Trunk Function and Ischial Tissue Health in Spinal Cord Injury

by

Sharon Gabison

A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
Institute of Medical Science
University of Toronto

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Doctor of Philosophy
Institute of Medical Science
University of Toronto
2018

Abstract

Pressure injuries are a common secondary complication following spinal cord injury (SCI). Since individuals with SCI have sensorimotor impairments, they neither can feel pain associated with tissue damage due to prolonged unrelieved pressure nor are able to prevent pressure injuries due to mobility impairments. Deep tissue injury is a form of pressure injuries that occurs in the muscle and subcutaneous tissue before tissue breakdown appears at the skin surface.

This thesis attempted to address four research questions pertinent to deep tissue injury and offloading in individuals with SCI. First, we proposed a quantitative ultrasound imaging approach to characterize the integrity of the tissues overlying the ischial tuberosity. We demonstrated that the thickness and gray scale measures of the skin, subcutaneous tissue and muscle has potential to be used as a tissue health monitoring approach.

The second study investigated our ability to assess trunk strength and function using the multidirectional reach test. This study demonstrated that monitoring changes in trunk strength and reach distance could be used to assess trunk function in individuals with SCI.
The third prospective cross-sectional study aimed at determining if there is a relationship between trunk function and offloading of the ischial tuberosities in individuals with SCI. We discovered that trunk strength was significantly higher in people who were able to Reach compared to Non-Reachers, and that offloading times over the ischial tuberosities were lower in Non-Reachers vs. Reachers. Regardless of an individual’s ability to engage in a reaching task, participants with SCI spent more time offloading the left ischial tuberosity compared to the right ischial tuberosity.

The fourth exploratory prospective cross-sectional study compared thickness and texture measures of tissue overlying the ischial region in able-bodied vs. SCI participants. We discovered that the area occupied by muscle was significantly greater in the SCI participants when compared with the able-bodied cohort. Individuals who did not engage in offloading had more homogenous skin, subcutaneous tissue and muscle.

These studies represent the first step towards better understanding the relationships between offloading, trunk function and health of tissue overlying the ischial tuberosity in SCI population.
In memory of my father Dr. Raphael Gabison, who was unable to see the completion of a task that he so strongly encouraged me to do.

This thesis is dedicated to my children.
Acknowledgments

Undertaking a PhD while managing the responsibilities of family and a career could not have been possible without the incredible support that I have received by so many along my journey.

I am indebted to my thesis advisor Professor Molly Verrier who continually inspires me to do my best. Your mentorship, support and opening doors for me will forever be appreciated. You constantly challenge me and have expected nothing but the best. I am only so lucky that I had the opportunity to work under your supervision before your retirement.

Ethne, I am grateful for the 25-year history of mentorship in which you inspired a passion in me as a Physical Therapist with an interest in pressure injuries, wound care and electrophysical agents. Your guidance and constant challenge for enquiry is something I will forever cherish.

Milos, I first met you at Lyndhurst in your lab in 2007 while working on another project. Your welcoming and down to earth approach with a lab culture focused on expertise, collaboration and mentorship is something I could not have gone without while embarking on research after being out of school for so long. You provided a nice balance of being practical, approachable yet having very high standards.

Sunita, thank you for all your support over the many years that it has taken me to complete this project. Your attitude has made the work of doing a PhD nothing less than amazing. Your patience, knowledge, ideas and insight have been invaluable throughout my journey. You kept things ‘real’ when the going got tough. Your energy and enthusiasm for research is contagious.

To my partner Andy, we met long before I was planning on returning to school. I am in awe of your constant emotional support after spending your entire working day supporting others. You have put up with many weekends of me working in the presence of my laptop. What more can I ask from a partner?

To my family, thank you for all your support as I juggled the challenges of single parenting while maintaining an active career and completing this task that I’ve always wanted to do.
Most importantly, I would like to thank all the study participants who have devoted their time and energy to help advance research in Spinal Cord Injury and pressure injuries.
Contributions

This thesis was prepared exclusively by Sharon Gabison (author). The author performed the entire body of work including planning, execution, analysis and writing of all original research and publications in whole or in part. Contributions by the following individuals are hereby acknowledged:

Professor Molly Verrier (Primary Supervisor and Thesis Committee Member) who provided mentorship, laboratory resources, guidance and assistance in planning, execution, and analysis of experiments in addition to manuscript and thesis preparation.

Dr. Milos Popovic (Co-Supervisor and Thesis Committee Member) who provided mentorship; laboratory resources; guidance and assistance in planning, execution and analysis of experiments as well as manuscript/thesis preparation.

Dr. Sunita Mathur (Thesis Committee Member) who provided mentorship; laboratory resources; guidance in interpretation of results as well as manuscript/thesis preparation.

Dr. Ethne Nussbaum (Thesis Committee Member) who provided mentorship; equipment; guidance in interpretation of results as well as manuscript/thesis preparation.

Dr. Dany Gagnon who provided guidance and assistance in planning, and analysis of experiments for Chapter 3 and 4 and manuscript preparation for Chapters 3 and 4.

Dr. Sylvie Nadeau who provided guidance and assistance in planning, and analysis of experiments for Chapter 4 and manuscript preparation for Chapter 4.

Dr. Kei Masani (Assistant Professor, Scientist) who provided assistance in analysis of experiments for Chapter 5 and 6.

Dr. Masae Miyatani (Post-Doctoral Fellow) who provided guidance and assistance in planning, execution of experiments for Chapter 6.

Dr. Rahim Moineddin (Professor, Department of Family and Community Medicine) who provided statistical guidance of experiments for Chapters 5 and 6.
Gildas Thilon, Engineering Student, who developed the MATLAB program required for analysis of ultrasound images of experiments for Chapters 3, 5 and 6.
# Table of Contents

Acknowledgments .......................................................................................................................... v

Contributions ............................................................................................................................... vii

Table of Contents .......................................................................................................................... ix

List of Tables ................................................................................................................................. xiv

List of Figures ............................................................................................................................... xvi

List of Appendices ......................................................................................................................... xviii

List of Abbreviations ..................................................................................................................... xix

Glossary of Terms .......................................................................................................................... xx

Chapter 1 General Introduction ..................................................................................................... 1

1.1 Preamble ................................................................................................................................... 2

1.2. Thesis Organization ................................................................................................................ 3

Chapter 2 The Implications of Secondary Complications in Spinal Cord Injury and Tissue Health ................................................................................................................................. 4

2.1 Introduction ............................................................................................................................ 5

2.2 Spinal Cord Injury .................................................................................................................. 5

2.2.1 Secondary Complications following Spinal Cord Injury .................................................. 8

2.3 Trunk Function ....................................................................................................................... 9

2.3.1. Impaired Trunk Function ................................................................................................. 13

2.4 Tissue Health ........................................................................................................................ 15

2.4.1 Pressure Injuries .............................................................................................................. 25

2.4.1.1 Early Detection of Pressure Injuries ........................................................................... 29
2.4.2 Ultrasound Imaging to Assess Tissue Integrity ......................................................... 30
2.5 Loading the Ischial Tuberosity and Pressure Relief ..................................................... 32
2.6 Thesis Aims and Hypotheses ......................................................................................... 36

Chapter 3 The Exploration of Quantitative Ultrasound Imaging to Inform Tissue Assessment ........................................................................................................ 38

3.1 Abstract ......................................................................................................................... 39
3.2 Introduction ..................................................................................................................... 40
3.3 Materials and Methods .................................................................................................. 42
  3.3.1 Participants ................................................................................................................. 42
  3.3.2 Ultrasound Imaging Protocol ..................................................................................... 42
    3.3.2.1 Ultrasound Device .............................................................................................. 42
    3.3.2.2 Ultrasonographer ................................................................................................. 43
    3.3.2.3 Image acquisition ............................................................................................... 43
    3.3.2.4 Image Processing ................................................................................................. 44
  3.3.3 Statistical Analysis ..................................................................................................... 45
3.4 Results ........................................................................................................................... 46
  3.4.1 G-Study: Magnitude of Component Variances ......................................................... 50
  3.4.2 D-Study: Coefficients of Dependability, Inter-Trial and Inter Participant Reliability .................................................................................................................. 51
3.5 Discussion ....................................................................................................................... 55
3.6 Conclusion ..................................................................................................................... 58

Chapter 4 Trunk Strength and Function Using the Multidirectional Reach Test in Individuals with Non-Traumatic Spinal Cord Injury ................................................ 59

4.1 Abstract .......................................................................................................................... 60
4.2 Introduction .................................................................................................................... 61
5.4.1 Participants’ Demographics and Clinical Status............................................. 92
5.4.2 Trunk strength .................................................................................................. 95
5.4.3 Pressure offloading .......................................................................................... 96
5.4.4 Relationship between trunk strength and pressure offloading ..................... 98
5.5 Discussion ........................................................................................................... 98
5.6 Conclusions ......................................................................................................... 102

