervous system and brain [24,27].

The mechanical oscillation of a wheel and bicycle in this case are difficult to predict but occur at the bicycle point of contact with the ground and thus provides periodical mechanical oscillation applied to the athlete's body [23]. As such, a likely explanation to any reduced economy is the combined effect of rolling resistance (tyre-terrain level) and the consequential vibration damping effect.

The gradient of vibration dissipation from the body-bike interface (hands and feet) through the appendages to the lower back and head have been used to explain vibration mechanics in XCO-MTB [18]. This is supported by observations of increased muscular work of the upper body [9]. Studies not specific to cycling [3,21,28] identify the negative effect of vibration on muscle force production through reduced temporal recruitment [12]. Such superimposed muscle vibrations are typically associated with force reductions of ~8% [3] but vary according to protocol used. For that reason, reductions in vibrations during cycling should not only improve

accepted after revision
November 06, 2014

Bibliography
DOI http://dx.doi.org/10.1055/s-0034-1398534
Int J Sports Med 2015; 36: 1–6 © Georg Thieme Verlag KG Stuttgart · New York
ISSN 0172-4622

Correspondence
Paul William Macdermid,
School of Sport & Exercise,
Massey University, Private Bag
11-222, Palmerston North, 4474,
New Zealand
Tel.: +64/6/356 9099
P.W.Macdermid@massey.ac.nz

performance during XCO-MTB, but also reduce the work demand and associated physiological stresses. Although the latter statement is unsubstantiated, the effects of suspension systems used on mountain bikes have been shown to lead to either reduced vibrations [5] and/or physiological variables associated with increased rider efficiency [10, 20, 22, 26].

On the other hand, acute effects of the addition of vibrations to a non-vibration load include increased local and general blood circulation, enhanced oxygen delivery to the working muscle, increased muscle temperature, and enhanced muscle activation [12]. While contrary to the conclusions from XCO-MTB-specific studies [18, 19] the benefits or detriments of vibration are unconfirmed either way since no comparison between XCO-MTB and road has been performed over comparable terrain such as a climb, which is particularly important for XCO-MTB athletes [1].

The aim of this study was therefore to investigate the work demand and physiological consequences of riding at the same speed on a tar-sealed road climb compared to a comparable (distance and gradient) off-road single-track mountain bike climb. We hypothesised that off-road single-track riding produces significantly more vibrations, requiring greater muscle damping, which equates to greater work demand, and increased metabolic requirement and associated physiological stress.

Methods

▼

Participants

7 nationally competitive XCO-MTB athletes (mean ± *s*: age 27.2 ± 10.7 years, height 178.0 ± 7.5 cm, mass 61.5 ± 6.0 kg) participated in this study, which consisted of one laboratory trial and one field test trial comprising 2 conditions. All participants provided written consent in accordance with the University Human Ethics Committee and the IJSM's ethical standards document [7].

Laboratory test

Upon visiting the laboratory participants were weighed in minimal clothing and then performed a ramp style test on an electronically-braked cycle ergometer (Lode Excalibur Sport, NL). The test workload commenced at 100 W and increased by 25 W per minute until the participant could no longer maintain the required power output [19]. Throughout this test heart rate (Polar Electro, Kempele, Finand) and expired respiratory gases were collected for analysis using a breath-by-breath system (K42b, Cosmed, Italy). Expired air data averaged every 15 s enabled calculation of $\dot{V}O_2$ peak, respiratory compensation point (RCP), and ventilatory threshold (VT) [16].

Field test trial

Participants attended a 3 h testing session in which they were fitted to the same mountain bike (GT Zaskar elite 29" Full Suspension, Optimized Force Constructed Carbon, USA) with the same settings (fork and tyre pressure), the portable gas analyser, heart rate monitor and accelerometers (Emerald, APDM, OR, USA), whereupon they commenced a 20 min warm-up period, which included a minimum of one ascent each on the road climb and single-track climb to be used as conditions for this study. Both had comparable characteristics (except track surface): a distance of 740 m with a vertical ascent of 31 m, providing an average gradient of 4.2 %.

Following a 5 min recovery, participants were instructed to complete a maximal effort on the single-track climb. As previous work [18] has indicated that speed affects magnitude of accelerations, this study controlled speed. Immediate data recall from the Garmin bicycle computer (Garmin Edge 500 including GSC + 10 speed sensor, USA) following the maximal effort climb on the single-track, enabled determination of speed ($km \cdot h^{-1}$), set to 80 % of average speed from the maximal trial for use during the 2 conditions.

Each condition commenced with a 4 min constant load effort (equating to 80 % W_{max} taken from the initial laboratory test) on rollers positioned at the start of the climb. The purpose of this period was to allow physiological variables to stabilize. However, there was a small delay (< 6 s) upon completion of this effort in moving the mountain bike from the rollers and onto the starting line of the designated climb. Upon reaching the starting line, participants commenced the climb at the set speed previously determined, controlled by viewing speed on the Garmin Edge. A counterbalanced order (separated by 15 min epochs for recovery) was used to prevent any order effect on the dependent variables of interest.

Outcome measures

Speed ($km \cdot h^{-1}$), power output (W) and cadence (rpm) were continuously sampled and logged every second (SRAM QUARK S2275 MTB Power Meter, USA) throughout the trial. The Quark CinQo powermeter has been previously used for such studies [18] and has a reported accuracy ± 1.5 % [2]. Data recorded from the power meter and GPS device were transmitted to a conventional personal computer and processed with the Garmin Training Centre software (version 3.6.5).

Participants completed each condition wearing the automated, portable gas analyser (Cosmed K42b), enabling continuous breath-by-breath sampling. Data for $\dot{V}O_2$ ($ml \cdot min^{-1} \cdot kg^{-1}$) and heart rate were logged every second, allowing comparisons between conditions for work done and physiological strain when compared to performance time (s) and power output (W).

Wireless, tri-axial accelerometer, magnetometers and gyroscope with a reported accuracy 0.0012 $m \cdot s^2 \cdot \sqrt{Hz}^{-1}$ (Emerald, APDM, OR, USA) were used in a synchronised data-logging mode to measure accelerations in accordance with the International Standards (ISO 2631-1) for measuring vibrations [11] and reported elsewhere in similar studies [18]. The accelerometers were placed on the lower left arm (frontal distal position); left lower leg (frontal, distal position); seat post (within 10 cm of saddle-rider contact area); lumbar region of lower back; and medial forehead [18]. The Emerald accelerometers were synchronised with the Garmin Edge 500 and the Cosmed K42b, were sampled at 128 Hz, and all data were logged to a standard personal computer, converted to a hierarchal data format file (.h5) and processed using MATLAB R2014a. All data were analysed for total (XYZ), vertical (Z-axis), and horizontal (X- and Y-axis) accelerations. Root mean squares of the accelerations were calculated to quantify the amount of vibration the participants experienced [11, 18]. Spectral analysis was performed using a Fast Fourier transform to determine whether the acceleration characteristics were induced voluntarily or involuntarily. Measures included: (1) half frequency, used to determine the frequency at which half the total power was below the frequency; (2) maximum frequency and maximum magnitude at < 5 Hz, enabling more detailed quantification of voluntary movements or vibrations, and > 5 Hz for vibrations and physiological tremor [8, 13, 14, 18].

Statistical analyses

Descriptive data (mean ± SD and (95 % CI), where relevant) were calculated for variables measured during the laboratory ramp test and all dependent variables over the field trial. Data analysis of speed, power, time, heart rate and $\dot{V}O_2$ between conditions (Road and Off-Road) were compared using paired Student's *t*-tests to assess overall control and performance of the study.

Accelerometer data comparisons (Acceleration RMS) for total, vertical and horizontal axis plus additional spectral analysis data were made via univariate analysis of variance (two-way ANOVA), including within-subject variables, surface and accelerometer location, tested for main effects and interactions (Surface * Location).

Where significant difference was found the main effect was analysed using Bonferroni post-hoc testing for pairwise comparisons. All statistical analyses were performed using IBM SPSS Statistics 20. Significance was set at $P < 0.05$.

Results

▼

Laboratory fitness assessment provided mean ± SD (95 % CI) descriptive data for participants W_{max} 408 (363–452) W or 6.6 (6.5–6.8) $W \cdot kg^{-1}$; $\dot{V}O_2$ peak 66.7 (64.7–68.9) $ml \cdot kg^{-1} \cdot min^{-1}$; HR_{max} 187 (175–199) bpm; VT 258 (231–284) W or 4.2 (4.0–4.4) $W \cdot kg^{-1}$; RCP 321 (290–352) W or 5.2 (5.1–5.4) $W \cdot kg^{-1}$.

The main aim of the study was to complete 2 climbs of identical distance and gradient but with different track surfaces (tar-sealed road and off-road single-track) at the same speed. Paired Student's t-test analysis showed no significant difference between road and off-road condition for time (160.9 ± 13.12 and 162.3 ± 11.61 s; $t_{(6)} = 1.474$, $p = 0.1908$) speed (16.7 ± 1.4 and 16.5 ± 1.2 $km \cdot h^{-1}$; $t_{(6)} = 1.520$, $p = 0.1793$) or cadence (78 ± 5 and 78 ± 6 rpm; $t_{(6)} = 0.4300$, $p = 0.6822$), respectively.

