

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

Quantification and description of braking during mountain biking using a novel brake power meter

A thesis presented in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

in

Sport & Exercise Science

at Massey University, Palmerston North, New Zealand.

Matthew Curtis Miller

Bachelor of Science in Exercise Science

Master of Science in Exercise Science

2017

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. This thesis was completed under the guidelines set by Massey University's College of Health, for the degree of Doctor of Philosophy and has not been submitted for a degree or diploma at any other academic institution.

Candidate: _____

Date: _____

Foreword

When I came to New Zealand to do my PhD, I wasn't very sure of what I wanted to study. I knew I wanted to study mountain biking, but it's such a diverse sport with many genres, and I really had no clear direction of where my studies would go. However, one thing was for sure: I was in the right place!

My supervisory team had what I felt was a good mixture of specialities within Sport & Exercise Science, and the further I went through my research, the more I understood the perfect mixture of talent surrounding me. Strangely, while this same team had previously paved the way to new ideas in mountain biking research, I was given full liberty to shape my own ideas and make my own mistakes.

The brake power meter idea was born during an actual mountain bike competition. I found myself racing against my supervisor, Steve, who was much more fit than myself. As we continued the race and I could hear Steve's squeaky brakes, I knew the only reason I was able to keep up with him was for not braking myself.

Rather than being told it was a silly idea to measure braking for my PhD, I was taught how to apply for funding, given advice on what kind of variables we should measure, and had conversations on how we might run experiments. It was these kinds of events that taught me the depth of expertise and highly innovative scientists I'm surrounded by. I've been tested more than I ever expected throughout this process, but have gained knowledge and experience beyond that of sports experiments.

Thank you for believing in me.

Acknowledgements

Acknowledgements

Thank you to my family and friends for motivating me and assuring me that this process will be worth it in the end. GUNAX LBH GB ZL FGVAXL.

Thank you to Giant Bicycles NZ and Crank It Cycles for their generous equipment support in each experimental study and for my own cycling adventures.

Thank you to Massey Ventures Limited, Massey University and SENSITIVUS Gauge for supporting the commercial advancement of the Brake Power Meter.

This is for the haters.

Publications & Presentations

Publications

Miller, M. C., Fink, P. W., Macdermid, P. W., & Stannard, S. R. (2017). Validation of a normalized brake work algorithm designed to output a single metric to predict non-propulsive mountain bike performance. (IN REVIEW).

Miller, M. C., Fink, P. W., Macdermid, P. W., & Stannard, S. R. (2017). Calculation of brake power during skidding in road and off-road cycling conditions. (IN REVIEW).

Miller, M. C., Macdermid, P. W., Fink, P. W., & Stannard, S. R. (2017). Magnitude differences in braking variables and their effects on performance when comparing experienced and inexperienced mountain bikers navigating and isolated off-road turn. (IN REVIEW).

Miller, M. C., Fink, P. W., Macdermid, P. W., & Stannard, S. R. (2017). Quantification of brake data acquired with a brake power meter during simulated cross-country mountain bike racing. *Sports Biomechanics* (IN PRESS).

Miller, M. C., Fink, P. W., Macdermid, P. W., Perry, B. G., & Stannard, S. R. (2017). Validity of a device designed to measure braking power in bicycle disc brakes. *Sports Biomechanics*, 1-11. Macdermid, P. W., Miller, M. C., Fink, P. W., & Stannard, S. R. (2017). The effectiveness of front fork systems at damping accelerations during isolated aspects specific to cross-country mountain biking. *Sports Biomechanics*, 1-13.

Miller, M.C., Macdermid, P. W., Fink, P. W., and Stannard, S. R., (2017). Performance and physiological effects of different descending strategies for cross-country mountain biking. *European Journal of Sport Science*, **17**(3): p. 279-285.