Chapter 6 The Relationship between Pressure Offloading and Ischial Tissue Health in Individuals with Spinal Cord Injury: An Exploratory Study.................................................. 103

6.1 Abstract ............................................................................................................. 104
6.2 Introduction ....................................................................................................... 105
6.3 Materials and Methods ...................................................................................... 108
   6.3.1. Study design ................................................................................................. 108
   6.3.2 Participants ................................................................................................... 109
      6.3.2.1. Able-bodied Individuals ........................................................................... 109
      6.3.2.2 Individuals with Spinal Cord Injury ......................................................... 109
   6.3.3 Pressure Offloading ....................................................................................... 109
   6.3.4 Ultrasound Imaging ...................................................................................... 110
   6.3.5 Data Analysis ............................................................................................... 111
6.4 Results .............................................................................................................. 112
   6.4.1 Ischial Tissue Health: Able-bodied vs. SCI ................................................. 114
      6.4.1.1 Skin ........................................................................................................ 118
      6.4.1.2 Subcutaneous Tissue ............................................................................... 118
      6.4.1.3 Muscle ................................................................................................... 118
      6.4.2 Comparison of Tissue Health Between Loaders vs. Offloaders in SCI Cohort..... 118
6.5 Discussion .......................................................................................................... 125
6.6 Limitations .................................................................................................................. 127
6.7 Conclusions .................................................................................................................. 128

Chapter 7 Concluding Summary, Unifying Discussion and Future Directions .......... 129
7.1 Concluding Summary ................................................................................................. 130
7.2 Unifying Discussion ................................................................................................... 133
    7.2.1 Trunk Function, Offloading Behaviour and Tissue Health ......................... 133
    7.2.2 Mechanical Stimuli and Its Effect on Tissue Health ................................. 135
7.3 Future Directions ........................................................................................................ 136
    7.3.1. Methods to Evaluate Tissue Health ....................................................... 137
    7.3.2. Technology to Effect Offloading Behaviour During Sitting ................. 137

References .......................................................................................................................... 139

Copyright Acknowledgements ......................................................................................... 166

Appendix ............................................................................................................................ 167
List of Tables

Table 2-1 American Spinal Injury Association Impairment Scale (AIS) (from McDonald and Sadowsky, 2002) ................................................................................................................................. 7

Table 2-2 Muscles of the Trunk, Function and Innervation ................................................................. 10

Table 2-3 Assessment of Tissue Health in Response to Loading ........................................................... 16

Table 2-4 Pressure Injury Staging (National Pressure Ulcer Advisory Panel) ...................................... 26

Table 3-1 Demographics of Study Participants .................................................................................... 46

Table 3-2 Intra-Rater reliability from Repeated Measurements on the Same Image by the Same Rater with 95% Confidence Intervals .................................................................................. 47

Table 3-3 Mean and Standard Deviations of Thickness, Echogenicity and Contrast in Skin, Subcutaneous Tissue and Muscle over the Regions of Interest for Time 1 (n = 10), Time 2 (n = 10) and Overall (n = 20) .............................................................................................................. 49

Table 3-4 Magnitude of Variance Components Expressed as a Percentage of the Total Variance for Each Source of Variance (P = Participant, I = Image) and Interactions (PI = Interaction of Participant and Image) for All Measures. Data Obtained from the G-Study ............................................ 50

Table 3-5 Inter-Trial Reliability (measured by Coefficient of Dependability $\phi$) Obtained for a Mixed D-Study Design with 1 Evaluator Using 1 Image, the Average of 2 Images, 3 Images, 4 Images and 5 Images for Thickness, Echogenicity and Contrast .................................................. 52

Table 3-6 Relative Standard Error of Measurement (SEM-rel) in Thickness, Echogenicity and Contrast of Repeated Measures of Skin, Subcutaneous Tissue and Muscle Thickness .............. 53

Table 4-1 Characteristics (mean $\pm$ SD) for All Participants and Subgroups ....................................... 70

Table 4-2 Means, Standard Deviations and Range of Trunk Strength in 4 Directions and Hip in Flexion and Extension at Admission and Discharge (Nm/kg) for All Participants and Subgroups ......................................................................................................................... 72
Table 4-3 Mean, Standard Deviation and Range of Multidirectional Reach Test (MDRT) in 6 Directions at Admission and Discharge (% of Trunk Length) for All Participants and Subgroups ................................................................. 75

Table 5-1 Patient Characteristics .................................................................................................................. 93

Table 6-1 Demographics of Able-Bodied Individuals and Individuals with SCI................................. 112

Table 6-3 Ultrasound Measurements Over the Right Ischial Tuberosity of Able-Bodied Individuals and Individuals with Spinal Cord Injury......................................................... 117

Table 6-4 Ultrasound Measures of Offloaders and Loaders in Individuals with Spinal Cord Injury for the Left and Right Ischial Tuberosities ................................................................. 122

Table 6-5 Correlation Coefficients and corresponding p-values (in brackets) between thickness, echogenicity and contrast and percent of offloading time. ..................................................... 124
List of Figures

Figure 2-1 Schematic illustration of the moments created during reaching or offloading and the counteracting moments of the trunk muscles required to maintain upright stability.................. 11

Figure 2-2 Sequalae following SCI................................................................. 28

Figure 2-3 The Ischial Tuberosity................................................................. 32

Figures 3-1A and 3-1B Ultrasound image of the tissue overlying the ischial tuberosity in one healthy participant................................................................. 48

Figure 3-2A -3-2D Summary of the Relative Mean Detectable Change with 90% Confidence Interval (MDC90%-rel) for Maximal and Mean Thickness, Echogenicity and Contrast of the skin, subcutaneous tissue and muscle................................................................. 54

Figure 4-1 Representation of the MDRT......................................................... 68

Figure 4-2 Mean sitting MDRT (% trunk length) for all participants (n=22-25) at admission and for matched pairs of Walkers (n=7) and Wheelchair Users (n=7-8) at admission and discharge 74

Figure 4-3 Mean sitting MDRT (% trunk length) for all participants (n=22-25) at admission and for matched pairs of Walkers (n=7) and Wheelchair Users (n=7-8) at admission and discharge. 77

Figure 4-4 Scatterplots showing significant (p=0.01) association between changes in sitting MDRT (% trunk length) for matched pairs of Walkers (blue diamonds) (n=7) and wheelers (red squares) (n=7) and hip or trunk strength changes.............................................. 78

Figure 5-1 Total seconds of offloading time over the right (R) and left (L) ischial tuberosities were captured using a pressure mat, “SensiMAT™” ......................................................... 90

Figure 5-2 Mean isometric trunk strength (expressed as Nm) with 95% Confidence Intervals for Reachers (n=8) and Non-Reachers (n=9). ......................................................... 96

Figure 5-3 Mean offloading times (expressed as s/hour) with 95% Confidence Intervals for Reachers (n=7) and Non-Reachers (n=8) ......................................................... 97
Figure 6-1A and 6-1B Ultrasound image of tissues overlying the ischial tuberosity (IT) obtained from able-bodied individual. ........................................................................................................ 114

Figure 6-2A and 6-2B Unprocessed ultrasound image over the left ischial tuberosity in one individual with spinal cord injury (A) with regions of interest outlined in processed image (B). ................................................................................................................................................... 115

Figure 6-3 Mean thickness of skin, subcutaneous tissue and muscle over the left IT in Loaders vs. Offloaders .................................................................................................................................................. 114

Figure 6-4 Mean thickness of skin, subcutaneous tissue and muscle over the right IT in Loaders vs. Offloaders .................................................................................................................................................. 121

Figure 6-5 Mean echogenicity of skin, subcutaneous tissue and muscle over the right IT in Loaders vs. Offloaders .................................................................................................................................................. 123
List of Appendices