Measurement of total accelerations experienced by participants (◉ **Fig. 1a**) revealed significant interactions between terrain surface * accelerometer position ($F_{(5,72)} = 15.24$, $p < 0.0001$) along with a main effect for both surface ($F_{(1,72)} = 150.35$, $p < 0.0001$) and accelerometer location ($F_{(5,72)} = 120.42$, $p < 0.0001$). Post-hoc analyses revealed significant differences between conditions (road vs. off-road) for handlebar ($t_{(6)} = 7.228$, $p < 0.001$), left arm ($t_{(6)} = 11.800$, $p < 0.001$), left leg ($t_{(6)} = 3.731$, $p < 0.010$) and seat post ($t_{(6)} = 3.965$, $p < 0.010$), but not the lower back ($t_{(6)} = 1.637$, $p > 0.05$) or head ($t_{(6)} = 1.678$, $p < 0.05$). When separated to individual axis, acceleration in the vertical and horizontal plane (◉ **Fig. 1b, c**) shows significant interaction between terrain surface * accelerometer position $F_{(5,72)} = 2.78$, $p = 0.0235$; $F_{(5,72)} = 2.62$, $p = 0.0314$, respectively. There were also main effects for surface ($F_{(1,72)} = 27.31$, $p < 0.0001$ and $F_{(1,72)} = 23.98$, $p < 0.0001$) and accelerometer position ($F_{(1,72)} = 10.81$, $p < 0.0001$ and $F_{(1,72)} = 41.91$, $p < 0.0001$), respectively. Post-hoc analysis identified differences for handlebar and left arm ($p < 0.05$) but not left leg, seat post, lower back or head in both vertical and horizontal plane (◉ **Fig. 1b, c**).

Two-way ANOVA of spectral analysis data provided a significant interaction between terrain surface and accelerometer position ($F_{(5,60)} = 2.40$, $p = 0.0476$) for half frequency with post-hoc analysis identifying significantly ($p < 0.0001$) greater values for the seat post during the road condition and the leg during the off-road condition (◉ **Fig. 2**). There were no interactions (terrain surface * position) for maximum frequency or maximum magnitude when analysed for bands < 5 Hz and > 5 Hz. All spectral analysis showed significant ($p < 0.0001$) main effects for acceleration positions (◉ **Table 1**).

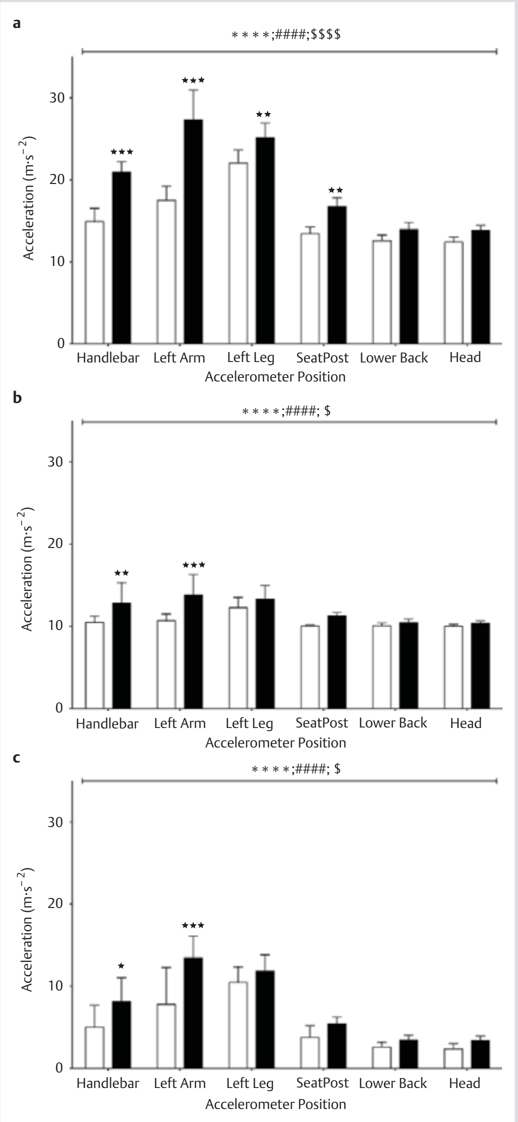


Fig. 1 Mean ± SD amplitude (RMS) for **a** Total; **b** Vertical; and **c** Horizontal components of acceleration over the climb. □ denotes the tar-sealed road condition, while ■ denotes single-track off-road condition. * * * * (*P*<0.0001) main effect of terrain surface; #### (*P*<0.0001) main effect of acceleration location; \$\$\$\$ (*P*<0.0001), \$ (*P*<0.05) terrain surface * accelerometer location interaction; Post-hoc analysis differences ★★★ (P<0.001), ★★ (P<0.01) and ★ (P<0.05) when tar-sealed Rd is compared to single-track off-Rd (MTB).

Paired student's *t*-test of power output (◉ **Fig. 3a**) confirms the significantly ($t_{(6)} = 7.419$, $p = 0.0003$) increased demand of bicycling off-road (312 ± 74 (244–380)) compared to the tar-sealed road (280 ± 69 (215–344)). Accordingly, physiological measures (◉ **Fig. 3b, c**) including $\dot{V}O_2$ (48.5 ± 7.5 (41.6–55.4); 51.4 ± 7.3

(44.6–58.2) ml·kg^{-1}·min^{-1}); $t_{(6)}=4.717$, $p=0.0033$) and heart rate (161 ± 10 (151–171); 170 ± 10 (161–180); $t_{(6)}=9.037$, $p=0.0001$) were lower for the road compared to off-road condition, respectively.

Discussion

▼

The aim of this study was to assess the work demand (propulsive and non-propulsive) and the physiological consequences during a climb of identical distance and gradient on 2 different surfaces (road and off-road) while riding at the same speed on the same bicycle. The main findings were: (a) A single-track MTB climb (off-road) exposed the riders to significantly greater accelerations at the point of contact with the bicycle when compared to a comparable tar-sealed road; (b) while there was no difference between accelerations experienced at the head and lower back for either conditions; and (c) the metabolic demands and cardiovascular stress (HR) were greater during the off-road compared to the road. Participants successfully completed the 2 conditions at identical speeds and cadence suggesting that differences in accelerations and subsequent physiological variables could be largely attributed to either condition rather than any difference in speed [18] of bicycle or cadence of participants [4].

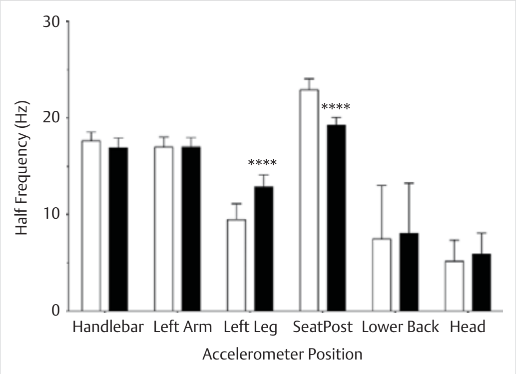


Fig. 2 Mean ± SD for half frequency data from spectral analysis for each condition (tar-sealed road ☐ and the single-track off-road ■) and acceler-ometer position. **** (P<0.0001) significantly different to Rd.

It has previously [28] been identified that the measurement of total acceleration (X+Y+Z) is most useful in quantifying vibration exposure in humans. This is because in studies such as this, soft tissue oscillation tends to occur in all orthogonal directions. Our data (**Fig. 1a**) indicate significantly greater total, vertical and horizontal accelerations experienced during the single-track off-road climb. This is important as hysteric losses in tyre-ground interaction could potentially be the cause of the extra energetic demand associated with XCO-MTB [9,18,19]. As such, the difference between the tar-sealed road and off-road conditions suggest that hysteric losses as caused by the terrain surface play an important part in additional propulsive and non-propulsive work demands [17]. However, the greater rigidity (firmness) and evenness of the tar-seal combined with tyre tread protrusions could cause an increase in high-frequency involuntary vibrations experienced during road cycling on the a mountain bike compared to off-road cycling where there is greater plasticity in the relationship. This is supported through spectral analysis half-frequency data (**Fig. 2**), which suggests a greater proportion of accelerations occur at higher frequencies for the road condition compared to off-road. Accelerometer specific differences occurred at the leg and seat post level but not at the handlebar. This suggests that the front suspension system helps to dampen some of the high-frequency vibration. However, no further differences when comparisons for maximum frequency or magnitude (<5 Hz or >5 Hz) were uncovered, making any association between tread pattern – surface interaction difficult. **Table 1** shows the variability between accelerometer locations and differences between surfaces, which is the probable cause for non-significance and possibly due to dissimilarities in participant technique. Interestingly, but not soft tissue-related, there seems to be some trend for greater maximum fre-

Table 1 Mean ± SD for maximum frequency (Hz) and magnitude (g^2) of accelerations during the hill climb, separated for frequency banding and condition.

