

**NOVEL ASSESSMENT OF GAIT AND MOBILITY FUNCTION  
IN TRANSTIBIAL AMPUTEES**

Submitted by Brenton Graham Hordacre  
BPhy (Hon), University of South Australia, Adelaide

For the Degree of Doctor of Philosophy in the  
Department of Rehabilitation, Aged and Extended Care  
School of Health Sciences, Faculty of Medicine, Nursing and Health Sciences  
Flinders University, Adelaide, Australia

Submitted August, 2014

## **TABLE OF CONTENTS**

<b>SUMMARY</b>	<b>x</b>
<b>PUBLICATIONS ARISING FROM THIS RESEARCH</b>	<b>xiv</b>
<b>DECLARATION</b>	<b>xvii</b>
<b>ACKNOWLEDGEMENTS</b>	<b>xix</b>
<b>LIST OF FIGURES</b>	<b>xxi</b>
<b>LIST OF TABLES</b>	<b>xxiv</b>
<b>LIST OF ABBREVIATIONS</b>	<b>xxvii</b>
<b>STRUCTURE OF THESIS</b>	<b>xxix</b>
<b>CHAPTER ONE: INTRODUCTION</b>	<b>1</b>
1.1 Introduction	2
1.1.1 Amputee rehabilitation service	2
1.1.2 Characterising gait and mobility function	3
1.1.2.1 Gait variability to assess function	4
1.1.2.2 Wearable technology to assess community function	5
1.1.2.3 Neurophysiological biomarkers of function	6
1.2 Research Objectives	7
<b>CHAPTER TWO: LITERATURE REVIEW</b>	<b>9</b>
2.1 Amputation	10
2.1.1 Etiology of lower-limb amputation	10
2.2 Challenges Facing Amputee Rehabilitation Services	12
2.2.1 How can these challenges be addressed?	13

2.3 Scope of Thesis	14
2.4 Amputee Rehabilitation Services in Australia	16
2.4.1 Review of prosthetic rehabilitation outcomes	17
2.5 Spatial-Temporal Gait Variability to Assess Gait Function	18
2.5.1 Gait variability	19
2.5.2 Falls	20
2.5.3 Test protocols for gait variability	21
2.5.4 Gait variability in lower-limb amputees	22
2.6 Wearable Technology to Assess Community Mobility	24
2.6.1 Activity and participation	25
2.6.2 Current assessment of activity and participation	27
2.6.3 Wearable technology to assess activity and participation	30
2.6.3.1 Accelerometers	30
2.6.3.2 Global positioning system	31
2.6.3.3 How has GPS aided rehabilitation?	32
2.6.3.4 Wearable technology to assess function in lower-limb amputees	34
2.7 Amputee Neurophysiology and Motor Control	37
2.7.1 Neuroplasticity	38
2.7.1.1 Neuroplasticity resulting from amputation of a limb	38
2.7.1.2 Modulation of cortical excitability following amputation	45
2.7.2 The Ipsilateral Cortex	46
2.7.2.1 Functional implication of the ipsilateral M1	50
2.7.3 Motor control	50
2.7.3.1 Motor control of locomotion in animals	50
2.7.3.2 Motor control of locomotion in humans	52

2.7.3.3 Bilateral cortical innervation of proximal lower-limb muscles	53
2.7.4 Ipsilateral M1 and motor control	55
2.7.5 Neurophysiological biomarkers of function	56
2.7.6 Transcranial magnetic stimulation as a tool to identify neurophysiological biomarkers of function	57
2.7.7 Summary of amputee neurophysiology and motor control	62
2.8 Literature Review Summary	62

## **CHAPTER THREE: LOWER-LIMB AMPUTEE REHABILITATION IN AUSTRALIA: ANALYSIS OF A NATIONAL DATA SET 2004 - 2010**

	<b>64</b>
3.1 Abstract	66
3.2 Introduction	67
3.3 Methods	68
3.3.1 Design	68
3.3.2 AROC dataset	69
3.3.3 Analysis	71
3.4 Results	72
3.4.1 Episodes	72
3.4.2 Demographics	73
3.4.3 Clinical characteristics	74
3.4.4 Rehabilitation outcomes	76
3.5 Discussion	81
3.6 Conclusion	84