A1 – Abstract – Toronto Rehabilitation Institute Research Day November 2013 ................. 167
List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>Able-bodied</td>
</tr>
<tr>
<td>AD</td>
<td>Autonomic Dysreflexia</td>
</tr>
<tr>
<td>ADL</td>
<td>Activities of Daily Living</td>
</tr>
<tr>
<td>AIS</td>
<td>ASIA Impairment Scale</td>
</tr>
<tr>
<td>ASIA</td>
<td>American Spinal Cord Injury Association</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
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<tr>
<td>BMI</td>
<td>Body Mass Index</td>
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<tr>
<td>BOS</td>
<td>Base of Support</td>
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<tr>
<td>COM</td>
<td>Centre of Mass</td>
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<tr>
<td>COP</td>
<td>Centre of Pressure</td>
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<tr>
<td>DTI</td>
<td>Deep Tissue Injury</td>
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<tr>
<td>EMG</td>
<td>Electromyography</td>
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<tr>
<td>IP</td>
<td>Interface Pressure</td>
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<tr>
<td>IT</td>
<td>Ischial Tuberosity</td>
</tr>
<tr>
<td>ITH</td>
<td>Ischial Tissue Health</td>
</tr>
<tr>
<td>MDRT</td>
<td>Multi Directional Reach Test</td>
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<tr>
<td>MRI</td>
<td>Magnetic Resonance Imaging</td>
</tr>
<tr>
<td>N</td>
<td>Newtons</td>
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<tr>
<td>N*m</td>
<td>Newton*metre</td>
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<tr>
<td>NMES</td>
<td>Neuromuscular Electrical Stimulation</td>
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<tr>
<td>NPUAP</td>
<td>National Pressure Ulcer Advisory Panel</td>
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<tr>
<td>NTSCI</td>
<td>Non-Traumatic Spinal Cord Injury</td>
</tr>
<tr>
<td>PI</td>
<td>Pressure Injury</td>
</tr>
<tr>
<td>PSIS</td>
<td>Posterior Superior Iliac Spine</td>
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<tr>
<td>PO</td>
<td>Pressure Offloading</td>
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<tr>
<td>PU</td>
<td>Pressure Ulcer</td>
</tr>
<tr>
<td>PUT</td>
<td>Pressure Ulcer Target</td>
</tr>
<tr>
<td>ROM</td>
<td>Range of Motion</td>
</tr>
<tr>
<td>SAPU</td>
<td>Seated Acquired Pressure Ulcer</td>
</tr>
<tr>
<td>SCI</td>
<td>Spinal Cord Injury</td>
</tr>
<tr>
<td>TcPO₂</td>
<td>Transcutaneous oxygen tension</td>
</tr>
<tr>
<td>TH</td>
<td>Tissue Health</td>
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<tr>
<td>TS</td>
<td>Trunk Strength</td>
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<tr>
<td>TSCI</td>
<td>Traumatic Spinal Cord Injury</td>
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<tr>
<td>US</td>
<td>Ultrasound</td>
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<tr>
<td>WS</td>
<td>Weight Shifting</td>
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### Glossary of Terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Base of Support</td>
<td>Area of an object that is in contact with a supporting surface.</td>
</tr>
<tr>
<td>Centre of Mass</td>
<td>Refers to the point in body where all mass of the individual would be concentrated if this individual is represented as a single point of mass in space. Center of Mass is calculated from the weighted average of all body parts of the person.</td>
</tr>
<tr>
<td>Centre of Pressure</td>
<td>Refers to the location where the force vector would act on a standing or walking or sitting surface if all the force acting on the body through that surface were concentrated at a single point.</td>
</tr>
<tr>
<td>Deep Tissue Injury</td>
<td>A unique form of pressure injury defined by the National Pressure Ulcer Advisory Panel (NPUAP). This type of pressure injury occurs under the skin in the subcutaneous tissue or muscle. These injuries appear as maroon colour. Deep tissue injuries may resolve without opening up at the skin surface.</td>
</tr>
<tr>
<td>Dynamic Stability</td>
<td>The ability to move within a defined region without a loss of balance. The defined region may be within or beyond the base of support.</td>
</tr>
<tr>
<td>Erythema</td>
<td>Skin redness</td>
</tr>
<tr>
<td>Grey scale analysis</td>
<td>A method used for analysis of diagnostic images to obtain metrics of tissue texture. Outcomes of grey scale analysis include echogenicity and contrast. Grey scale measures can be extracted from ultrasound images.</td>
</tr>
<tr>
<td>Ischial Tissue Health</td>
<td>Refers to the integrity of the tissues overlying the ischial tuberosity.</td>
</tr>
<tr>
<td>Pressure Offloading</td>
<td>An activity resulting in removal of pressure from weight bearing surfaces. Pressure offloading or pressure relief can be described in terms of a maneuver in which pressure over the weight bearing surface is removed.</td>
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</table>
through a forward lean, side lean or push up. Pressure offloading can also be achieved through the use of cushions that redistribute pressures over the seated surface. Individuals with spinal cord injury are recommended to engage in frequent weight shift to relieve pressure under their ischial tuberosity to prevent the development of a seated acquired pressure injury. Sprigle and Sonenblum (2011) describe two different constructs of pressure relief; one focusing on altering the magnitude of pressure which can be achieved by consideration of the support surfaces, positioning devices and posture and secondly, those focused on duration which can be achieved by repositioning, weight shifting and the use of active surfaces (e.g. customized wheelchair cushions that actively redistribute pressure).

Reactive hyperaemia  The process whereby there is increased blood flow in tissue after a prolonged period of vascular occlusion. Reactive hyperaemia may occur in tissues such as the tissues overlying the ischial tuberosity after prolonged period of pressure and subsequent pressure relief.

Trunk Function  The ability of the trunk to move and generate force in order to maintain upright stability in sitting or standing, or during activities that require maintaining the centre of mass within the base of support.

Trunk strength  The ability of the trunk muscles to generate force.
Chapter 1 General Introduction
1.1 Preamble

Individuals with Spinal Cord Injury (SCI) are at high risk of developing seated acquired pressure injuries (PI) due to prolonged unrelieved pressure secondary to paralysis, muscle weakness, muscle atrophy, lack of sensation and microvascular changes in soft tissues. Paralysis or weakness of the trunk muscles, which occurs in SCI, creates challenges for the individual to alter their sitting posture. During sitting, most of the pressure occurs under the ischial tuberosities (IT), also described as the “sit bones”. Deep tissue injury (DTI), a form of PI, occurs under intact skin in the subcutaneous tissue and muscle and has been recognized as a form of PI. One of the common locations for DTI in individuals with SCI is over the IT due to inability to offload the IT. Unfortunately, by the time DTI has been detected at the surface, tissue breakdown has occurred. While several methods have been used to assess health of tissues overlying the IT, a non-invasive method using quantitative ultrasound (US) methodology incorporating grey scale analysis has not been examined. Additionally, the relationship between trunk function, pressure offloading (PO) of the IT and health of the tissue overlying the IT has not been studied. The purpose of this thesis was to explore the relationship between trunk function and ischial tissue health (ITH) in individuals with SCI.
1.2. Thesis Organization

This thesis is presented in manuscript format. The structure of this thesis was selected to reflect how this project evolved from inception to completion. As each study began, additional questions were generated which lead to more in depth investigation. Chapter 2 provides a background of trunk function, SCI, secondary complications following spinal cord injury, ITH and what is known about the relationship between trunk function and ITH in individuals with SCI. This chapter ends with a culmination of the research aims and hypothesis. Chapters 3-6 present unaltered manuscripts, which have been formatted to adhere to the guidelines of this thesis. Chapter 3 presents a non-peer reviewed paper evaluating the reliability of measuring thickness and grey scale measures from ultrasound images in individuals without spinal cord injury. This study formed the basis of the assessment of tissue health using diagnostic ultrasound imaging. Chapter 4 is a reformatted version of a paper published in the “Journal of Spinal Cord Medicine” examining trunk strength and function in individuals with Non-Traumatic Spinal Cord Injury during the subacute phase of rehabilitation. Chapter 5 is a reformatted version of a paper also published in the “Journal of Spinal Cord Medicine”, examining trunk function and ischial offloading in individuals with Traumatic and Non-Traumatic Spinal Cord Injury. Chapter 6 presents an unpublished reviewed article examining the relationship between trunk function and ischial offloading in individuals with Traumatic and Non-Traumatic Spinal Cord Injury. Chapter 7 of this thesis presents a concluding summary, unifying discussion and future directions.
Chapter 2  The Implications of Secondary Complications in Spinal Cord Injury and Tissue Health
2.1 Introduction

This section is divided into six sections. The first section (2.2) begins with a description of trunk function. The second section (2.3) describes spinal cord injury, impaired trunk function and pressure injuries. The third section (2.4) provides a description of tissue health. The fifth section (2.5) explores the concept of tissue health and pressure offloading in spinal cord injury. Section 2.6 concludes with the Research Aims and Hypotheses.

2.2 Spinal Cord Injury

Spinal cord injury (SCI) occurs when there is pathology to the spinal cord anywhere from the foramen magnum to the cauda equina resulting in neurological impairment affecting the sensory, motor and autonomic systems. Due to neurological damage, individuals with SCI present with significant impairments resulting in profound disability affecting an individual’s ability to engage in their activities of daily living (ADL), employment and leisure activities, resulting in a significant burden for themselves, their family, society and the health care system (Noonan et al., 2012).