Accelerometer Location	Road Maximum frequency	Road Maximum magnitude	Off-Road Singletrack Maximum frequency	Off-Road Singletrack Maximum magnitude	Two-way ANOVA
			Frequency band (<5 Hz)		
handlebar	3.009 ± 0.427	0.090 ± 0.079	2.701 ± 0.413	0.163 ± 0.096	Cond * A.Loc: NS Cond: NS A.Loc: P<0.0001
left arm	2.767 ± 0.328	0.130 ± 0.070	2.858 ± 0.274	0.203 ± 0.124	
left leg	1.361 ± 0.090$_{(Hb; La)}$	1.434 ± 0.352$_{(Hb; La)}$	1.346 ± 0.074$_{(Hb; La)}$	1.430 ± 0.250$_{(Hb; La)}$	
seat post	2.801 ± 0.143$_{(LL)}$	0.078 ± 0.023$_{(LL)}$	3.074 ± 0.518$_{(LL)}$	0.120 ± 0.025$_{(LL)}$	
lower Back	2.728 ± 0.555$_{(LL)}$	0.355 ± 0.259$_{(LL)}$	2.626 ± 0.369$_{(LL)}$	0.395 ± 0.183$_{(LL)}$	
head	2.872 ± 0.510$_{(LL)}$	0.235 ± 0.176$_{(LL)}$	3.078 ± 0.481$_{(LL)}$	0.362 ± 0.127$_{(LL)}$	
			Frequency band (>5 Hz)		
handlebar	14.585 ± 2.419	0.146 ± 0.059	15.198 ± 2.955	0.272 ± 0.043	Cond * A.Loc: NS Cond: NS A.Loc: P<0.0001
left arm	12.349 ± 6.108	0.243 ± 0.178	10.647 ± 4.494	0.357 ± 0.081	
left leg	5.466 ± 2.472$_{(Hb; La)}$	1.243 ± 0.630$_{(Hb; La)}$	8.442 ± 4.859$_{(Hb; La)}$	1.190 ± 0.535$_{(Hb; La)}$	
seat post	14.614 ± 2.024$_{(LL)}$	0.087 ± 0.023$_{(LL)}$	14.075 ± 2.604$_{(LL)}$	0.215 ± 0.040$_{(LL)}$	
lower Back	5.467 ± 0.249$_{(Hb; La; SP)}$	0.260 ± 0.224$_{(LL)}$	5.476 ± 0.365$_{(Hb; La; SP)}$	0.363 ± 0.212$_{(LL)}$	
head	5.415 ± 0.232$_{(Hb; La; SP)}$	0.203 ± 0.178$_{(LL)}$	5.477 ± 0.280$_{(Hb; La; SP)}$	0.302 ± 0.160$_{(LL)}$	

Where, Cond * A.Loc refers to the two-way interaction between conditions (Cond) and accelerometer location (A.Loc). NS denotes a non-significant effect ($p > 0.05$). Within condition differences ($p < 0.05$) for specific accelerometer position shown via subscript abbreviations with regard to positional differences. Where, Hb = handlebar; LA = left arm; LL = left leg; SP = seat post; LB = lower back; and H = head.

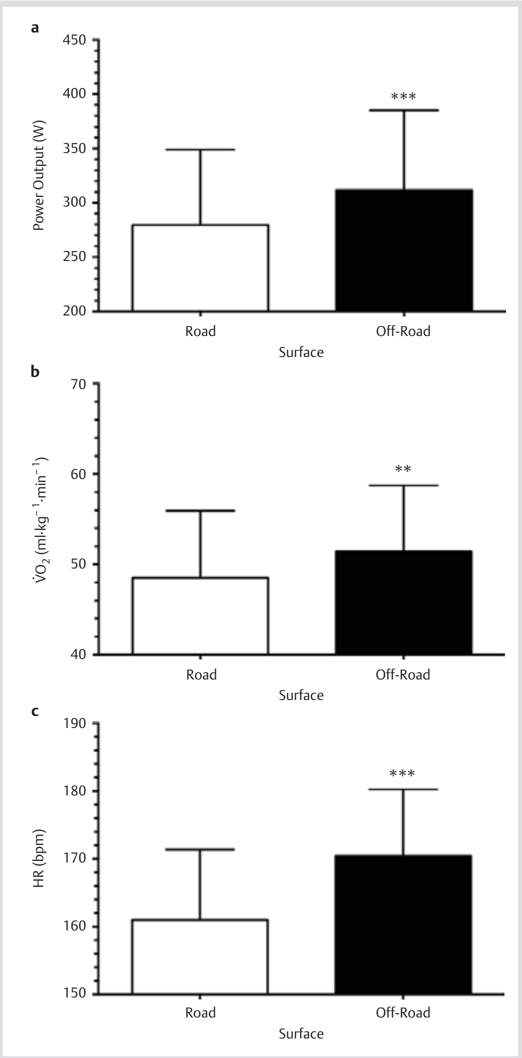


Fig. 3 Mean ± SD for **a** Power Output (W); **b** $\dot{V}O_2$ (ml · min^{-1} · kg^{-1}); and **c** Heart Rate (bpm) for both the tar-sealed road □ and the single-track off-road ■, where * * * ($P<0.001$) and * * ($P<0.01$) single-track off-road is significantly different to road.

quency values in the <5 Hz band for the off-road and >5 Hz for the road. This aspect requires further research focussing specifically on vibrations at the bike level and how they interact with soft tissue and the relationship between terrain surface and tyre tread patterns.

An important finding of this study is the confirmation that while surface terrain affected total vibrations experienced at the bicycle level and the appendages, there was no effect on levels experienced at the axial body (lower back or head). This confirms a recent XCO-MTB study [18] which posits that damping occurs within the limbs perhaps to protect the central nervous system and brain from damage [24], but also to limit the effects of disturbance to coordination and balance [21]. As such, if the vibrations experienced at either the bicycle or outer extremities are lower, it might be assumed that measures associated with physiological work would also be lower during a trial with decreased damping. To this extent total accelerations experienced were significantly greater during off-road single-track riding (▶ **Fig. 1**), and there were subsequently greater power outputs required to maintain the same speed during an uphill trial (▶ **Fig. 3a**). Consequently, physiological demand increased and was expressed through both heart rate and $\dot{V}O_2$ (▶ **Fig. 3b, c**). Therefore, any intervention that can reduce damping could well lead to an improvement in overall performance during XCO-MTB racing through an improvement in cycling economy. An alternative view might be that the additional stress of vibrations during exercise to the neuromuscular system [21] could serve to increase long-term training adaptions and ultimately, the overall performance of road cyclists.

A limitation of this study is the inability to differentiate between the extra demand as a result of voluntary and involuntary movements and their interactions. While in all likelihood the total vibrations experienced is the most important factor for a performance based analysis [2], it is useful to understand the influence of involuntary movements experienced and the subsequent effect on performance.

Conclusion
▼

Riding at the same speed over an identical distance, on a track of the same gradient, but differing in surface (tar-sealed vs. off-road single track) caused participants to experience greater vibrations at the bicycle level and points of contact between bicycle and body while riding off-road. There were no differences for vibrations experienced at the head and lower back indicating a greater amount of non-propulsive work performed during XCO-MTB compared to road cycling. The increased damping led to increases in measures of work done and associated physiological variables explaining the decreased economy associated with XCO-MTB when compared to road cycling.

References

1 *Abbiss CR, Ross MLR, Garvican LA, Ross N, Pottgiesser T, Gregory J, Martin DT.* The distribution of pace adopted by cyclists during a cross-country mountain bike World Championships. J Sports Sci 2013; 31: 787–794
2 *Aguilar S, Becker P, Gonzalez D, Kaminski B, Knopp N, Jankhot C, Marcellis B, Poli D, Ruidera R, Tsosie H.* Power Measurement for Road Bicycles: Towards a Universal Solution (Semester Unknown). IPRO 2008; 324: 53
3 *Bongiovanni LG, Hagbarth KE, Stjernberg L.* Prolonged muscle vibration reducing motor output in maximal voluntary contractions in man. J Physiol 1990; 423: 15–26
4 *Chavarren J, Calbet JAL.* Cycling efficiency and pedalling frequency in road cyclists. Eur J Appl Physiol Occup Physiol 1999; 80: 555–563
5 *Faiss R, Praz M, Meichtry A, Gobelet C, Deriaz O.* The effect of mountain bike suspensions on vibrations and off-road uphill performance. J Sports Med Phys Fitness 2007; 47: 151–158
6 *Gregory J, Johns DP, Walls JT.* Relative vs. absolute physiological measures as predictors of mountain bike cross-country race performance. Journal of Strength and Conditioning Research 2007; 21: 17–22
7 *Harriss D, Atkinson G.* Ethical Standards in Sport and Exercise Science Research: 2014 Update. Int J Sports Med 2013; 34: 1025–1028
8 *Hines W, O'Hara-Hines R, Brooke J.* A multivariate solution for cyclic data, applied in modelling locomotor forces. Biological cybernetics 1987; 56: 1–9
9 *Hurst HT, Swarén M, Hébert-Losier K, Ericsson F, Sinclair J, Atkins S, Holmberg H-C.* Influence of course type on upper body muscle activity in elite Cross-Country and Downhill mountain bikers during off Road Downhill Cycling. Journal of Science and Cycling 2012;1: 2–9

10 *Ishii T*, *Umerura Y*, *Kitagawa K*. Influences of mountain bike suspension systems on energy supply and performance. Japanese Journal of Biomechanics in Sports and Exercise 2003; 7: 2–9

11 *ISO*. Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements. In. [Geneva]; 1997;

12 *Issurin VB*. Vibrations and their applications in sport. A review. J Sports Med Phys Fitness 2005; 45: 324–336

13 *Jäncke L*, *Steinmetz H*, *Benilow S*, *Ziemann U*. Slowing fastest finger movements of the dominant hand with low-frequency rTMS of the hand area of the primary motor cortex. Experimental Brain Research 2004; 155: 196–203

14 *Kay BA*, *Saltzman EL*, *Kelso J*. Steady-state and perturbed rhythmical movements: A dynamical analysis. Journal of Experimental Psychology: Human Perception and Performance 1991; 17: 183

15 *Levy M*, *Smith G*. Effectiveness of vibration damping with bicycle suspension systems. Sports Eng 2005; 8: 99–106

16 *Lucia A*, *Hoyos J*, *Perez M*, *Chicharro JL*. Heart rate and performance parameters in elite cyclists: a longitudinal study. Med Sci Sports Exerc 2000; 32: 1777–1782

17 *Macdermid PW*, *Fink PW*, *Stannard SR*. The influence of tyre characteristics on measures of rolling performance during cross-country mountain biking. J Sports Sci 2014; doi:10.1080/02640414.2014.942682: 1–9

18 *Macdermid PW*, *Fink PW*, *Stannard SR*. Transference of 3D accelerations during cross country mountain biking. Journal of biomechanics 2014; 47: 1829–1837