**CHAPTER FOUR: PHYSIOTHERAPY REHABILITATION FOR  
INDIVIDUALS WITH LOWER-LIMB AMPUTATION: A 15 YEAR**

<b>CLINICAL SERIES</b>	<b>86</b>
4.1 Abstract	88
4.2 Introduction	90
4.3 Methods	94
4.3.1 Design	94
4.3.2 Subjects	94
4.3.3 Outcome measures	95
4.3.4 Data analysis	96
4.4 Results	97
4.4.1 Outcome of patients through rehabilitation	97
4.4.2 Patient demographics and clinical characteristics	98
4.4.3 Rehabilitation outcomes	100
4.4.4 Effect of demographics, clinical characteristics and the changing model of rehabilitation services on rehabilitation outcomes	102
4.5 Discussion	107
4.6 Conclusion	112

**CHAPTER FIVE: ASSESSING GAIT VARIABILITY IN  
TRANSTIBIAL AMPUTEE FALLERS BASED ON SPATIAL-  
TEMPORAL GAIT PARAMETERS NORMALISED FOR WALKING**

<b>SPEED</b>	<b>114</b>
5.1 Abstract	116
5.2 Introduction	118

5.3 Methods	119
5.3.1 Participants	119
5.3.2 Procedures	120
5.3.3 Analysis	122
5.4 Results	123
5.4.1 Non-normalised spatial-temporal gait variability	124
5.4.2 Normalised spatial-temporal gait variability	124
5.5 Discussion	126
5.6 Conclusion	127

**CHAPTER SIX: USE OF AN ACTIVITY MONITOR AND GPS  
DEVICE TO ASSESS COMMUNITY ACTIVITY AND  
PARTICIPATION IN TRANSTIBIAL AMPUTEES**

	<b>128</b>
6.1 Abstract	130
6.2 Introduction	132
6.3 Methods	136
6.3.1 Participants	136
6.3.2 Equipment	136
6.3.2.1 Step activity monitor	136
6.3.2.2 Global positioning system	137
6.3.3 Procedure	137
6.3.4 Data analysis	140
6.3.4.1 Data linkage	140
6.3.4.2 Statistical analysis	142
6.4 Results	144

6.5 Discussion	156
6.6 Conclusions	163
 <b>CHAPTER SEVEN: CORTICOMOTOR EXCITABILITY</b>	
<b>ASSOCIATION WITH GAIT VARIABILITY IN TRANSTIBIAL</b>	
<b>AMPUTEES</b>	
	<b>165</b>
7.1 Abstract	167
7.2 Introduction	169
7.3 Materials and Methods	171
7.3.1 Participants	171
7.3.2 Protocol	174
7.3.3 Electromyography	174
7.3.4 Transcranial magnetic stimulation	174
7.3.5 Spatial-temporal gait variability	178
7.3.6 Data analysis	179
7.3.6.1 Corticomotor excitability	179
7.3.6.2 Functional gait variability	180
7.3.6.3 Corticomotor excitability and gait function	180
7.4 Results	181
7.4.1 Corticomotor excitability measures	181
7.4.2 Functional gait variability	183
7.4.3 Corticomotor excitability and gait function	184
7.5 Discussion	186
7.6 Conclusion	193

## **CHAPTER EIGHT: REORGANISATION OF THE PRIMARY MOTOR**

### **CORTEX FOLLOWING LOWER-LIMB AMPUTATION 194**

8.1 Abstract	196
8.2 Introduction	198
8.3 Methods	201
8.3.1 Participants	201
8.3.2 Protocol	201
8.3.3 Electromyography	202
8.3.4 Transcranial magnetic stimulation	202
8.3.5 Spatial-temporal gait variability	204
8.3.6 Data analysis	205
8.3.6.1 Demographics	205
8.3.6.2 Neurophysiological assessments pre and post amputation	205
8.3.6.3 Neurophysiological assessments through prosthetic rehabilitation	206
8.3.6.4 Association with gait function	207
8.4 Results	207
8.4.1 Demographics	207
8.4.2 Neurophysiological assessment of impending amputees and controls	208
8.4.3 Neurophysiological assessments through prosthetic rehabilitation	211
8.4.4 Association with gait function	217
8.5 Discussion	220
8.6 Conclusion	230