There are several etiologies of SCI, which are classified into two main categories: Traumatic Spinal Cord Injury (TSCI) and Non-Traumatic Spinal Cord Injury (NTSCI). TSCI occurs when there is mechanical trauma to the spinal cord as a result of external events, such as a motor vehicle accident, work related injury, fall, recreational activities or violence (McDonald and Sadowsky, 2002). Mechanical trauma by way of traction, compression and shearing forces, damage axons, neural cell membranes and blood vessels, resulting in swelling of the spinal cord leading to secondary ischemia (McDonald and Sadowsky, 2002). Following the primary injury, haemorrhage, inflammation and the release of chemical mediators ensue, leading to further cord damage (Nas et al., 2015). Furthermore, systemic hypotension secondary to neurogenic shock results in further ischemia of the spinal cord (McDonald and Sadowsky, 2002).
NTSCI occur as a result of congenital and developmental disorders (e.g. cerebral palsy), degenerative central nervous system disorders (e.g. amyotrophic lateral sclerosis), genetic and metabolic disorders (e.g. B_{12} deficiency), infection (e.g. bacterial and viral), inflammatory conditions (e.g. transverse myelitis), ischemia (e.g. aortic dissection), tumours (e.g. primary and metastatic), rheumatological and degenerative disorders (e.g. spondylosis, stenosis) and toxic causes (e.g. radiation) leading to damage of the spinal cord (McDonald and Sadowsky, 2002). The presentation of individuals with TSCI and NTSCI vary significantly. Individuals with NTSCI have been described as being older, more likely to be female, with additional comorbidities and often presenting with paraplegia compared to tetraplegia (Guilcher et al., 2010, New, Simmonds and Stevermuer, 2010, Cosar et al., 2010).

Neurological impairment of individuals with SCI depends on the level and completeness of pathology, e.g. whether there is full or partial sensory and motor loss distal to the injury level (Gibson, 2003). Individuals with SCI are defined as suffering from tetraplegia (occurring with damage to the cervical cord) or paraplegia (occurring with damage to the thoracic, lumbar or sacral levels) (Noonan et al., 2012). Individuals with tetraplegia present with sensory and/or motor impairments in the arms, trunk, legs and pelvic organs (Nas et al., 2015). Individuals with paraplegia present with sensory and/or motor impairments in the thoracic, lumbar or sacral areas, and may have involvement in the trunk, legs and pelvic organs depending on the level of injury (Nas et al, 2015). Furthermore, classification of TSCI is based on the severity of injury according to the American Spinal Cord Injury Association (ASIA) Impairment Scale, which is graded from A-E. The ASIA Impairment Scale (AIS) classifies motor function in 10 muscle groups (arms: C5-T1; legs: L2-S1) and sensation in 28 dermatomes (C2-S4/5) bilaterally (McDonalds and Sadowsky, 2002) (Table 2-1). What is important to note is that individuals with an initial diagnosis of AIS A or AIS B (individuals with greater degree of SCI) may convert to higher functional levels (McDonald and Sadowsky, 2002) as recovery occurs. Individuals who have sustained a SCI can regain one level of motor function within 6 months following the injury, however recovery can occur several years later (Stauffer, 1984).
Table 2-1 American Spinal Injury Association Impairment Scale (AIS) (from McDonald and Sadowsky, 2002)

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Complete; no sensory or motor function preserved in the sacral segments (S4-S5)</td>
</tr>
<tr>
<td>B</td>
<td>Incomplete; sensory but not motor function preserved below the neurological level and extending through the sacral segment S4-S5</td>
</tr>
<tr>
<td>C</td>
<td>Incomplete; motor function preserved below the neurological level; most key muscles have a grade &lt;3</td>
</tr>
<tr>
<td>D</td>
<td>Incomplete; motor function below the neurological level; most key muscle have a grade &gt;3</td>
</tr>
<tr>
<td>E</td>
<td>Normal motor and sensory function</td>
</tr>
</tbody>
</table>

NTSCI can be classified according to the International Data Sets for NTSCI. This classification system enables NTSCI to be classified according to etiology (including timeframe of onset of NTSCI), the use of International Statistical Classification of Diseases (ICD) and Related Health Problems (New and Marshall, 2014). While the classification system of NTSCI has not been formally classified and validated in the same way as TSCI, the general classification system of paraplegia or tetraplegia has been used to assess neurological level and completeness of the injury.

Worldwide, approximately 40 million people per year sustain a spinal cord injury (Nas et al., 2015). The incidence of SCI in Canada is 3,675 (Noonan, Fingas et al., 2012) including traumatic (1,785) and non-traumatic (2,286). The prevalence of SCI in Canada has been
estimated to be 85,556 persons with 51% of those individuals living with TSCI and 49% of those individuals living with NTSCI (Noonan, Fingas et al., 2012). The majority of individuals with SCI are young males between the ages of 20-35 years (Nas et al., 2015)

2.2.1 Secondary Complications following Spinal Cord Injury

SCI can lead to many secondary health complications including neurogenic bowel and bladder, urinary tract infections, spasticity, pressure injuries (PI), orthostatic hypotension, osteoporosis, fractures, deep vein thrombosis, spasticity, pulmonary and cardiovascular impairment, depression and autonomic dysreflexia (Nas et al., 2015). Secondary complications reduce quality of life (Anson and Shepherd, 1996) and life expectancy. Health behaviours such as smoking and alcohol use, in additional to psychological and socioeconomic factors including personality, poverty and social supports, further exacerbate secondary complications (Krause, 1996). Age related changes including cardiac and respiratory complications might further compound secondary health complications (Hitzig et al., 2008). In addition to reducing quality of life and life expectancy, secondary health complications following SCI increase the burden on the healthcare system (Dryden et al., 2005) due to increase in risk of repeated hospitalizations and access to medical care (Chiodo et al., 2007).

The most common secondary complication following SCI is a PI (McKinley et al., 1999). Other secondary complications include but are not limited to abnormal renal function and autonomic dysreflexia (McKinley et al., 1999). The likelihood of developing a PI increases with years post injury in individuals with complete injuries (Hitzig et al., 2008) and is the second most common reason for rehospitalization following SCI.
2.3 Trunk Function

The “trunk” or “core” has been referred to as a “muscular box” with physical boundaries including the anterior abdominal muscles (e.g. rectus abdominis), posterior paraspinals (e.g. multifidus and erector spinae), superior diaphragm and the inferior pelvic floor and hip girdle muscles (Granacher et al., 2013). The muscles around the trunk enable movement of the trunk through the sagittal, horizontal and coronal planes and stabilize the spine and pelvis to prevent loss of balance during daily activities including energy transfer, weight shifting and movement of the upper extremities (Kinoshita et al., 2015, Kibler et al., 2013) (Table 2-2).

Trunk function can be defined as the ability of the trunk to generate force and move in order to maintain upright stability in sitting or standing, or during activities that require maintaining the centre of mass (COM) within the base of support. The COM is located at the level of the umbilicus. During sitting, the COM falls within the base of support. During reaching, the COM is displaced beyond the base of support, generating a moment about the trunk. In order to maintain upright stability, the muscles of the trunk must counteract this moment by generating a moment equal and opposite in direction to prevent a loss of balance.
Table 2-2 Muscles of the Trunk, Function and Innervation

<table>
<thead>
<tr>
<th>Muscle(s)</th>
<th>Movement</th>
<th>Spinal Neurological Innervation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectus Abdominis</td>
<td>Trunk flexion</td>
<td>T2-T12</td>
</tr>
<tr>
<td>External Obliques</td>
<td>Trunk flexion, ipsilateral</td>
<td>T8-L1</td>
</tr>
<tr>
<td></td>
<td>trunk flexion, contralateral</td>
<td></td>
</tr>
<tr>
<td></td>
<td>trunk rotation</td>
<td></td>
</tr>
<tr>
<td>Internal Obliques</td>
<td>Trunk flexion, ipsilateral</td>
<td>T8-L1</td>
</tr>
<tr>
<td></td>
<td>trunk flexion and rotation</td>
<td></td>
</tr>
<tr>
<td>Transverse Abdominis</td>
<td>Compression of abdomen</td>
<td>T8-T12</td>
</tr>
<tr>
<td>Quadratus Lumborum</td>
<td>Trunk extension, ipsilateral</td>
<td>T12-L4</td>
</tr>
<tr>
<td></td>
<td>trunk flexion</td>
<td></td>
</tr>
<tr>
<td>Erector Spinae</td>
<td>Trunk extension</td>
<td>Dorsal rami of spinal nerves</td>
</tr>
<tr>
<td>(Iliocostalis, Longissimus,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spinalis)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transversospinalis</td>
<td>Trunk extension, trunk</td>
<td>Dorsal rami of spinal nerves</td>
</tr>
<tr>
<td>(Semispinalis, Multifidus,</td>
<td>rotation</td>
<td></td>
</tr>
<tr>
<td>Rotatores)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sitting balance requires the use of even distribution of body weight over a seated surface (i.e. symmetry), and the ability to shift weight without the loss of balance based on the task condition (Figure 2-1). For example, in Figure 2-1a, the individual is reaching towards the right. This creates a trunk moment denoted by $M_{\text{trunk}}$. In order to maintain upright stability and prevent a loss of balance, a lateral flexion moment ($M_{\text{lateral flexion}}$) is generated. Altered trunk function as a result of muscular, neurological or skeletal impairments at any or all of the levels can affect balance and stability and can impair functional tasks such as reaching and can have a detrimental
effect on postural control including maintaining upright sitting stability (Cabanas-Valdés et al., 2013). Furthermore, trunk impairment can result in difficulty ambulating and engaging in arm function (Verheyden et al, 2004).