Macdermid, P. W., Fink, P. W., Miller, M. C., and Stannard, S., (2017). The impact of uphill cycling and bicycle suspension on downhill performance during cross-country mountain biking. *Journal of Sports Sciences*, 1-9.

Miller, M. C., Macdermid, P., Fink, P., and Stannard, S. Agreement between Powertap, Quarq and Stages power meters for cross-country mountain biking (2016). *Sports Technology*, p. 1-7.

Stannard, S., Macdermid, P., **Miller, M**. C., and Fink, P., The power of cycling (2015). *Movement, Health & Exercise*, 4(2).

Miller M. C., Macdermid P. W. Ergonomic Strategies Related to Health and Efficiency in Mountain Biking (2015). *Journal of Ergonomics* 5:e139.

Miller, M. C., & Macdermid, P. (2015). Predictive validity of critical power, the onset of blood lactate and anaerobic capacity for cross-country mountain bike race performance. *Sport and Exercise Medicine Open Journal*, 1(4), 105-110.

Macdermid, P. W, **Miller, M. C.**, Macdermid, F. M., & Fink, P. W. (2015). Tyre Volume and Pressure Effects on Impact Attenuation during Mountain Bike Riding. *Shock and Vibration*, 10.

Miller, M. C., Moir, G. L., & Stannard, S. R. (2014). Validity of using functional threshold power and intermittent power to predict cross-country mountain bike race outcome. *Journal of Science and Cycling*, *3*(1), 16.

Conference Presentations

Matthew C. Miller, Philip W. Fink, Paul W. Macdermid, Steven R. Stannard (2017). The utilization of a bicycle brake power meter for cross-country mountain biking. Australian Strength and Conditioning Association, Gold Coast, Australia, 10-12 Nov

Matthew C. Miller, Paul W. Macdermid, Philip W. Fink, Steven R. Stannard (2016). Performance and physiological effect of different pacing strategies for mountain bike racing. European College of Sports Science, Vienna, Austria, July 9

Matthew C. Miller, Chad A. Witmer, Gavin L. Moir, Shala E. Davis (2014). The Predictive Validity of Critical Power and Functional Threshold Power for Mountain Bike Race Performance. Tsukuba Summer Institute, Tsukuba University, Japan, July 23

Matthew C. Miller, Chad A. Witmer, Gavin L. Moir, Shala E. Davis (2014). The Predictive Validity of Critical Power and Functional Threshold Power for Mountain Bike Race Performance. ACSM Annual Meeting, Orlando, FL, USA May 27-31

Emily J. Sauers, **Matthew C. Miller**, Benjamin Sina, Bryce J. Muth, Brandon W. Snyder, Shala E. Davis (2014). Effects of Full-fat and Fat-free Chocolate Milk On Recovery Following Endurance Running. ACSM Annual Meeting, Orlando, FL, USA May 27-31

Abstract

Olympic format cross country mountain biking is both physically and technically demanding. The demands of this cycling genre are in contrast to road cycling because of the demanding off-road terrain. With its many obstacles and different surfaces, riders must make their way up and over steep hills a number of times throughout a lap. It's very easy to be able to measure the performance of the riders on ascending sections of the track thanks to on-the-bike personal power meter that measure the propulsive work rates in the pedals. However, there is currently no commercially available method to assess the way the rider handles the bike on descending sections. This thesis first highlighted the differences in physiological demand of descending on off-road versus on-road (Chapter 4). An interesting finding in Chapter 4 also showed that riders might be able to save energy by adopting a coasting strategy down hills. This caused the researchers to question the bicycle handling attributes that might allow this, which led to the development and validation of a device designed to measure how the rider uses the brakes while riding/racing (Chapter 5). From there, we completed an investigation akin to the early mountain biking descriptive studies (Chapter 6), but instead of focusing on data related to respiratory and metabolic load, the brake power meter was employed. The finding that braking patterns were related to mountain biking performance was not surprising, but being the first team to quantify this was very exciting. Since most of the braking was occurring on the descents in that study, we examined the differences in braking between training groups on an isolated turn (Chapter 7). The finding that inexperienced riders use their brakes differently—and that this results in reduced performance—left no doubt to the importance of braking. From there, we revisited the method used to calculate rear brake power, since current methods led to inaccurate measurement during skidding