### **CHAPTER NINE: DISCUSSION AND FUTURE RESEARCH 232**

9.1 Discussion	234
----------------	-----

9.2 Challenges Facing Lower-Limb Amputee Rehabilitation Units in Australia	236
9.3 Speed Normalised Gait Variability is Associated with Falls History	237
9.4 Wearable Technology is Feasible to Assess Community Mobility Function	241
9.5 TMS Measures as Neurophysiological Biomarkers of Gait Function	245
9.5.1 ICE as a neurophysiological biomarker of gait function	246
9.5.2 SICI as a neurophysiological biomarker of gait function	248
9.5.3 Neurophysiological biomarker summary	250
9.6 Limitations	251
9.7 Future Research Directions	256
9.8 Conclusion	260
<b>APPENDICES</b>	<b>262</b>
<b>REFERENCES</b>	<b>264</b>

## SUMMARY

Lower-limb amputees require extensive rehabilitation to restore gait and mobility function and achieve successful re-integration into the community. Decreasing length of hospital stays and resources shortages have increased the need for more efficient treatment to hasten recovery. However, complex issues such as older age, various levels of amputation and associated comorbidities pose additional challenges to the restoration of gait and mobility function. Much research into lower-limb amputees has focussed on vascular interventions and prosthetic technology, with limited literature investigating alternative approaches to characterise gait and mobility function. A good understanding of issues influencing amputee rehabilitation is necessary to help identify aspects of amputee rehabilitation requiring attention and to drive more effective and efficient rehabilitation approaches. New assessments of gait and mobility function have the potential to progress our understanding of lower-limb amputee rehabilitation. The purpose of this thesis was to investigate novel assessments of gait and mobility function in transtibial amputees. These assessments were investigated from a clinical rehabilitation perspective to determine their potential contribution to future amputee rehabilitation.

There are four sections to this thesis. The first section established the state of amputee rehabilitation in Australia by reviewing contemporary data from amputee rehabilitation services at a national level ( $n = 6,588$ ), and from a single regional rehabilitation service ( $n = 531$ ). Trends for increasing length of stay and decreasing age were identified. Many amputees (43.4%) presented with multiple comorbidities. Time to achieve key rehabilitation milestones increased over the period of

observation. These findings identified shifts in patient characteristics which affected the timely and optimal restoration of function by amputee rehabilitation services.

New and novel assessments of gait and mobility function may assist future amputee rehabilitation and should be investigated. Greater understanding of amputee gait and mobility may allow for more efficient functional assessments and identify individuals likely to need additional therapy input, assisting rehabilitation units in planning and prioritising treatment.

The second section of the thesis investigated the potential that spatial-temporal gait variability has as a measure of gait function in transtibial amputees. Forty-seven community dwelling amputees were recruited from the single prosthetic rehabilitation facility reviewed in the first section of this thesis. The influence of intra-subject gait speed variability was examined and the variability of speed normalised spatial-temporal gait parameters was calculated for individual participants. Greater normalised gait variability was observed in amputees with a history of falls. This study identified that gait variability may be an important measure of gait function and additionally demonstrated the importance of normalising for walking speed in the analysis of gait variability.

The third section of the thesis investigated wearable technology as a novel method to assess community activity and participation. Amputees recruited for the previous gait variability study also participated in this experiment. Data from an accelerometer based device to assess step counts, and a global positioning system (GPS) to assess community visits, were linked to identify community activity and participation.

Measures of activity and participation in the community were negatively associated

with normalised gait variability, further suggesting gait variability is an important clinical marker of gait function.

The final section of the thesis investigated the use of transcranial magnetic stimulation to determine if neurophysiological measures of brain function may assist clinical practice as neural biomarkers of gait function. A subset of community living transtibial amputees who had participated in the previous studies were recruited. A ratio of corticomotor excitability of ipsilateral and contralateral projections to the amputated limb (index of corticospinal excitability, ICE) was calculated. Relatively greater excitability of ipsilateral compared to contralateral projections to motoneurons innervating residual muscles of the amputated limb was associated with increased normalised gait variability. Further investigation of the contribution of ipsilateral and contralateral motor cortex to gait function was conducted in amputees completing prosthetic rehabilitation. Bilateral reorganisation of the motor cortex occurred following lower-limb amputation and continued through prosthetic rehabilitation. Intracortical inhibition within a hemisphere at key phases of rehabilitation was predictive of gait function at discharge. For the contralateral motor cortex, reduced intracortical inhibition at admission to rehabilitation and when undertaking first walk with a prosthetic limb was associated better gait function. However, for the ipsilateral motor cortex, reduced intracortical inhibition at discharge from rehabilitation was associated with poor gait function. Combining outcomes from these two studies, it appears that ongoing cortical reorganisation of the ipsilateral motor cortex following rehabilitation is associated with poor gait function. Both ICE and intracortical inhibition may be appropriate neurophysiological biomarkers of gait function in transtibial amputees.