Figure 2-1a and 2-1b Schematic illustration of the moments created during reaching or offloading and the counteracting moments of the trunk muscles required to maintain upright stability (centre of mass = circle, $M_{\text{trunk}}$ = Trunk Moment generated during reaching, $M_{\text{lateral flexion}}$ / $M_{\text{trunk extension}}$ = counteracting moments generated by the muscles to prevent loss of balance).

Age related changes in trunk function could be attributed to anatomical changes (e.g. kyphosis) (Granacher et al., 2013) and neural changes including delayed (Hwang et al., 2008) or impaired recruitment of trunk muscles (Ferreira et al., 2010). Furthermore, impairments in trunk function can occur as a result of neurological or neuromuscular impairments including stroke, spinal cord injury, cerebral palsy, sarcopenia, deconditioning or degenerative muscular conditions.
There are several ways that trunk function can be assessed and quantified. Activation of trunk muscles to generate the forces required for upright posture can be assessed in different planes using portable tools or non-portable tools that evaluate strength (i.e. hand held dynamometer, isokinetic dynamometers) or muscle activation (i.e. electromyography) (Seelan et al., 1997). Motion analysis can be used to assess trunk movements during various activities including the assessment of static and dynamic stability. Trunk function can be assessed in the context of stability in which postural sway, dynamic stability and weight shifting ability are measured (Cabanas-Valdés et al., 2013, Grangeon et al., 2012, Seelan et al., 1997). The measurement of postural sway involves an examination of the centre of pressure (COP) excursions within a defined base of support while an individual is seated or standing over a force plate. In the assessment of dynamic stability, an individual’s ability to maintain balance when transitioning from a dynamic to static posture is assessed (Goldie, Back and Evans, 1989). Furthermore, the Trunk Impairment Scale (TIS) (Verheyden et al., 2004, Karthikbabu et al. 2011) can be used to evaluate trunk performance. Specific tests such as the Functional Reach Test (FRT) (Granacher et al., 2013), Modified Reach Test (MRT) which measures reach distance in multiple directions (Dean & Shepherd, 1997) and the Balance Performance Monitor (BPM) which measures weight distribution and dynamic reaching in sitting (Nichols, 1997) have also been used to assess trunk function. T-shirt dressing time has also been used a surrogate measure of trunk function (Chen et al., 2003) in addition to the “trunk righting test” (Kinoshita et al., 2015).

Numerous studies have examined the trunk with respect to its ability to generate force, move and stabilize the spine and pelvis during activities of daily living across various populations. Studies have also examined therapeutic interventions on the improvement of trunk function (Karthikbabu et al., 2011, Granacher et al., 2013, Triolo et al., 2013). Muscle strength has been evaluated in healthy controls (Granacher et al., 2013, Madsen, 1996), older adults (Suri et al., 2009), wheelchair basketball players (da Silva Santos et al., 2017), stroke patients (Tsang and Mak, 2004, Fujita et al., 2015), individuals with low back pain (Nagai et al., 2015), individuals undergoing surgical lumbar decompression (Keller et al., 2003) and individuals with SCI (Larson et al., 2010). Limits of stability have been evaluated in wheelchair basketball players (da Silva Santos et al., 2017). Static and dynamic stability has been evaluated in individuals with high and low thoracic SCI (Chen et al., 2003, Seelan et al., 1997, Gauthier et al., 2013). Quasi static sitting
stability has also been compared in healthy controls and individuals with SCI (Grangeon et al., 2012).

Given that trunk function is important for overall functioning, neurological conditions including SCI that may result in impaired trunk function, may have detrimental effects on functional sitting and reaching. The course of recovery of trunk function in individuals with SCI has not been explored to date. The importance of recovery of trunk function following SCI is paramount in order to develop rehabilitation programs that would improve functional sitting and reaching and potentially mitigate any secondary complications following SCI.

2.3.1. Impaired Trunk Function

When comparing individuals with SCI to those without SCI, individuals with SCI who lack trunk control, tend to sit with the pelvis tilted posteriorly and with increased kyphosis of their thoracic spine to maintain stability (Hobson et al., 1992). Global stability index and direction specific index (as measured by COP excursion relative to base of support (BOS)) is lower in individuals with SCI with paralysis of the abdominal and low back muscles compared with healthy individuals (Gauthier et al., 2013). Individuals with SCI present with less stability (as noted by increased COP displacement) during static sitting when compared with healthy controls (Grangeon et al., 2012).

When examining trunk function in individuals with SCI, trunk flexion and extension strength is highly correlated with athletic ability (da Silva Santos et al., 2017). Interestingly, Chen et al. (2003) found that trunk strength did not correlate to dynamic sitting stability in individuals with SCI. The sit and reach test, a measure of trunk stability, was correlated with the mobility score on the functional independent measure (FIM) in individuals with acute stroke (Tsang and Mak, 2004). Anterior pelvic tilt, bimanual reaching and reach distance improved with electrical stimulation of trunk muscles in individuals with cervical and thoracic injuries (Triolo et al., 2013).
The severity of trunk impairment in an individual with SCI will depend on the level of the injury and the completeness of the injury (Desroches, Gagnon, Nadeau, and Popovic, 2012). In a study by Gauthier et al (2013), individuals with higher thoracic injuries who had complete paralysis of their low back and abdominal muscles demonstrated a reduction in multidirectional seated postural stability when compared with individuals whose injury level was in the lower thoracic region and had partial or total use of their low back and abdominal muscles. These findings are consistent with those of Chen et al. (2003) who found that dynamic sitting stability is higher in individuals with lower thoracic injuries compared with higher thoracic injuries while static stability is not different between individuals with high versus low thoracic injury. Individuals with high thoracic SCI tend to use their latissiumus dorsi, upper trapezius, pectoralis major, serratus anterior and high thoracic erector spinae in perturbed sitting when compared with non-SCI participants, who do not rely as much on non-postural muscles. Individuals with lower thoracic injuries rely less on non-postural muscles than those with higher thoracic injuries (Seelan et al., 1997). Additionally, Shin and Sosnoff (2013) noted that individuals with SCI above T10 demonstrated shorter virtual contact times (movement of centre of pressure to the stability boundary) than those with injuries between T10 and L4. It is suggested that individuals with shorter virtual contact time have less time to recover from loss of balance which increases their risk of falls (Shin and Sosnoff, 2013).

Impairment of trunk function in individuals with SCI has detrimental consequences since sitting is considered one of the most essential activities of daily living for individuals with SCI (Serra-Ano et al., 2013). Impaired trunk function affects stability, and functional tasks, including sitting and weight shifting, resulting in the use of non-postural muscles as a compensatory mechanism to support sitting balance. Impairments in trunk function during sitting can reduce an individual’s independence and reduce quality of life. What is known is that trunk impairments can be quantified using various measures. However, what remains to be studied is how trunk function is related to pressure offloading of seated weight bearing surfaces in individuals with SCI and if there is any relationship between trunk function and ischial tissue health in individuals with SCI.
2.4 Tissue Health

Tissue health (TH) can be conceptualized as the absence of disease or injury of the tissue using a similar definition as the World Health Organization utilizes for health. In order to maintain adequate TH, oxygenation and adequate nutrient supply is essential. Risk factors for impairment of TH include impaired vascularity and oxygenation (Dietrick et al., 2007) and impaired nutritional intake. Pressure over the tissue can result in ischemia depriving tissue of necessary oxygen and nutrients.