(**Chapter 8**). This thesis culminated with the exploration of an algorithm that could quickly and easily describe mountain bike descending performance with one single metric (**Chapter 9**); the hope is that the normalized brake work algorithm should increase the utility of the brake power meter for training purposes and post-competition performance analysis. Overall, this thesis highlights the need, importance and utility of a bicycle brake power meter to assess mountain bike performance.

List of Abbreviations

- ANOVA analysis of variance
- AT aerobic threshold
- CP critical power
- DH downhill (descending) terrain
- E_K kinetic energy
- F force
- FTP Functional threshold power
- HR heart rate
- I inertia
- IP intermittent power
- J joule
- LT lactate threshold
- FLAT flat terrain
- m meters
- ω (omega) angular velocity
- OBLA onset of blood lactate
- r radius
- RCP respiratory compensation point
- rad radians
- RMS root mean square
- s seconds
- SD standard deviation
- t-time

au - torque

TRIMPS - training impulse

UP - uphill (ascending) terrain

v - velocity

 $VO_2-volume \ of \ oxygen \ uptake$

W-watt

 W^l – anaerobic work capacity

XCO-MTB – Olympic format cross-country mountain bike racing

Table of Contents

Student Dec	larationi
Foreword	ii
Acknowledg	gementsiv
Publications	& Presentationsv
Abstract	ix
List of Abbr	reviations xi
Table of Co	ntentsxiii
List of Figur	resxvii
List of Table	esxxi
Chapter 1	
INTRODUC	CTION 1
Chapter 2	
REVIEW O	F LITERATURE
2.1	Demands of Olympic format cross-country mountain bike racing4
2.2	Indices of performance
2.3	Performance analysis and technological tools15
2.4	Descending performance
Chapter 3	
AIMS & ST	RUCTURE
3.1	Background
3.2	Aims
3.3	Thesis structure
Chapter 4	

PERFORMA	ANCE AND	PHYSIOLOGICAL	EFFECTS	OF	DIFFERENT
DESCENDI	NG STRATEGIE	ES FOR CROSS-COU	NTRY MOU	INTAI	N BIKING.34
4.1	Abstract				
4.2	Introduction				
4.3	Methods				
4.4	Results				
4.5	Discussion				
4.6	Conclusion				
Chapter 5					55
VALIDITY	OF A DEVICE	DESIGNED TO ME	EASURE BR	AKINO	G POWER IN
BICYCLE D	ISC BRAKES				
5.1	Abstract				55
5.2	Introduction				
5.3	Methods				60
5.4	Results				69
5.5	Discussion and	Implications			73
5.6	Conclusion				79
Chapter 6					
QUANTIFIC	CATION OF BR	AKE DATA ACQUI	RED WITH	A BR	AKE POWER
METER DU	RING SIMULAT	TED CROSS-COUNT	RY MOUN	TAIN E	SIKING 81
6.1	Abstract				
6.2	Introduction				
6.3	Methods				
6.4	Results				91
6.5	Discussion and	Implications			97
6.6	Conclusion				