In summary, three aspects of gait and mobility function in transtibial amputees were investigated. These findings expand current understanding of amputee gait and mobility and demonstrate the importance of investigating alternative assessments that may improve outcomes of clinical rehabilitation. The results of the work in this thesis have potential to improve understanding and knowledge of transtibial amputee rehabilitation and may inform future studies to improve outcomes of amputee rehabilitation.

## **PUBLICATIONS ARISING FROM THIS RESEARCH**

### **Refereed manuscripts**

Hordacre, B, Bradnam, L, Barr, C, Patritti, BL & Crotty, M 2014, 'Ipsilateral corticomotor excitability is associated with increased gait variability in unilateral transtibial amputees', *European Journal of Neuroscience*, vol. 40, no. 2, pp. 2454-62.

Hordacre, B, Barr, C & Crotty, M 2014, 'Use of an activity monitor and GPS device to assess community activity and participation in transtibial amputees', *Sensors*, vol. 14, no. 4, pp. 5845-59.

Hordacre, B & Bradnam, L 2013, 'Reorganisation of primary motor cortex in a transtibial amputee during rehabilitation: A case report', *Clinical Neurophysiology*, vol. 124, no. 9, pp. 1919-21.

Hordacre, B, Birks, V, Quinn, S, Barr, C, Patritti, BL & Crotty, M 2013, 'Physiotherapy rehabilitation for individuals with lower limb amputation: a 15-year clinical series', *Physiotherapy Research International*, vol. 18, no. 2, pp. 70-80.

Hordacre, BG, Stevermuer, T, Simmonds, F, Crotty, M & Eagar, K 2013, 'Lower-limb amputee rehabilitation in Australia: Analysis of a national data set 2004-10', *Australian Health Review*, vol. 37, no. 1, pp. 41-7.

**Invited conference concurrent session presentations**

Hordacre, B, Bradnam, L, Barr, C, Patrilli, BL & Crotty, M 2013, 'Emerging Technologies In Amputee Rehabilitation: “What will the Future Look Like?”', paper presented to 2<sup>nd</sup> Singapore Rehabilitation Conference, Singapore.

**Conference abstracts**

Hordacre, B, Bradnam, L, Barr, C, Patrilli, BL & Crotty, M 2014, 'Influence of the ipsilateral motor cortex on functional performance in unilateral transtibial amputees', paper presented to Australasian Military Medicine Association, Adelaide, Australia.

Hordacre, B, Bradnam, L, Barr, C, Patrilli, BL & Crotty, M 2014, 'Reorganisation of the primary motor cortex in amputees undertaking prosthetic rehabilitation', paper presented to Australasian Neuroscience Society: Sensorimotor Satellite Meeting, Adelaide, Australia.

Hordacre, B, Bradnam, L, Barr, C, Patrilli, BL & Crotty, M 2013, 'The relationship of ipsilateral and contralateral projections to the quadriceps on control of gait and balance in transtibial amputees', paper presented to Australasian Brain Stimulation Meeting, Melbourne, Australia.

Hordacre, B, Bradnam, L & Crotty, M 2013, 'Reorganisation of the primary motor cortex in amputees undertaking prosthetic rehabilitation', paper presented to Australasian Brain Stimulation Meeting, Melbourne, Australia.

Hordacre, B, Bradnam, L, Barr, C, Patrilli, BL & Crotty, M 2012, 'Influence of the ipsilateral motor cortex on functional performance in unilateral transtibial amputees', paper presented to New Zealand Applied Neuroscience Conference, Auckland, New Zealand.

Hordacre, B, Birks, V, Quinn, S, Barr, C, Patrilli, B & Crotty, M 2011, 'Changes in rehabilitation outcomes of lower limb amputees over 15 years: A clinical series', paper presented to Annual Scientific Meeting of ISPO Australia, Sydney, Australia.