The concept of TH or tissue integrity has been assessed in the dental field (Moraguez, Vailati, and Belser, 2015, van Brakel et al., 2010), allograft transplantation in patients with burns (Fletcher et al., 2015), white matter of the brain (Ryu et al., 2016), within the context of SCI and healthy controls in response to applied loads (Table 2-3) and in individuals with PI (Andersen and Karlsmark, 2008). Methodologies used to evaluate TH include biophysical markers such as erythema, skin temperature, transcutaneous oxygen and carbon dioxide, byproducts of anaerobic and aerobic metabolism, elasticity index, hydration and presence of edema using ultrasound imaging. While many studies have examined tissue health in response to loading, many of these studies required invasive methods, and/or a period of acclimatization of the study participant prior to data collection.
### Table 2-3 Assessment of Tissue Health in Response to Loading

<table>
<thead>
<tr>
<th>Authors (date)</th>
<th>Purpose</th>
<th>Population</th>
<th>Experimental Paradigm</th>
<th>Outcome Measures</th>
<th>Findings</th>
</tr>
</thead>
</table>
| Barnett et al., 1995 | To assess the effects of duration and compliance of seating surfaces on reactive hyperaemia in skin overlying the ischial tuberosities while sitting on a hard surface | • 4 able-bodied individuals, one individual with paraplegia, one individual with cerebral palsy, age range 22-49 years | Participants sat on a Plexiglas on a wooden chair with an opening to transmit infrared radiation over the ischial tuberosity and on a hospital bed | • Skin temperature via thermography using an Agema Model 870  
• Interface pressures using an array of 512 pressure sensors  
• Examination of hyperaemia using video of ischial tuberosity during loaded condition | Intensity of hyperaemic reaction proportional to duration of sitting on a hard surface  
• Hyperaemic response 3 minutes after sitting for 15-minutes |
<table>
<thead>
<tr>
<th>Study</th>
<th>Objective</th>
<th>Participants</th>
<th>Outcome Measures</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bogie et al., 1995</td>
<td>To assess response of tissue to ischemia</td>
<td>• 42 individuals with traumatic SCI within 1 year (23 had sustained injury above T6, 19 individuals sustained injury below T6)</td>
<td>Participants sat on a seated surface. Outcome measures were collected. Individuals engaged in up to 3 min of pressure relief if TcPO$_2$ fell below 20 mmHg for two minutes</td>
<td>• Individuals with injuries below T6 show decrease in ability to maintain blood flow in sitting when compared to individuals with injuries above T6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 14 females</td>
<td></td>
<td>• Individuals with injury above T6 show improvement in tissue viability at seated support interface compared with individuals with injuries below T6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Mean age 27.5 years</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knight et al., 2001</td>
<td>To assess soft tissue response to different applied pressures</td>
<td>• 14 healthy volunteers (9 males)</td>
<td>Participants lay prone on a hospital bed. An indenter with an instrumented CO$_2$ and O$_2$ tension electrode and</td>
<td>• Local oxygen tension and local carbon dioxide tension at sites adjacent to the sacrum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Male mean age 26.7 years (range 23-41 years)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Oxygen levels lower in soft tissues when pressure between 40-120 mmHg were applied, with CO$_2$ levels at higher pressure above normal levels of 45</td>
</tr>
<tr>
<td>Thorfinn et al., (2002)</td>
<td>To study the distribution of sitting pressure and hyperaemic responses in healthy controls and individuals with SCI following 12 minutes of sitting</td>
<td></td>
<td></td>
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<tr>
<td>---</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
| **Participants** | • Eight Individuals with traumatic SCI (3 tetraplegia), mean age 55 years (range 42-73 years), C4-T12, mean time post SCI 15 years (range 4-37 years)  
• 10 healthy participants (5 men), mean age 28 years (range 21-44)  
| **Methods** | Participants sat on an instrumented chair for 12 minutes following 10 minutes of unloaded rest  
• Sitting Pressure (using a pressure sensitive plate “Mini-EMED System” with resolution of 3.24 sensors/cm²)  
• Reactive hyperaemia  
• Perfusion using laser Doppler perfusion |
| **Measurements** | • Collection of sweat lactate and urea  
• Increase in concentration of sweat lactate and urea in loaded site compared to control site, up to two-fold |
| **Results** | • Mean pressure in healthy controls significantly lower on both sides when compared with individuals with SCI (p < 0.05). Maximum pressure in controls: 12.0 N/cm² on left and 12.9 N/cm² on right, in patients 42.9 N/cm² left and 48.7 N/cm² right  
• Perfusion decreased in loaded condition and |
<table>
<thead>
<tr>
<th>Study</th>
<th>Summary</th>
<th>Participants</th>
<th>Methods</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bogie and Triolo (2003)</td>
<td>To evaluate changes in tissue health in individuals with SCI with neuromuscular electrical stimulation (NMES) of gluteal muscles</td>
<td>• 8 individuals with SCI: 6 ASIA A, 2 ASIA B, 9 males</td>
<td>Electrical stimulation of gluteal muscles for a period of 8 weeks</td>
<td>• Unloaded tissue oxygenation in ischial region • Interface pressures at seating support surfaces • Increase in unloaded tissue oxygenation and reduction in pressure interface at seating support surface over ischial region following 8 weeks of NMES</td>
</tr>
<tr>
<td>Thorfinn et al.</td>
<td>To investigate signs of reduced tissue health in wheelchair users</td>
<td>• 16 healthy individuals (8)</td>
<td>Individuals sat on wheelchair</td>
<td>• Oxygen (PO₂) using • PO₂ and glucose significantly reduced</td>
</tr>
</tbody>
</table>
| al., 2009 | perfusion and ischaemia in subcutaneous fat in buttocks during sitting | men), mean age 26 years, mean BMI 22.6 kg/m² | cushion and on a hard surface | microelectrodes
- Metabolites of aerobic and anaerobic metabolism: glucose, lactate, pyruvate and glycerol using CMA 60 microdialysis catheters inserted into the subcutaneous fat
- Sitting pressures using Tekscan for the right and left buttock regions
- Thickness of subcutaneous fatty layer using during sitting, more profound decrease in \( PO_2 \) when sitting on a hard surface
- After unloading, glucose and \( PO_2 \) increased significantly
- Sitting pressure for right and left buttock higher when participants were sitting on a cushion when compared with a hard surface (\( p < 0.01 \))
- No significant difference in sitting pressures between right and left buttock
- Significantly higher sitting pressure in men when compared with |
<p>| Kim et al. (2012) | To investigate the hypotheses that 1) tissue oxygenation decreases with sustained pressure, 2) tissue oxygen and interface pressures are inversely correlated in loaded soft tissues and 3) multisite assessment are unnecessary because healthy individuals are able-bodied adults (10 males), mean weight 78 kg for males, 60 kg for females, mean age 24 years | Individuals assumed the sitting and supine lying position for 20-minutes. Interface pressures and transcutaneous oxygen was assessed at 5-minute intervals | • Interface pressures using Tekscan CONFORMat® Pressure Measurement System over the sacrum and ischial tuberosities • Transcutaneous tissue oxygen using multichannel Radiometer | women |
| | • Subcutaneous thickness measures significantly greater in women compared with men (p &lt; 0.05) | | • 10-minute assessment can reliably indicate tissue health • Tissue may adapt to applied loads over time • No significant differences between transcutaneous oxygen and interface pressures between 10-20 minutes in either position • No significant correlation between transcutaneous oxygen |</p>
<table>
<thead>
<tr>
<th>Study</th>
<th>Methodology</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stojadinovic et al., (2013)</td>
<td>To assess the effect of load and ischemia of human skin specimens of different ages</td>
<td>- 10 full-thickness 7 mm skin specimens obtained from 6 women undergoing abdominoplasty within 15 minutes post surgery</td>
</tr>
</tbody>
</table>

| Wu et al., | To determine if | - 7 individuals with | Individuals | - TcPO₂ | - For individual who sat |

The TCM400 monitor was used over the sacrum and ischial tuberosities and interface pressures.

Left and right ischia were significantly different for transcutaneous oxygen and interface pressure in supine and sitting positions.
<table>
<thead>
<tr>
<th>Year</th>
<th>Study Design</th>
<th>Participants</th>
<th>Procedures</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>Combined trunk and gluteal NMES alters seated posture and improves tissue health in individuals with SCI</td>
<td>SCI who received implanted lower extremity NMES systems (8 or 16 channels to the trunk, hip and lower extremity muscles) for standing and walking</td>
<td>underwent 5 minutes of combined trunk and gluteal NMES in sitting</td>
<td>bilaterally over the ischial tuberosities • Seating interface pressure • Individuals who did not sit on their sacrum showed few changes in $T_cPO_2$ on their sacrum, NMES decreased the sacral region IP and increased transcutaneous oxygen pressure</td>
</tr>
<tr>
<td>Kottner et al., 2015</td>
<td>To study the effect of loading on skin in sacrum and heels</td>
<td>20 healthy females, mean age 69 years</td>
<td>Participants lay in a supine position for 90 and 150 min on a standard hospital mattress Measures obtained prior to and following loading for 90 and 150 minutes</td>
<td>• Surface temperature (using an infrared thermometer), erythema (using Mexameter MX 18) • Stratum corneum hydration (using Corneometer) • Increased skin surface temperature and erythema at sacrum and heels from prolonged loading • Transepidermal water loss at heels, but not sacrum from sustained loading • Stratum corneum hydration stable</td>
</tr>
</tbody>
</table>
- Epidermal water loss (using Tewameter TM 300) following loading
2.4.1 Pressure Injuries

Pressure injuries (PIs) occur in the tissues over bony prominences (e.g. sacrum, greater trochanters, ischial tuberosities, malleoli and heels) when there is unrelieved pressure. The physiological development of PIs has been described as a process whereby capillary occlusion reduces perfusion thereby depriving tissues of oxygen and nutrients (Thorfinn et al., 2009). As skin is re-perfused from relieved pressure, additional injury occurs secondary to the accumulation of inflammatory byproducts, which are not adequately removed secondary to lymphatic impairment (Thomas, 2010). Cells are also subject to mechanical deformation which further contributes to cell damage (Thomas, 2010). Damaged tissue is unable to dispose of the byproducts of inflammation causing further cell destruction and eventual cell death (Park, 1992).