19 *Macdermid PW*, *Stannard S*. Mechanical work and physiological responses to simulated cross country mountain bike racing. J Sports Sci 2012; 30: 1491–1501

20 *MacRae H-H*, *Hise KJ*, *Allen PJ*. Effects of front and dual suspension mountain bike systems on uphill cycling performance. Med Sci Sports Exerc 2000; 32: 1276–1280

21 *Mester J*, *Spitzenfeil P*, *Schwarzer J*, *Seifriz F*. Biological reaction to vibration – implications for sport. Journal of Science and Medicine in Sport 1999; 2: 211–226

22 *Nishii T*, *Umemura Y*, *Kitagawa K*. Full suspension mountain bike improves off-road cycling performance. J Sports Med Phys Fitness 2004; 44: 356–360

23 *Redfield R*. Large motion mountain biking dynamics. Vehicle System Dynamics 2005; 43: 845–865

24 *Samuelson B*, *Jorfeldt L*, *Ahlborg B*. Influence of vibration on endurance of maximal isometric contraction. Clinical Physiology 1989; 9: 21–26

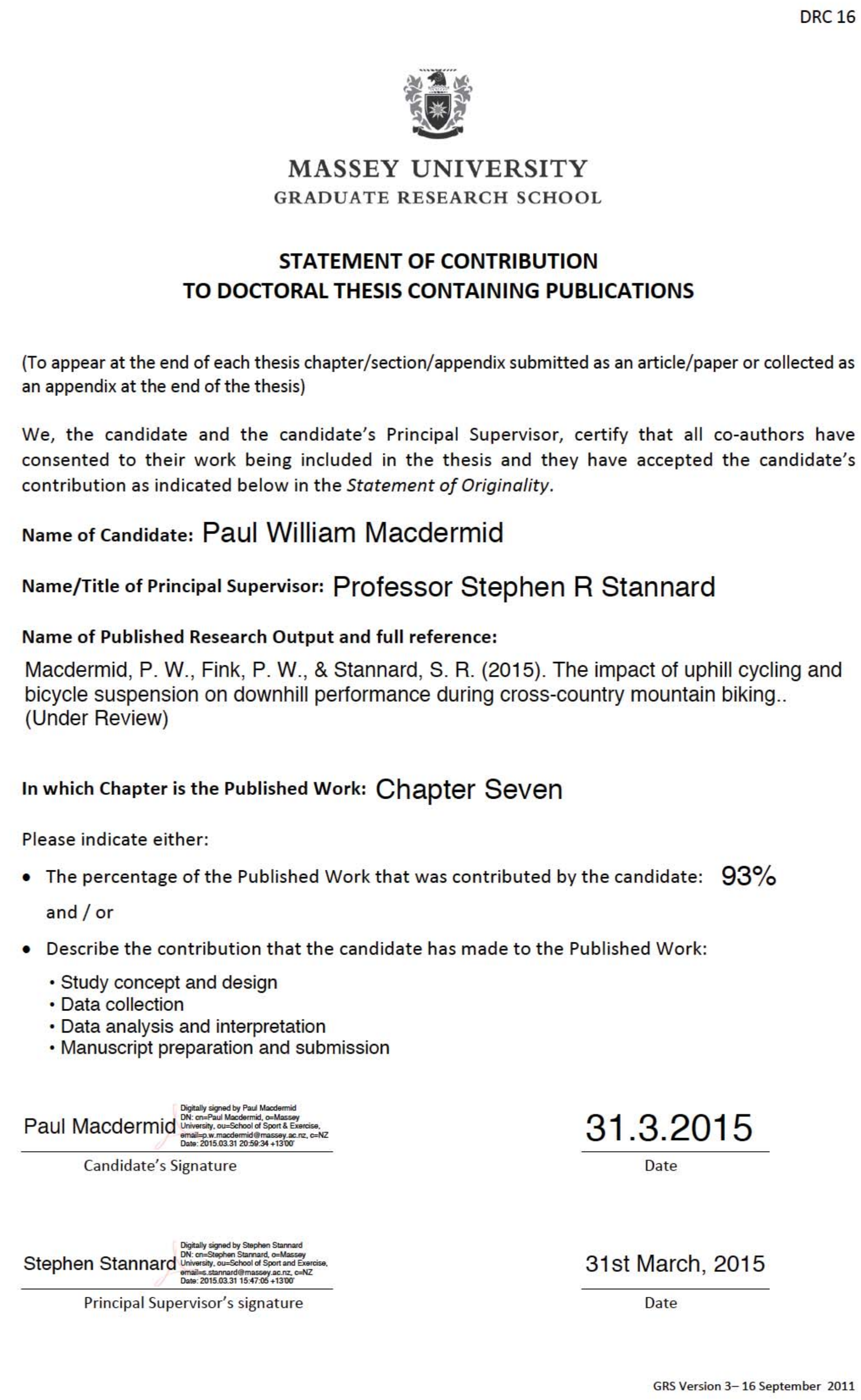
25 *Stapelfeldt B*, *Schwirtz A*, *Schumacher YO*, *Hillebrecht M*. Workload demands in mountain bike racing. Int J Sports Med 2004; 25: 294–300

26 *Titlestad J*, *Fairlie-Clarke T*, *Whittaker A*, *Davie M*, *Watt I*, *Grant S*. Effect of suspension systems on the physiological and psychological responses to sub-maximal biking on simulated smoothand bumpy tracks. J Sports Sci 2006; 24: 125–135

27 *Vibert D*, *Redfield RC*, *Rudolf H*. Benign Paroxysmal Positional Vertigo in Mountain Bikers. Ann Otol Rhinol Laryngol 2007; 116: 887–890

28 *Wakeling JM*, *Nigg BM*, *Rozitis AI*. Muscle activity damps the soft tissue resonance that occurs in response to pulsed and continuous vibrations. J Appl Physiol 2002; 93: 1093–1103

Appendix 5



DRC 16

MASSEY UNIVERSITY
GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
TO DOCTORAL THESIS CONTAINING PUBLICATIONS

(To appear at the end of each thesis chapter/section/appendix submitted as an article/paper or collected as an appendix at the end of the thesis)

We, the candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of Candidate: Paul William Macdermid

Name/Title of Principal Supervisor: Professor Stephen R Stannard

Name of Published Research Output and full reference:

Macdermid, P. W., Fink, P. W., & Stannard, S. R. (2015). The impact of uphill cycling and bicycle suspension on downhill performance during cross-country mountain biking.. (Under Review)

In which Chapter is the Published Work: Chapter Seven

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate: 93%

  and / or

- Describe the contribution that the candidate has made to the Published Work:
  - Study concept and design
  - Data collection
  - Data analysis and interpretation
  - Manuscript preparation and submission

Paul Macdermid
Digitally signed by Paul Macdermid
DN: cn=Paul Macdermid, o=Massey University, ou=School of Sport & Exercise, email=p.w.macdermid@massey.ac.nz, c=NZ
Date: 2015.03.31 20:59:34 +13'00'

Candidate's Signature

31.3.2015

Date

Stephen Stannard
Digitally signed by Stephen Stannard
DN: cn=Stephen Stannard, o=Massey University, ou=School of Sport and Exercise, email=s.stannard@massey.ac.nz, c=NZ
Date: 2015.03.31 15:47:05 +13'00'

Principal Supervisor's signature

31st March, 2015

Date

GRS Version 3– 16 September 2011

Appendix 6

2nd World Congress of Cycling Science, 2nd and 3rd July 2014, Leeds **J Sci Cycling.** Vol. 3(2), 17

BOOK OF ABSTRACTS **Open Access**

Quantification of vibrations during mountain biking

P Macdermid [1]✉, PW Fink and S Stannard

Abstract

Background: During cross-country mountain biking, riders are subjected to vibrations due to the terrain, which must be damped before reaching the central nervous system. Damping vibrations requires work, which may help to explain the decrease in economy for mountain biking as compared to road cycling (Titlestad et al., 2006 Journal of Sports Sciences, 24(2), 125-135). Purpose: To describe the relationship between vibration mechanics and their interaction with terrain, bicycle and rider during a race pace effort on a cross country mountain bike track.

Methods: Participants (n=8) completed two separate laps on a cross country track using 26” and 29” wheels, at race speed. Power, cadence, speed, heart rate, and geographical position were sampled and logged every second for control purposes. Tri-axial accelerometers located at handlebar centre, lower left arm, lower left leg, seat post, lower back and medial forehead, recorded accelerations with a output rate 128 Hz to measure vibrations experienced during the whole lap and over terrain sections (uphill and downhill). Vibrations were quantified using a root mean square (RMS) and using Fourier analyses.

Results: RMS data showed greater total accelerations for 29” vs 26” wheels (p=0.0020), and a significant interaction of terrain and accelerometer location (p<.0001). While climbing, accelerations were generally low and concentrated at low movement frequencies. While descending, however, high RMS values were seen on the bicycle (handlebar and seat post) and the parts of the body near the interface with the bicycle (left arm and left leg), while lower accelerations at the lower back and head were not significantly different than the accelerations during climbing. In addition, Fourier analyses showed that the accelerations occurred at a higher frequency when compared to uphill sections. No differences between overall power output (p=0.3062) and heart rate (p=0.8423), yet overall time was greater for 26” compared to 29” wheels (p=0.0061). Discussion: The results show that mountain bikers are subjected to large accelerations, or vibrations, particularly during downhill sections. These vibrations are damped before reaching the lower back and head, which requires metabolic work. In addition, 29 inch wheels showed a clear performance advantage, going faster for the same average power, although resulting in greater vibrations for the riders.

Conclusion: This study demonstrates an additional non-propulsive, muscular challenge to riding during cross country mountain biking represented by a change in accelerations at the point of interface between bike-body compared to lower back and head.