#### **Accepted conference abstracts**

Hordacre, B, Barr, C & Crotty, M 2014, 'Wearable technology to assess community activity and participation in transtibial amputees', paper presented to 22nd Annual Scientific Meeting of the Australasian Faculty of Rehabilitation Medicine, Adelaide, Australia.

## **DECLARATION**

I certify that this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge I believe it does not contain any material previously published or written by another person except where due reference is made in the text.

The study in chapter three was conceived by myself and MC. I was responsible for applying for ethical approval. Data were obtained from the Australasian Rehabilitation Outcomes Centre (Wollongong, NSW). Data analyses were performed by myself under the guidance of TS. Interpretation of the data was completed by myself and MC. I was responsible for drafting the manuscript, and TS, FS, MC, KE reviewed the manuscript. The study in chapter four was conceived by myself, CB, BP and MC. I was responsible for applying for ethical approval. Data were collected by VB. I conducted data analyses under guidance from SQ. Interpretation of the data were completed by myself, CB, BP and MC. I was responsible for drafting the manuscript, and VB, SQ, CB, BP, MC reviewed the manuscript. The study in chapter five was conceived by myself and CB. I was responsible for applying for ethical approval, participant screening and recruitment, data collection, analysis and interpretation. I was responsible for drafting the manuscript, and CB, BP and MC reviewed the manuscript. The study in chapter six was conceived by myself and CB. I was responsible for applying for ethical approval, participant screening and recruitment, data collection and analysis. Interpretation of data was completed by myself and CB. I was responsible for drafting the manuscript, and CB, BP and MC reviewed the manuscript. The study in chapter seven was conceived by myself and

LB. I was responsible for applying for ethical approval, participant screening and recruitment, data collection and analysis. Interpretation of data was completed by myself and LB. I was responsible for drafting the manuscript, and LB, CB, BP and MC reviewed the manuscript. The study in chapter eight was conceived by myself and LB. I was responsible for applying for ethical approval, participant screening and recruitment, data collection and analysis. Interpretation of data was completed by myself and LB. I was responsible for drafting the manuscript, and LB and MC reviewed the manuscript.

I took a leadership role in preparing all manuscripts for submission to journals, and responding to reviewer comments. These responses were reviewed by all co-authors before re-submitting to the journals.

The funding source for the duration of the PhD was the Australian Postgraduate Award Scholarship.

## **ACKNOWLEDGEMENTS**

There are a number of people who have been of great assistance along my PhD journey. Firstly I would like to thank all participants who volunteered their time to participate in these studies. Without their assistance, completing this thesis would have been very difficult. I am therefore very grateful for their willingness to participate, and making my PhD journey easier.

I also would like to thank the support and assistance of my supervisors, Professor Maria Crotty, Associate Professor Lynley Bradnam, Doctor Christopher Barr and Doctor Benjamin Patrilli. I consider myself lucky to have had four different supervisors who are experts in their fields of research. I particularly thank them for their time and effort in helping me develop my research skills.

I would like to acknowledge both the Physiotherapy Department at the Repatriation General Hospital and Orthotics and Prosthetics South Australia for their assistance over the past four years. I would particularly like to acknowledge Vicki Birks in the Physiotherapy Department for her continual assistance and expertise in amputee rehabilitation. I would also like to thank Sally Cavenett and the prosthetists at Orthotics and Prosthetics South Australia for their assistance with participant recruitment and technical knowledge of prosthetics which was often called upon throughout my candidature.

I am grateful for the expertise of Dr Charitha Perera from the Department of Rehabilitation and Aged Care at the Repatriation General Hospital for assistance

with medical screening for studies in this thesis. Without Dr Perera's assistance and advice regarding medical conditions these studies could not have been completed safely.

I would like to acknowledge the funding provided to me from the Australian Postgraduate Award Scholarship. In addition I wish to thank the Physiotherapy Department at the Repatriation General Hospital who provided me with the opportunity to continue to work as a Physiotherapist throughout my candidature.

Finally, I would like to thank my family for their patients and encouragement throughout my candidature. In particular I would like to thank my wife, Monica, for her continual support and willingness to provide feedback on my ideas and thoughts over the past few years.