It has also been reported that the duration and intensity of pressure contributes to the severity of PI (Reswick and Rogers, 1974). There is conflicting information in the literature regarding the safe pressures under the IT, ranging between 30 mmHg (Rogers, 1973) to 60 mmHg (Ferguson-Pell, Wilkie, Reswich and Barbenel, 1980). With prolonged loading/pressure of 300 kPa, morphological changes in the skin occur including subepidermal separation (Stojadinovic et al., 2013), with changes occurring more rapidly with aged skin (Stojadinovic et al., 2013).

PIs are classified based on their severity and extent of tissue injury. PIs are distinguished from moisture associated skin damage (MASD) as a result of incontinence or dermatitis, medical adhesive related injury (MARI) or traumatic wounds including skin tears, burns and abrasions. The National Pressure Ulcer Advisory Panel (NPUAP) developed a staging system (Table 2-4) to characterize PIs based on their severity and extent of tissue damage.
<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Non-blanchable erythema in intact skin. In darkly pigmented skin, blanching may not be visible however the colour may differ from the surrounding skin. The area may be painful, soft, warmer or cooler compared to adjacent tissue in the absence of any changes in skin colour.</td>
</tr>
<tr>
<td>2</td>
<td>Partial-thickness skin loss with exposed dermis. The bed of the wound may appear pink or red, and/or appear moist, or may appear as an intact ruptured serum-filled blister. Fat and deeper tissue is not visible. There is no granulation tissue, slough or eschar.</td>
</tr>
<tr>
<td>3</td>
<td>Full thickness skin loss with exposure of fat. Granulation tissue, rolled edges, slough and/or eschar, undermining and tunnelling may be present. Fascia, muscle, tendon, ligament, cartilage and/or bone are not visible. Depth of tissue damage depends on the location of the injury</td>
</tr>
<tr>
<td>4</td>
<td>Full thickness skin loss with exposed fascia, muscle, tendon, ligament, cartilage and/or bone. Rolled edges, undermining and/or tunnelling are often present.</td>
</tr>
<tr>
<td>Unstageable</td>
<td>Refers to pressure injury in which the extent of tissue loss is unknown as it is obscured by eschar or slough.</td>
</tr>
<tr>
<td>Deep Tissue Injury</td>
<td>Intact or non-intact skin with an area of persistent localized non-blanchable deep red, maroon, purple discolouration or epidermal separation which reveals a dark wound bed or blood filled blister, which may appear differently in darkly pigmented skin. The wound may resolve without tissue loss, or evolve rapidly to tissue loss.</td>
</tr>
</tbody>
</table>
Tissues overlying bony prominences respond differently to pressure (Van Loocke, Lyons and Simms, 2008). For example, the lower metabolic rate of adipose tissue (Thorfinn et al., 2009) may potentially increase the threshold for damage secondary to ischemia. Injury may occur first in the muscle overlying bony prominences prior to changes observed over the skin (NPUAP, 2016). This form of PI is referred to as Deep Tissue Injury (DTI).

Up to 66% of individuals with SCI will experience a PI at some point in their lifetime (Schubart, Hilgart and Lyder, 2008). It has also been reported that 50% of individuals who are wheelchair users experience tissue breakdown due to prolonged sitting (Cuddigan et al., 2001). 31% of PI in individuals with SCI occur over the ischium, followed by the trochanters (26%), sacrum (18%), heel (5%), malleolus (4%) and feet (2%) (Sezer, Akkus and Ugurlu, 2015). The location of a PI is dependent on the position of the individual in which pressure has accumulated (e.g. sitting, supine, side lying) and where pressure has accumulated. For example, in the side lying position, PIs can develop over the lateral and medial malleoli, whereas in the supine position, PIs can develop in the occipital region or the heels.

Following SCI, disuse atrophy and loss of gluteal muscle bulk (Wu and Bogie, 2013) alters pressure distribution at the support surfaces (Bogie and Triolo, 2003) and increases interface pressure (Kim et al., 2012). Individuals with SCI demonstrate greater sitting pressure when compared with healthy controls (Thorfinn et al., 2002). In addition to altered pressure distribution and increased pressure, there are additional intrinsic factors that contribute to the development of PI (Figure 2-2). Individuals with SCI are at increased risk of tissue breakdown due to sensorimotor impairments. Due to reduced sensation, individuals with SCI are unable to sense when increased pressure has accumulated over weight bearing surfaces altering the individual the need to offload. Furthermore, due to motor impairments as a result of paralysis, the ability to actively recruit the muscles required for weight shifting and engage in anticipatory and reactive balance strategies is impaired. Inability to actively recruit the trunk muscles may reduce an individual’s ability to control their COM and may thus prevent adequate weight shifting to unload weight bearing surfaces. Additionally, vasomotor control of the circulation is also impaired in individuals with SCI, reducing the ability of the body to respond to the need to increase or decrease blood flow in areas that require it. In individuals with injuries above T6, reflex function of the spinal cord returns following the spinal shock phase with a return or increase in vascular tone. However in individuals with injuries below T6, reduced vascular tone
is permanent below the injury level (Bogie, Nusiebeh and Bader, 1995). These findings suggest that tissue integrity can differ between individuals with injuries above or below T6 and individuals with paraplegia may be at higher risk of tissue breakdown than individuals with tetraplegia.

Figure 2-2 Sequalae following SCI
2.4.1.1 Early Detection of Pressure Injuries

By the time tissue breakdown has occurred at the surface, tissue damage is severe (Swisher et al., 2015). There are several methods to assess the development of PIs before tissue breakdown appears at the surface in addition to measurement of tissue healing (Figure 2-3). A tristimulus colorimeter can be used to capture colour dimensions of the skin and thus capture non-blanchable erythema, which is present with impending pressure injuries. Skin redness can also be assessed through the use of digital camera computer-based colour image analysis (Staro and Spravigna, 2002). Impedence spectroscopy was used to assess changes in tissue in a rat model and has been correlated with TH (Swisher et al., 2015), while bioimpedance has been used to assess electrical properties of tissue (Chandler et al., 2014). Subepidermal moisture in the skin, a biophysical marker correlating with edema, has been measured in skin surrounding stage III and stage IV PIs and found to be higher than in control sites (Harrow and Mayrovitz, 2014). Local transcutaneous oxygen levels (Bogie, Nuseibeh and Bader, 1995, Bogie and Triolo, 2003, Reenalda et al., 2009) and/or carbon dioxide in the skin have been used to measure the risk or healing of PIs both in loaded and unloaded tissue. Bogie, Nuseibeh and Bader (1995) noted blood flow differences at the seated support interface between individuals with SCI below and above T6 and found that tissue viability was higher in individuals with tetraplegia vs. paraplegia suggesting that individuals with paraplegia were at higher risk of tissue breakdown at the seated support interface. Additionally, sweat lactate and urea (Knight et al., 2001) and glucose, glycerol and lactate pyruvate ratio levels in the tissue have also been used as a measure of TH (Thorfinn et al., 2009). US has been used to assess changes in integrity in tissues at risk for development of PI (Quintavalle et. al., 2006), while ultrasound based elastography has been used to assess mechanical properties of tissues (Gao et al., 1996).
Figure 2-3. Etiology of Pressure Injuries and Potential Measures

Tissue health and the assessment of tissue health must be considered in the context of the development of PIs. While there are many studies that have examined the tissue in response to loading, the etiology of the development of PIs must be considered in addition to the selection of the most appropriate measures. It is not possible for the researcher to use all measures to evaluate tissue health, rather the selection of the measure(s) will depend where along the pathway the researcher chooses to examine the development of PIs while taking into consideration the sensitivity, specificity, responsiveness to change and predictive utility of each of these measures.

2.4.2. Ultrasound Imaging to Assess Tissue Integrity

Diagnostic US has been used to document wound healing, assess changes in scar tissue and evaluate the effect of steroids atrophy (Rippon et al. 1998). Brightness mode (B-mode) US can be used to produce high quality images of muscle morphology and soft tissue integrity (Schmid-Wendtner and Burgdorf, 2005) visualization of epidermal and dermal regions, collagen, sweat
glands, hair follicles, muscles, tendons and joints by providing cross-sectional images of scanned tissues in real time. High frequency US scanning has many applications including evaluation of skin thickness, muscle size and quality, spatial orientation of blood vessels, identification of areas of calcification, necrosis and changes in inflammation over time.