✉ **Contact email:** p.fink@massey.ac.nz (P. Macdermid)

[1] School of Sport and Exercise, Massey University, Palmerston North, New Zealand.

Received: 1 May 2014. Accepted: 1 June 2014.

Appendix 7

weight: does it matter?

PART TWO

WORDS BY **PAUL MACDERMID**
PHOTOGRAPHY BY **NICK LAMBERT**
UNLESS NOTED OTHERWISE

Following on from issue 56 where we looked at Rob Metz's take on the physics of bike weight, this time we've enlisted the help of Paul MacDermid, lecturer for the School of Sport and Exercise at Massey University, to carry out some testing of the effect of bike weight on climbing times. Paul has researched many aspects of mountain bike performance - his current research focus is the impact of terrain induced vibrations on bike, body and performance. We asked for his help to set up a test of the importance of bike weight, especially as it relates to the rider's relative body weight. Paul's analysis and test follows:

82 | www.nzmtbr.co.nz

The cross-country scene is filled with passionate discussions about how light this bike is or how many grams aresaved by riding this saddle rather than that one. The issue of bike weight has moved even further afield, spreading to recreational riders at the local forest and even the downhillers amongst us are starting to brag about the weight of their bikes.

Weight can be saved just about anywhere and everywhere, but always at a cost. For example, for one brand of pedals, the lightest model in the range weighs 98g less than the heaviest in the range and will cost you an additional $550. That's $5.76 for every gram saved. In other instances, the cost is not money but performance or reliability. Did anyone else see Marco Fontana's seat post snap in the final five minutes of the Olympic race? In the lead group of three he was intending to sprint for the win, but after his seat post snapped he had to settle for being dropped, and in fact had to dig deep to take the bronze medal (and not impale himself on the exposed broken shaft).

But does it really make a difference?

I'm not going to turn around and tell anybody that weight isn't important when trying to defy gravity. The greater your total weight (bike, rider and any gear), the more likely you will lose time to your lighter mates. But how much time?

To find out, I got together a group of enthusiastic volunteers from the School of Sport & Exercise Science at Massey University and set out to assess what difference the addition of dead weight to a bike frame would make while riding up a steep forest road relative to total (rider plus bike) weight.

Yes, I know many of you want to know whether saving 98 grams on super-light pedals will save you enough time to beat your buddy to the top of your local hill, but we just weren't confident in our ability to provide a conclusive result with such small changes in weight. So for this experiment we decided to add three quite heavy weights to the frame that would ensure we would see a difference in our results if weight was to be a determining factor.

Our volunteers included some youngsters weighing in at the same weight as the average Kenyan long distance runner, as well as some downhillers (who were happy to ride uphill?!) who weighed in at the same weight as the average All Black.

Our hypothesis (what we expected to find):

A heavy bike will negatively affect climbing performance and the negative effect will be more significant the lighter the rider is.

What we tested:

If the time to reach the top of our steep hill changed while climbing at the same relative intensity (i.e., the power output and heart rate of the rider stayed the same) then we would know that the weight was responsible for any difference in the time it took to get to the top of our hill. In addition to this we are interested in how that difference looks when the bike weight is expressed as a proportion of the total weight (bike and rider). Note that we're only testing static, or non-rotational weight here. (We'll be looking at wheel weight in an upcoming issue.)

How we tested it:

We sent the riders up a very steep dirt road hill climb on a GT Zaskar 29" XC race bike four times with varying bike weights. The hill climb was 1.125 km long with a vertical gain of 125 metres and an average grade of 13% (see figure 1) and took our riders around 11 minutes to climb. We fixed the riders' power output and monitored their heart rates and timed them to the top. Bike weight changed via the addition of sand filled water bottles to the bike. The test was blind, meaning the riders did not know whether any or all of three water bottles were empty or full of sand.

Subjects:

This started out as a little investigation using 60kg, 75kg and 95kg riders but we managed to gain 10 subjects of body weights ranging from 28 to 96kg (yes, 28kg - he's only 11, but he's pretty quick). All were experienced mountain bikers, but all were at different levels of fitness.

The Test:

We wanted our subjects to all ride at the same relative workload for a given kilogram of body weight (power:weight ratio) over the same hill (see profile below), using the same mountain bike, which weighed 10.7, 13.0, 14.4 and 19.0kg depending on how many of the bottles were full of sand. There was no difference in rotational component weight.

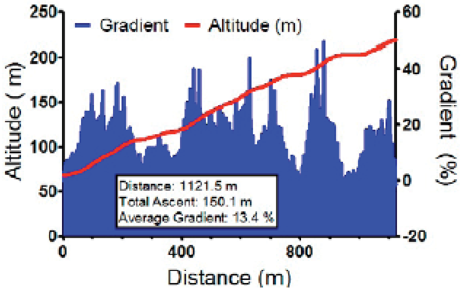


Figure 1. The hill profile and changing gradient over the distance.

The correct workload was achieved through assessing power output at the crank (using SRAM'S QUARK power meter), where data was wirelessly transmitted to a Garmin 505 Edge on the bike for the rider to view. The display was set to show only average lap power and power (time and speed were not visible), with subjects required to keep average power at a pre-determined power output of 2.8 W/kg of body weight. Why 2.8 W/kg? Well, this was determined by the heaviest rider being able to maintain 2.8 Watts per kilogram of their body weight for the amount of time we were asking (2.8 x 95 = 266W).

Variables Recorded:

Performance was measured by time (s) to complete the hill climb while controls of intensity included power output (W) and heart rate (bpm).

The Garmin recorded data every second and we were able to retrieve this using the Garmin training centre software for later analysis.

What we found:

The main finding, not surprisingly, was that adding weight to the bike decreased performance over our climb - the riders were slower to the top. Secondly, there were no differences between power output (W) and heart rate (bpm) for the different bike weights amongst our subjects, suggesting the test was very well controlled and provided reliable data.

Remember, we had 10 riders each performing the test with four

SRAM'S QUARQ POWER METER CRANKS ALLOWED US TO CONTROL THE RIDERS' POWER OUTPUT, ENSURING RELIABLE RESULTS

different bike weights, so we have a lot of result data. We found that adding 3.7kg and 8.3kg complemented what we found with the 2.3kg weight, so we'll focus on that one, as adding 2.3kg is enough of a difference to take a bike from what most riders would consider a 'light' bike to a 'heavy' bike.

While there is a range of data from our different weight riders (See Figure 2A for averages), to give you an idea, adding 2.3kg (21.5%) to our 10.7kg bike meant a decrease in performance of 22 seconds (3.3%) for the 95 kg rider, 27 seconds (4.0%) for the 70kg rider and 46 seconds (5.3%) for the 28kg rider.

As you can see the variation in the time (s) differences between participants was actually very high. This, however, was expected as the wide spectrum of body weights used (28-96kg) meant a huge range of differences in terms of the proportion of bike to body weight. If we analyse the results based on body weight (see figure 2A) or proportion of bike weight to total weight (figure 2B) you can see why the original analyses are so varied.

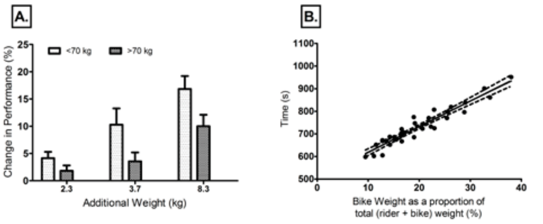


Figure 2. Performance over climb when participants were split for those weighing > 70kg and < 70kg (A), and the effect of bike weight as a proportion of total weight on performance (B).

What about 'tiredness'?

You might be thinking "yeah, but the longer the rider has to climb the more tired they'll get and the greater the difference the additional weight will make". Nope - that's why we controlled their power output. The difference in difficulty and their 'tiredness' is captured in the difference in time to the top. If you want to know how much difference it will make over a different hill climb e.g. one that is twice as high or long, just work out the time difference the gain or loss in weight (using the Weight -Performance Calculation) will make as a percentage and multiply by your typical time to climb.

Practical application:

Figure 3 provides an estimate of the effect of bike weight (all rotational parts are the same) on six different hypothetical body weights. Alternatively, for those mathematicians out there, use the calculation below to determine the difference saving a given amount of weight will make.

Weight-Performance Calculation

Time (s) = (11.31 x (bike weight / ((total rider weight + bike weight)) x 100)) + 506

An example of how this can be used is provided:

A 70kg rider using a RockShox Reverb Stealth (1250mm) drop saddle weighing 560g compared to a Truvati Noir T40 225g seat post and the effects of the extra weight on climbing performance. The bike excluding the seat post weighed 9.5kg.

Drop seat: (11.31 x (9.5+0.56) / ((70+(9.5+0.56)) x 100)) + 506 = 648s

Light weight seat post: (11.31 x (9.5+0.225) / ((70 + (9.5+0.225)) x 100)) + 506 = 644s

According to the results of our testing, for a 70kg rider, the time difference from adding a dropper post over an 11 minute, 170 vertical metre hill climb is 4 seconds, or 0.6%. To determine if that saving is worth it, you'll need to figure out if you'd be 4 seconds quicker back down the descent or if the ability to relax more on the descent will leave you more than 4 seconds worth fresher for the next climb. We'll leave that calculation to you.

Can you apply this information to your own hill climbs?