Chapter 7	
MAGNITUI	DE DIFFERENCES IN BRAKING VARIABLES AND THEIR
EFFECTS (ON PERFORMANCE WHEN COMPARING EXPERIENCED AND
INEXPERIE	ENCED MOUNTAIN BIKERS NAVIGATING AN ISOLATED OFF-
ROAD TUR	2N
7.1	Abstract 107
7.2	Introduction
7.3	Methods
7.4	Results 115
7.5	Discussion
7.6	Conclusion
Chapter 8	
CALCULA	TION OF REAR BRAKE POWER DURING SKIDDING IN ROAD AND
OFF-ROAD	CYCLING CONDITIONS
8.1	Abstract
8.2	Introduction
8.3	Methods
8.4	Results
8.5	Discussion and Implications
8.6	Limitations and Conclusion
Chapter 9	
VALIDATI	ON OF A NORMALIZED BRAKE WORK ALGORITHM DESIGNED
TO OUTPU	T A SINGLE METRIC TO PREDICT NON-PROPULSIVE MOUNTAIN
BIKE PERF	ORMANCE
9.1	Abstract
9.2	Introduction
9.3	Methods146

	9.1	Results
	9.2	Discussion and Implications155
	9.3	Conclusion
Chapter 1	10	
DISCU	JSSIO	N163
	10.1	General discussion
	10.2	Practical applications167
	10.3	Thesis limitations174
	10.4	Conclusions
Appendic	ces	
Appen	dix I	
Referenc	es	

List of Figures

Figure 2.1 Elevation profile of the XCO-MTB World Championships in Canberra,
Australia in 2009 was originally published by Abbiss <i>et al.</i> (2013)
Figure 2.2 Elevation profile, propulsive power output and physiological variables (heart
rate and VO ₂) from one individual during a simulated XCO-MTB race. This figure
appeared in Macdermid & Stannard, 2012
Figure 2.3 Example of placement of accelerometers for use in measuring vibrations
during cycling. This photo was first published by Macdermid <i>et al.</i> (2014)9
Figure 2.4 Example of a functional (albeit dirty) propulsive power meter located within
the chainring spider of a mountain bike crank set
Figure 2.5 Some of the cycling metrics used by cycling practitioners presented from
TrainingPeaks software. It is not expected that all this data is useful to the untrained eye.
Figure 2.6 Power (W; pink), heart rate (BPM; red) and elevation (Feet; grey) collected
from one competitive cyclist during actual racing using TrainingPeaks software 20
Figure 3.1. Thesis structure schematic
Figure 4.1 Descent profiles with elevation (m) for A. DH_C and $DH_P(1.01$ km, -16.3%
gradient), and B. DH _R (1.03 km, -15.7%)
Figure 4.2 Mean \pm SD for values of A. Heart Rate (bpm) and B. VO ₂ (ml·min ⁻¹ ·kg ⁻¹) and
C. Time (s)
Figure 4.3 Mean \pm SD of A. heart rate (bpm) and B. VO ₂ (ml·min ⁻¹ ·kg ⁻¹) continuously
sampled and reduced to 15 s averages
Figure 4.4 Comparison between DH _C , DH _P and DH _R for total accelerations
Figure 5.1 Non-drive side view of bike with A: data logger; B: front brake power meter;
and C: rear brake power meter

Figure 5.4. Braking example using both front and rear brakes highlighting measurements of brake torque (A-B), angular velocity of the brake rotor (C-D) and resultant brake power (E-F). Initial velocity was 3.7 m/s slowing a combined mass of 79.2 kg (rider plus cycling gear and bicycle) to 2.6 m/s. Sample duration was 0.9 s with a total brake work of 231 J. Mean brake power was 166 and 106 W for the front and rear brakes, respectively. 76

Figure 5.5. Braking example using front brake only. Mean power was 105 and 6 W for the front and rear brakes, respectively. Sample duration was 2.9 s with a total brake work of 322.0 J. Initial velocity was 3.63 m/slowing a 79.2 kg mass to 1.7 m/s with subsequent Figure 6.1. Lap profile for XCO-MTB time trial. The track was 1,240 m long and had 45 Figure 6.2. A. Brake Work (J), B. Brake Time (s), and C. Brake Power (W) for front Figure 6.4. Example of braking and propulsive data for one participant on lap 1 (A) and lap 3 (B). The participant was a 22-year-old male weighing 68.5 kg with gear, had a VO2max of 73.1 ml/kg/min and was competitive in international races. For lap 1, braking variables were 20342 J, 28.3 s and 719 W for brake work, brake time and brake power, respectively. Average propulsive power was 328 W with resultant lap duration of 263.3 s. For lap 3, braking variables were 18461 J, 27.0 s and 683 W for brake work, brake time and brake power, respectively. Average propulsive power was 306 W with resultant lap