Our test course was a very specific hill climb designed to show how much increased weight increases riding time up a steep hill. We chose a hill where the skill factor was minimal - great for isolating the potential impact of weight and allowing the experiment to produce measurable results, but maybe not so great for applying the results to our favourite and most ridden climbs, which are invariably singletrack. The most enjoyable tend to be between 3-7% gradient, and include corners, rocks, roots, and small descents where momentum helps during the next uphill section. In short, skill (or in some cases luck) plays an unknown, but presumably large portion of performance before we reach our favourite descent(s) and thus decreases the relative impact of non-functional weight gain or loss. As you see, it would be hard to gain reliable results where rider consistency plays a part in performance, and by eliminating that we are able to get a good handle on the direct effects of non-functional weight on uphill performance. To relate the results to a specific climb, you would be best to use our calculation and work out the percentage change and apply that to the duration of your climb. Remember, there will always be a bit of play in the answer due to the element of skill or luck!

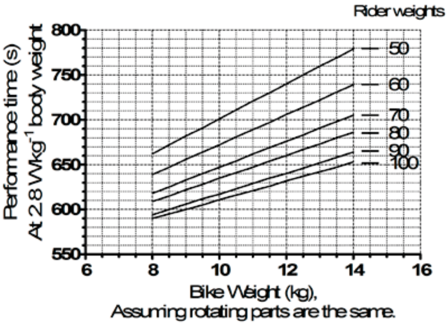


Figure 3. Hypothetical effects of different bike weights on performance over the hill climb.

Conclusion:

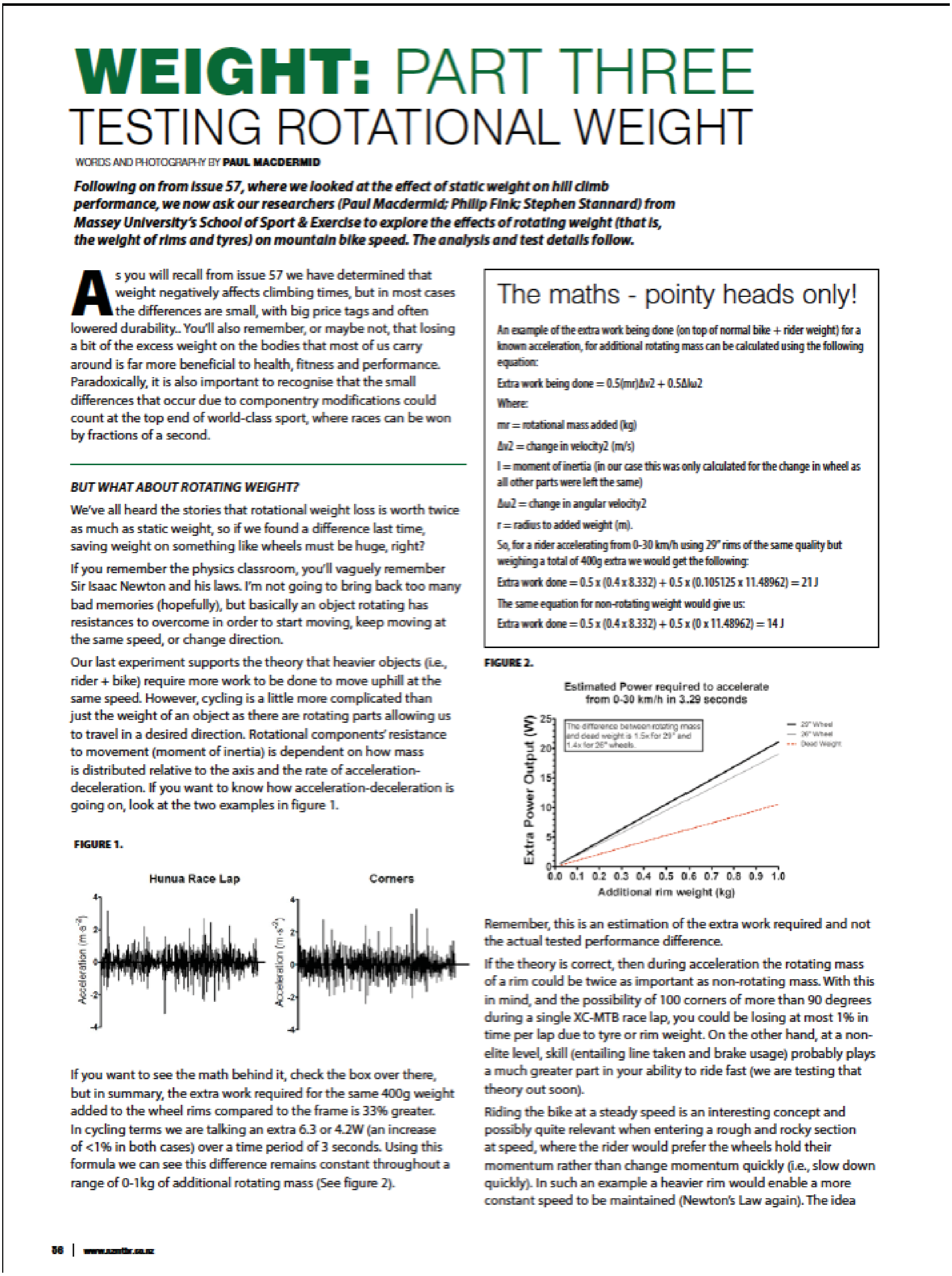
At a given watts per kilo power output, a heavier rider and bike combination are slower to the top of a hill. This means heavier riders have less to lose from heavier bikes, and lighter riders have more to lose. Knowing this information is very useful, as it means the skinny little weight savers amongst us can actually work out the performance value of paying an extra $500 to save 100g. Maybe knowing this, riders will concentrate more on enjoying the moment rather than stressing about a few grams lost here and there to an opponent. Also, it's worth acknowledging that investing in a slightly stronger frame or component might keep you in the game for longer in order to do more riding, or, in the case of the dropper post, result in more fun and possibly faster descending. Alternatively, if you are serious, dropping a few grams of body weight is a good option, but the worst that can happen if you don't worry about it is that your friends on their super-duper light bikes may have to wait at the top, literally a few seconds - or not, if you're fitter than they are...

WEIGHT WAS ADDED WITH THREE WATER BOTTLES EITHER EMPTY OR FILLED WITH SAND

What about rotational weight?

We've seen all sorts of claims about how much rotational weight (wheels and tyres) affects speed on a mountain bike versus static weight. However, it is true to say that when the bike is being accelerated, it is harder to get up to speed the heavier the wheels are. In that case, wheel weight makes more difference than static weight and therefore saving weight on the wheels will make more difference to speed than saving weight on the frame. However, it is important to remember this is only the case when you are accelerating. Accelerating is of course increasing from a speed to a higher speed. Accelerating is not 'trying really hard up a hill' - if you are riding hard up a very steep hill and maintaining your speed, that is effort but it is not accelerating, so therefore not relevant for rotational weight. When, how often and for how long do you accelerate on your mountain bike? And consequently, how important is wheel weight to mountain biking speed? That's a question we'll be looking at in an upcoming issue…

Appendix 8



WEIGHT: PART THREE
TESTING ROTATIONAL WEIGHT

WORDS AND PHOTOGRAPHY BY **PAUL MACDERMID**

Following on from issue 57, where we looked at the effect of static weight on hill climb performance, we now ask our researchers (Paul Macdermid; Philip Fink; Stephen Stannard) from Massey University's School of Sport & Exercise to explore the effects of rotating weight (that is, the weight of rims and tyres) on mountain bike speed. The analysis and test details follow.

As you will recall from issue 57 we have determined that weight negatively affects climbing times, but in most cases the differences are small, with big price tags and often lowered durability.. You'll also remember, or maybe not, that losing a bit of the excess weight on the bodies that most of us carry around is far more beneficial to health, fitness and performance. Paradoxically, it is also important to recognise that the small differences that occur due to componentry modifications could count at the top end of world-class sport, where races can be won by fractions of a second.

BUT WHAT ABOUT ROTATING WEIGHT?

We've all heard the stories that rotational weight loss is worth twice as much as static weight, so if we found a difference last time, saving weight on something like wheels must be huge, right?

If you remember the physics classroom, you'll vaguely remember Sir Isaac Newton and his laws. I'm not going to bring back too many bad memories (hopefully), but basically an object rotating has resistances to overcome in order to start moving, keep moving at the same speed, or change direction.

Our last experiment supports the theory that heavier objects (i.e., rider + bike) require more work to be done to move uphill at the same speed. However, cycling is a little more complicated than just the weight of an object as there are rotating parts allowing us to travel in a desired direction. Rotational components' resistance to movement (moment of inertia) is dependent on how mass is distributed relative to the axis and the rate of acceleration-deceleration. If you want to know how acceleration-deceleration is going on, look at the two examples in figure 1.

FIGURE 1.

If you want to see the math behind it, check the box over there, but in summary, the extra work required for the same 400g weight added to the wheel rims compared to the frame is 33% greater. In cycling terms we are talking an extra 6.3 or 4.2W (an increase of <1% in both cases) over a time period of 3 seconds. Using this formula we can see this difference remains constant throughout a range of 0-1kg of additional rotating mass (See figure 2).

The maths - pointy heads only!

An example of the extra work being done (on top of normal bike + rider weight) for a known acceleration, for additional rotating mass can be calculated using the following equation:

Extra work being done = $0.5(mr)\Delta v2 + 0.5\Delta I\omega 2$

Where:

mr = rotational mass added (kg)

$\Delta v2$ = change in velocity2 (m/s)

I = moment of inertia (in our case this was only calculated for the change in wheel as all other parts were left the same)

$\Delta\omega 2$ = change in angular velocity2

r = radius to added weight (m).

So, for a rider accelerating from 0-30 km/h using 29" rims of the same quality but weighing a total of 400g extra we would get the following:

Extra work done = $0.5 \times (0.4 \times 8.332) + 0.5 \times (0.105125 \times 11.48962) = 21$ J

The same equation for non-rotating weight would give us:

Extra work done = $0.5 \times (0.4 \times 8.332) + 0.5 \times (0 \times 11.48962) = 14$ J

FIGURE 2.

Remember, this is an estimation of the extra work required and not the actual tested performance difference.

If the theory is correct, then during acceleration the rotating mass of a rim could be twice as important as non-rotating mass. With this in mind, and the possibility of 100 corners of more than 90 degrees during a single XC-MTB race lap, you could be losing at most 1% in time per lap due to tyre or rim weight. On the other hand, at a non-elite level, skill (entailing line taken and brake usage) probably plays a much greater part in your ability to ride fast (we are testing that theory out soon).

Riding the bike at a steady speed is an interesting concept and possibly quite relevant when entering a rough and rocky section at speed, where the rider would prefer the wheels hold their momentum rather than change momentum quickly (i.e., slow down quickly). In such an example a heavier rim would enable a more constant speed to be maintained (Newton's Law again). The idea

here is that it requires less energy to maintain momentum with the heavier rim, so the rider is only penalised during the period of acceleration rather than the whole ride duration. Add to this a changeable gradient, bumps and a rider, and then it starts getting quite complicated. Classroom stuff is all well and good, but we know the real world is messy in comparison, and MTB is slightly messier than the average cycling discipline - so let's test the theory.

OUR HYPOTHESIS (WHAT WE EXPECTED TO FIND):

Additional rotating weight would make a greater difference during a flat corner (including an acceleration and deceleration period) and during a climb compared to static weight increases.

WHAT WE TESTED:

To assess the effects of rotating weight we used 29" DT Swiss 470 wheels and tested them in three separate conditions. These included no additional weight (rims 470g), as well as a total of 400g, and 800g of additional weight. Each lead strip weighed 200g and the appropriate number of strips were secured on the inside of the wheel rim.

FIGURE 3. FRONT WHEEL WITH ONE 200G LEAD RIM STRIP IN PLACE.

Two tests (see below) were used to identify specific performance aspects of the wheels, measuring time to complete the task and assessed via the percentage change from our control (normal wheel weight).

HOW WE TESTED IT:

Subjects:

Nine subjects varying in weight and fitness were used for the hill climb, with five of the subjects performing the MTB Corner test.

Test 1

To assess the acceleration-deceleration we measured: a) acceleration from a standing start into a corner, b) time to negotiate the corner, and c) acceleration away from the corner, which we called moving acceleration (see figure 4a). Each rider was very familiar with this test and performed it five times per trial in order to get a typical response. Riders were unaware of what wheel weight they were using and were asked to ride as fast as possible. Times were recorded with timing lights (See figure 4b), accurate to 1,000th of a second.

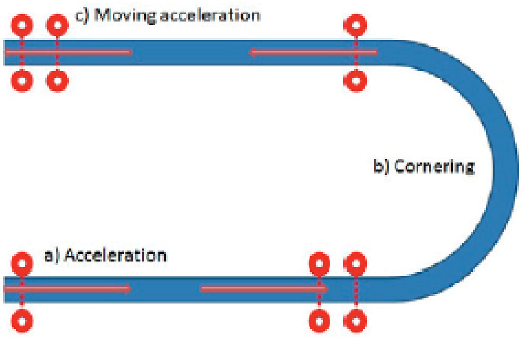


FIGURE 4. A) THE MTB CORNER TEST USED TO ASSESS POWER AND SKILL.

FIGURE 4. B) RIDER IN ACTION DURING THE TEST.

Test 2 included the hill climb (1.125km with a vertical gain of 125m, gradient 13%) from issue 57, where the time to reach the top was recorded for the same power outputs per subject. Power output was measured at the crank (using SRAM's QUARK power meter) and transmitted to a Garmin 505 edge on the bike for the rider to view average power and real time power. Riders were required to keep average power at a pre-determined power output of 2.8W/kg of body weight.

WHAT WE FOUND:

The main finding here is that rotational weight counts. Our predictive model for acceleration as per the start of the corner test suggests that a rider wanting to maintain time with an additional 400 or 800g would have to increase the work done by half again of that required for the equivalent static weight. However, as we can see from figure five this is not the case for acceleration or cornering in a field test.

The results of the moving acceleration part of the test are a more realistic way to judge any effect on overall riding, as there are very few instances when a rider comes to a complete stop during a race/ride and then accelerates back up to speed. For the corner used in this test (considered relatively tight at over 90 degrees) the average entry speed was 25km/h while exit speed was 20km/h. This equals a 20% decrease in speed, but more importantly, the additional difference between static weight and rotating weight is much less than the other two parts of the test. Taking all of this into account, the overall difference is 1.7 and 3 times greater for rotating weight over static weight when adding 400 and 800g of weight.

FIGURE 5. MTB CORNER TEST RESULTS FOR A) ACCELERATION; B) CORNERING; AND C) MOVING ACCELERATION.

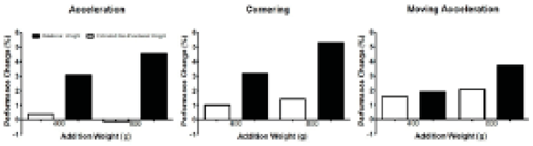
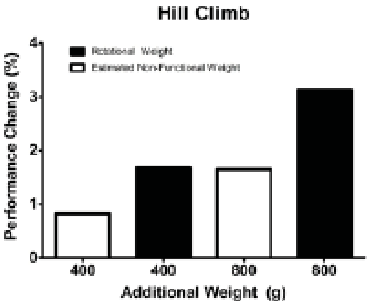


Figure 6 shows the hill climb difference between dead weight and rotating weight is almost double, agreeing with the theory. However, it might not have been expected as we would assume that on a steady climb we'd accelerate and then keep a constant speed. In this case, the difference would only be that which occurred from zero speed up to a more constant speed. Well, as we've already stated, the real world is messy and even on our hill the terrain is constantly changing, as is our perception of force application to the pedals. As a result, we saw that over what we called a steady climb constant pace was really just a period of micro accelerations and decelerations.

FIGURE 6. PERFORMANCE OVER THE HILL CLIMB WITH COMPARISONS OF ESTIMATED NON-FUNCTIONAL WEIGHT AND ROTATIONAL WEIGHT WITH NO ADDITIONAL WEIGHT.



PRACTICAL APPLICATION:

If you are in the business of trying to go faster without additional effort by replacing parts, then going for lighter tyres, wheels or wheel rims will make the most difference, followed by shoes and pedals, and then parts that do not rotate. However, the differences are not huge, especially to those who are not racing, and even for those who are, my advice would always be to also consider reliability - because saving an extra 50g is going to make very little difference if you puncture or fold a rim in half, and unlike the pros you have to buy your parts and pay entry fees. Especially if you weigh more than the average pro XC racer's 60-70kg, you may already be close to the limit some light weight rims and tyres are designed for. Also worth remembering is that this study did not take into account the stiffness or strength of a wheel, and it may well be possible that saving 100g per rim results in a more flexible wheel, providing different results to what we have here.

CONCLUSION:

Rotational weight (400 – 800g of rotational weight) decreases performance over short accelerations such as cornering at high speed, potentially adding up to around 10s of time (< 1%) over a typical XC lap of 15-20 minutes, but there is also the additional cost (≤1%) of small fluctuations in speed during normal riding. So in a racing situation we are talking a possible saving of 2% tops, or between 1-2 minutes depending on your age/gender category - but how many budding racers could save 800 grams of weight on their rims or tyres? For those who are not racing and for whom saving seconds does not matter, these results are important because they show that while additional wheel weight does make a difference, the difference is not as large as many cyclists assume (and much marketing would have us believe). Lighter rims and tyres will not drastically change how quickly you can ride your favourite loop or whether or not you can keep up with your buddies, but they could win you that sprint to the finish line.

Appendix 9

Ergonomics

Macdermid, J Ergonomics 2015, 5:1
http://dx.doi.org/10.4172/2165-7556.1000e130

Editorial Open Access

Ergonomic Interventions, Health and Injury Prevention during Off-Road Mountain Biking

Paul W Macdermid*

Massey University, School of Sport and Exercise, Private Bag 11-222,Palmerston North 4474,New Zealand

***Corresponding author:** Paul W Macdermid, Massey University, School of Sport and Exercise Private Bag 11-222, Palmerston North 4474, New Zealand, Tel: +64 6 951 6824; E-mail: p.w.macdermid@massey.ac.nz

Received: March 18, 2015; **Accepted:** March 19, 2015; **Published:** March 26, 2015

Keywords: Mountain biking; Vibration exposure; Damping; Suspension; Wheelsize

Editorial

Half of all Americans participated in outdoor recreation activities during 2013, of which 16% or 46.6 million (older than 6 yrs) take part in cycling (Road, Mountain bike, or BMX). Excursions totalled at 2.7 billion and ranked it 2nd for number of outings (887.9 million) for ages 6-17 yrs [1]. This presents a positive picture in regards to health promotion, yet there are concerns regarding bone health and excessive time spent in a weight supported position in road cyclists [2]. On the other hand, mountain bikes are the most popular bike ridden in the western world [3]. This discipline of cycling not only improves cardiovascular health, but also provides an osteogenic effect greater than both road cycling and normal recreational activity [4].

However, this sport does come with it's own risk and the overall injury rate is classed as very high, with 16.8 injuries per 1,000 h exposure [5]. While the majority of these injuries are acute, traumatic, and isolated to the minority [3], it is expected that many overuse injuries are not reported. This is supported by data showing 51.4% of participants completing an endurance mountain bike race suffered symptoms of overuse, particularly in the lower back, buttocks, knees and wrists [6]. Similarly, participants exposed to 4h of intense mountain biking suffered benign paroxysmal positional vertigo without any prior symptoms [7].