Figure 7.1. Schematic representation of the off-road track and turn highlighting profiles for terrain sections (A-D= distance, gradient; A= 14.50 m, -16%; B= 35.80 m, -16%; C=

13.65 m, 0%; D= 13.65 m, 0%), which were measured with a trundle wheel. Black dots represent boundary for each section
Figure 7.2. Two-way analyses for relative brake work (J/kg; A), brake time (s; B) and relative brake power (W/kg; C) for Experienced and Inexperienced groups 120
Figure 7.3. Example trace of relative brake power of one experienced (black) and one inexperienced (grey) riders throughout respective (A-D) sections of the track. The respective mass of each rider (plus cycling gear) was not overly dissimilar (63.6 and 64.8 kg, respectively). Relative brake work, brake time, and relative brake power were 33.36 J/kg, 2.46 s, and 13.57 W/kg for the experienced and 37.16 J/kg, 4.53 s, and 8.21 W/kg for the inexperienced rider, respectively. Individual braking strategies elicited performance time of 14.08 and 15.87 s for the experienced and inexperienced rider, respectively.
Figure 8.1. Correlation between the change in kinetic energy and adjusted energy removed from the bicycle-rider system
Figure 9.1. Elevation profile of the descending track used for testing in this study. The total distance was 1.01 km with a total elevation loss of 165 m (average gradient of -16.3%). This track was chosen based in its previous use which indicated that performance time was not dependent on propulsive work
Figure 9.2. The relationship between Performance Time (s) on the mountain bike descent and A) relative brake work (J/kg); B) brake time (s); C) relative brake power (W/kg); and D) normalized brake work
Figure 9.3. Graphical representation of normalized brake power (1/s) across a 150 m portion of the descent from one trial each by a high-performing and low-performing mountain biker. The normalized brake work was 0.13 and 0.80 for the high-performer and low-performer, respectively. The time to complete this section was 14.72 and 18.22 s for the high- and low-performer, respectively, which equated to 10.91 and 8.23 m/s, respectively.
Figure 9.4. Frequency distribution of normalized brake power (1/s) comparing a high- and low-performing mountain biker. Normalized brake power was separated in to 10 bins in 0.05 1/s steps, with values below 0.05 1/s removed from analysis and values above 0.5 1/s combined in the same bin

Figure 10.1 The Candidate with an early commercially viable prototype brake power
meter. Photo c. David Wiltshire, Massey University
Figure 10.2 An example of helmet video recording of the rider's view of the trail and the
braking trace completed throughout the trial

List of Tables

Table 2.1. These regression models were derived from Miller et al. (2014) and indicated
the strength of cycling field tests for XCO-MTB race prediction
Table 5.1. Mean \pm SD and range for mean power and derivatives during braking 70
Table 5.2. Mean ± SD and range for calculated variables of energy loss during braking.
Table 6.1. Descriptive performance data (mean \pm SD) per lap of a simulated XCO-MTB
time trial
Table 6.2. Multiple regression model incorporating brake time, brake work and relative
propulsive power to explain lap time
Table 7.1. Mean \pm SD of performance and braking variables between Experienced and
Inexperienced mountain bikers
Table 7.2. Mean \pm SD starting (Sections B-D) and maximum velocity (Sections A-D) for
Experienced and Inexperienced mountain bikers
Table 8.1. Mean \pm SD and range for calculated variables of energy loss during braking.
Table 9.1. Mean \pm SD for performance and braking variables