Purportedly, such negative effects are primarily due to the non-propulsive work demand caused by shock attenuation, a consequence of negotiating obstacles, and the continuous damping of vibrations. These vibrations are produced via the interaction of tyre surface area with trail surface [8] and are the very same thing that promote the sports osteogenic effect [4]. As such, the vibrations mountain bikers are exposed to are complex in nature, containing many frequencies (generally <50 Hz) in all directions and ranging in amplitude (rms) from 15-20 $m \cdot s^{-1}$ at the handlebar and 20-30 $m \cdot s^{-1}$ at the seat post [8]. The energy from such oscillating movements must be absorbed or else result in little or no wheel contact, albeit for a very short period of time. Even so, during these small epochs, the transfer of energy from the drive mechanism to the tyre-trail surface interaction cannot occur.

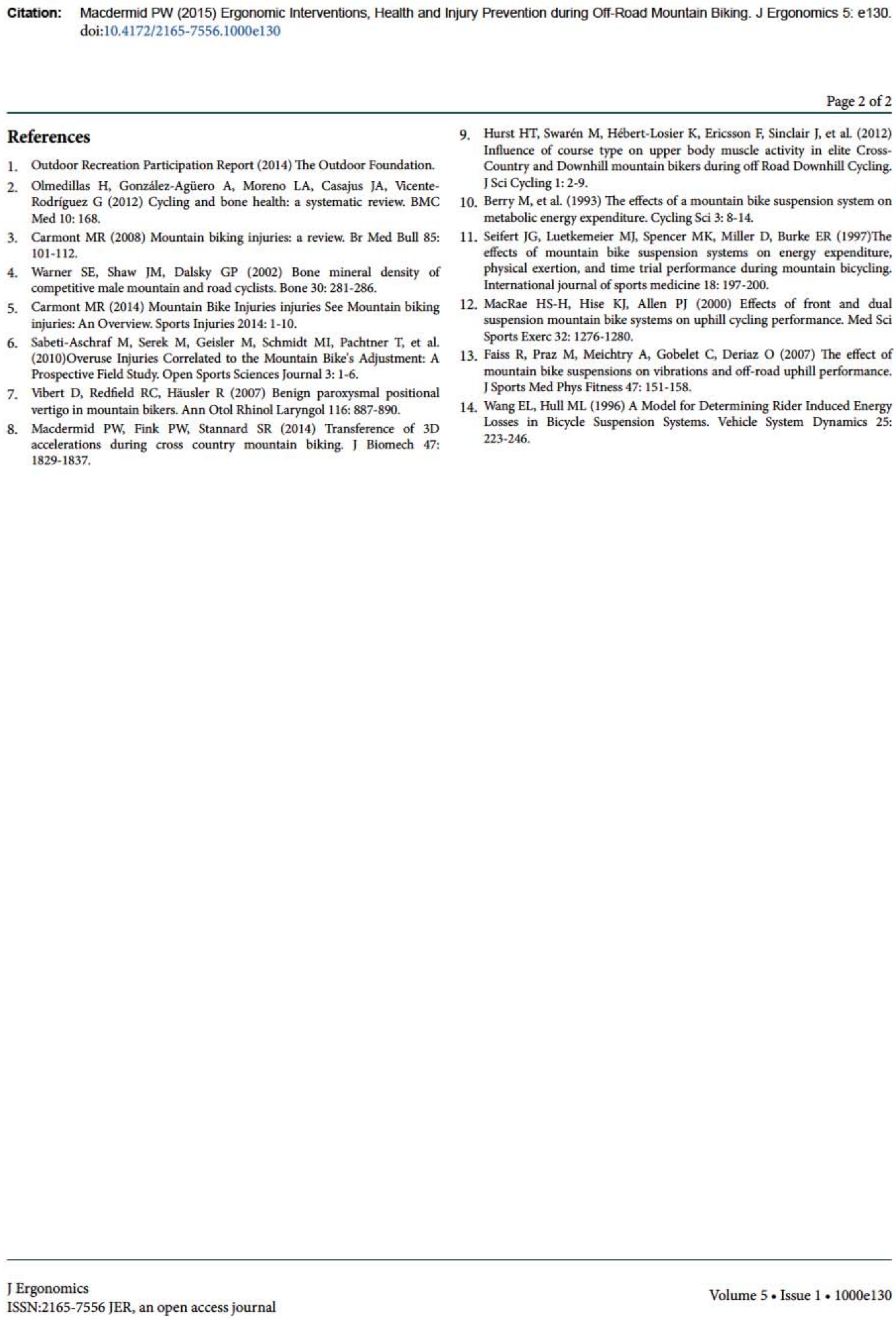
In order to negate this negative effect, the bikes mechanical parts and bike rider's soft tissue, absorbs energy in a damping mechanism enabling more efficient forward momentum and thus prevents injury to the axial skeleton. This occurs in the mechanical-biological system, particularly at the point of contact including handlebar-arm; pedal-foot-leg; and saddle-lower back [8]. It is reflected by an increase in upper body muscular work done [9] and likely plays a part in overall decreased economy during off-road compared to road cycling. The continuous nature of which leads to overuse injuries at the joints.

Therefore, the challenge for the mountain bike industry is to provide a bicycle that interacts in the most efficient and safe manner with regards to performance and comfort. As such, product research and development is obviously critical within the industry, yet little information is presented in a scientific manner through peer reviewed processes. This means the sport is industry driven, begging the question regarding conflict of interests between trying to sell new products and providing the customers with the best experience.

Mountan biking's roots are entwined in the use of bicycles for off-road commuting during the 1890's. However, these bicycles and their cyclocross cousins of the 1940's and current day, offer riders quite a different experience with regards to comfort and performance compared to present day mountain bikes. The individual experimental transformation of such bikes included frame geometry, tyre volumes, saddles, handlebar and handlebar grips, wheelsize, suspension systems, frame and component construction, a reversion to bigger wheels and the wider wheel.

Interestingly, the main emphasis of research has focussed on suspension systems, with initial results concluding that front suspension (HT) and full suspension (FS-front and back) are both effective at increasing rider efficiency over bumpy terrain [10,11]. Corroborated by laboratory studies that identified significantly increased efficiency and comfort of FS bicycles [12]. It is likely that the reduction in work done is a direct result of the capability of the mechanical system to reduce vibration exposure to the rider [13]. While this is positive for recreational riders with regards to reduced injury risk and improved comfort. There have been concerns that the additional weight of both the FS and HT systems and the power dissipation within the system, will reduce athletic performance [14]. It is important to recognise that technological development of bicycle suspension has improved considerably since these papers were published. As such it is envisaged that previous negative losses of energy have been reduced considerably. More recently, reductions in vibration exposure amongst competitive cyclists have been associated with a reduction in both propulsive and non-propulsive work done, thus justifying further work in this area.

Recognising the popularity and health benefits of such activities, the potential non-traumatic risks to participants, and the possible performance enhancement for elite athletes advocates the importance of ergonomic research in this area. The results of which would enhance enjoyment, performance and alleviate some of the current burden on the health systems around the world.



Citation: Macdermid PW (2015) Ergonomic Interventions, Health and Injury Prevention during Off-Road Mountain Biking. J Ergonomics 5: e130. doi:10.4172/2165-7556.1000e130

References

1. Outdoor Recreation Participation Report (2014) The Outdoor Foundation.
2. Olmedillas H, González-Agüero A, Moreno LA, Casajus JA, Vicente-Rodríguez G (2012) Cycling and bone health: a systematic review. BMC Med 10: 168.
3. Carmont MR (2008) Mountain biking injuries: a review. Br Med Bull 85: 101-112.
4. Warner SE, Shaw JM, Dalsky GP (2002) Bone mineral density of competitive male mountain and road cyclists. Bone 30: 281-286.
5. Carmont MR (2014) Mountain Bike Injuries injuries See Mountain biking injuries: An Overview. Sports Injuries 2014: 1-10.
6. Sabeti-Aschraf M, Serek M, Geisler M, Schmidt MI, Pachtner T, et al. (2010)Overuse Injuries Correlated to the Mountain Bike's Adjustment: A Prospective Field Study. Open Sports Sciences Journal 3: 1-6.
7. Vibert D, Redfield RC, Häusler R (2007) Benign paroxysmal positional vertigo in mountain bikers. Ann Otol Rhinol Laryngol 116: 887-890.
8. Macdermid PW, Fink PW, Stannard SR (2014) Transference of 3D accelerations during cross country mountain biking. J Biomech 47: 1829-1837.
9. Hurst HT, Swarén M, Hébert-Losier K, Ericsson F, Sinclair J, et al. (2012) Influence of course type on upper body muscle activity in elite Cross-Country and Downhill mountain bikers during off Road Downhill Cycling. J Sci Cycling 1: 2-9.
10. Berry M, et al. (1993) The effects of a mountain bike suspension system on metabolic energy expenditure. Cycling Sci 3: 8-14.
11. Seifert JG, Luetkemeier MJ, Spencer MK, Miller D, Burke ER (1997)The effects of mountain bike suspension systems on energy expenditure, physical exertion, and time trial performance during mountain bicycling. International journal of sports medicine 18: 197-200.
12. MacRae HS-H, Hise KJ, Allen PJ (2000) Effects of front and dual suspension mountain bike systems on uphill cycling performance. Med Sci Sports Exerc 32: 1276-1280.
13. Faiss R, Praz M, Meichtry A, Gobelet C, Deriaz O (2007) The effect of mountain bike suspensions on vibrations and off-road uphill performance. J Sports Med Phys Fitness 47: 151-158.
14. Wang EL, Hull ML (1996) A Model for Determining Rider Induced Energy Losses in Bicycle Suspension Systems. Vehicle System Dynamics 25: 223-246.