US images can subjectively interpreted and characterized to obtain metrics of TH. Areas of tissue damage may demonstrate areas of hypoechoiginicity secondary to tissue edema. Fatty infiltration of muscle secondary to disuse may show areas of hyperechoginicity. Grey-scale analysis of tissue using extracted data from ultrasound images can be used to assess healing in damaged tissues of rats (Moghimi et al, 2010). While US imaging does not replace histopathological examination of tissue, during inflammatory processes, the sonograms demonstrate areas of hypoechoic bands within the dermis and subdermal areas and can be used to indicate tissue damage.

A limitation of US is that it has a relatively limited depth and field of view compared with Magnetic Resonance Imaging (MRI) (Ahtiainen et al. 2009) and is operator dependent in that image quality relies on the scanning technique, probe placement (Dudley-Javoroski et al., 2010), quality of the ultrasound system and probe frequency. However US is non-invasive, quick to perform, safe, relatively inexpensive and a more widely available technique compared with MRI. While MRI is widely regarded as the “gold standard” for the assessment of muscle size and tissue damage, it is costly, time consuming and access to MRI for research and rehabilitation purposes is often limited (Ahtiainen et al. 2009). Furthermore, US provides adequate information about soft TH, muscle size and shape and is suitable for laboratory and clinical use at the bedside and can be used to assess tissue integrity. The accurate characterization of soft TH in vivo is important in patients with SCI for studying the effects of injury, disease related changes and the effects of immobility.
2.5 Loading the Ischial Tuberosity and Pressure Relief

The ischial tuberosity (IT) (Figure 2-3) is the main weight bearing bone in sitting and is often referred to as the “sit bone”. The hamstring tendons (semimembranosus, semitendinosus, biceps femoris) attach to the IT. The gluteus maximus overlies the tendon separated by a bursa. Overlying the gluteus maximus muscle is subcutaneous tissue and skin.

Figure 2-4 The Ischial Tuberosity. Overlying the ischial tuberosity is the gluteus maximus muscle, subcutaneous tissue and skin. Thickness measurements of tissues overlying the ischial tuberosity have been evaluated by several investigators.

While sitting, pressure occurs over the IT. Reduced muscle thickness overlying the IT reduces the ability of the tissues overlying the IT to bear loads during sitting (Makhsous et al., 2011) and
increases the vulnerability in developing seated acquired pressure injuries (Linder-Ganz and Gefen, 2009). In a Sprague Dawley rat model, Nola and Vistnes (1980) found that increased muscle mass under the skin by affixing a muscle flap over the skin assists in the diffusion of pressure thereby reducing the incidence of skin ulcerations.

The depth of the IT from the skin and its relationship to the gluteus maximus muscle and hamstrings has been reported in the literature. It has been recognized that relative position of the IT to the surrounding muscles is dependent on hip and pelvic position. Additionally, the tissue thickness overlying the IT is dependent on the relative position of the gluteus maximus and hamstring muscle (Makhsous et al., 2011). Furthermore, the relative thickness of tissues overlying the IT is dependent on loading, as would occur during sitting (Al-Dirini, Reed and Thewlis, 2015). The effects of both temporal and spatial redistribution of pressure over the IT and the physiological effects it has on the tissues have been investigated by several researchers using a number of different paradigms, tools and outcome measures.

Using MRI, Makhsous et al (2011) found that the tissue overlying the IT was significantly thinner ($P < 0.001$) at 90° of hip flexion and was reduced by up to 50% under weight bearing loads ($P < 0.001$) in the simulated sitting position. Greatest deformation was found in the muscle region when compared with adipose tissue and skin. These findings are consistent with Al-Dirini, Reed and Thewlis (2015) who found the greatest deformation in the gluteus muscle compared with the subcutaneous fat during loaded conditions.

In a case study by Sonenblum, Sprigle, Cathcart and Winder (2013) examining the response of the healthy buttocks and surrounding muscles in unloaded and loaded sitting position using an open MRI, the muscle tissue was compressed, displaced and distorted when loaded. During the unloaded condition, the gluteus maximus and hamstring overlapped and enclosed the IT, however in the loaded position, anterior displacement of the hamstring and posterior-lateral displacement of the gluteus muscle relative to the IT was found in addition to muscle deformation.

In a follow-up study by Sonenblum, Sprigle, Cathcart and Winder (2015), differences in tissue loading were compared between able-bodied individuals and individuals with SCI. Individuals with SCI were found to have atrophy of the muscle overlying the IT. Subcutaneous fat and gluteus muscle thickness in able-bodied individuals ranged from 8-59 mm and 0-21 mm in the
unloaded position respectively and between 7-32 mm and 0-8 in the loaded condition respectively. Subcutaneous fat thickness in individuals with SCI ranged from 6-30 mm in the unloaded position and between 6-15 mm in the loaded condition. Gluteus muscle thickness in the loaded and unloaded conditions was measured as 0 mm. Similarly, Thorfinn et al. (2009) found that thickness of the subcutaneous tissue overlying the ischial tuberosity in able-bodied women was 29 mm on the left and 31 mm on the right, whereas for men it was 17 mm on the left and 18 mm on the right. It is important to note that these researchers did not take into consideration differences in the shape of tissues overlying the IT during their unloaded experimental protocol which could affect their findings.

There have also been several investigations examining pressure under the IT during different seated postures, pressure relief maneuvers, positioning of power wheelchairs and the use of wheelchair cushions in order to study the effect on the overlying tissue. Lateral tilt of the wheelchair caused compression under the ipsilateral muscle and fat overlying the IT, with increasing compression with increasing tilt angle in 10 healthy individuals (Shabshin et al., 2010). Grip and Merbitz (1986) utilized a “custom portable computer” which not only recorded pressure relief, but also provided a cue for individuals with SCI to engage in weight shifting behaviours. This device also provided a signal to the individual to engage in a pressure relief maneuver based on pre-set criteria and the individual’s performance.

The effect of tilt and recline on loading over the IT and coccygeal areas in individuals with SCI who utilize a power wheelchair has been explored by several investigators by examining interface tissue pressures (Chen et. al 2014) while other investigators have examined different cushions on the generation of interface seating pressures (Akins, Karg and Brienza, 2011). When the back support was reclined to 10 degrees, the authors found a significant decrease in ischial interface pressures between a 15 and 35 degree tilt (i.e. angle of chair) (Chen et al., 2014). The authors also found that a decrease in ischial interface pressures occurred when the chair was reclined from 10-30 degrees. Therefore, one can conclude that unloading the IT can be achieved in power wheelchair users through the use power assisted repositioning techniques when the back support of the chair is 10 degrees and the angle of the seat tilts from 15-35 degrees and can also be achieved when the chair is tilted between 10-30 degrees.
In a study examining the pressure under the ITs during varying reach tasks, the authors found that a cross body reach provided unloading under the ischium of the corresponding reaching arm, while an ipsilateral reach caused loading of the ischium under the corresponding reaching arm (Swarts, Krouskop and Smith, 1988). These authors recommended that cross-body movements should be used to promote weight shifting. Park (1992) studied the effect of unloading at the IT during reaching at varying heights in varying directions and movements and noted forward and lateral reaches unloaded the IT.

The effect of implanted neuromuscular electrical stimulation of the vastus lateralis, gluteus maximus, hamstrings, and erector spinae oxygen levels on tissue overlying the IT in addition to measuring interface seated pressures was evaluated in a cohort of 8 individuals with SCI by Bogie and Triolo (2003). The authors found an increase in unloaded tissue oxygen levels in the gluteal region in most participants by upwards of 36% and a decrease in interface pressures over the ischial region following an 8 week exercise program which could be attributed to increased vascularity in the former and increased muscle bulk in the latter.

Individual with SCI are at risk of developing a PI over the IT due to prolonged unrelieved pressure while sitting as well as loss of muscle mass. Management strategies following SCI are focused on improving secondary complications, improving functional status and preventing further functional loss. Of particular focus is the development of a skin integrity program in order to prevent and manage pressure ulcers (McDonald and Sadowsky, 2002) by employing pressure relief strategies, engaging in regular skin checks, ensuring appropriate perineal hygiene in addition to ensuring adequate nutritional intake (Houghton and Campbell, 2013). The prescription of adequate seated support surfaces is also used to prevent skin breakdown. Best practice recommendations include weight shifting including every 15-30 minutes for at least 2-3 minutes (Coggrave et al., 2003) in order to relieve pressure and thereby prevent skin breakdown. Pressure relief in a wheelchair can take many forms including forward lean, side leans, and push ups. To date, it is unknown whether morphological differences in loaded vs. unloaded tissue can be detected using ultrasound imaging.

Morphological changes in the tissue may occur from prolonged unrelieved pressure. The inability to engage in adequate weight shifting due to sensorimotor impairments can therefore
affect tissue integrity. The relationship between pressure offloading in SCI and tissue integrity using quantitative ultrasound imaging has not been studied to date.

**2.6 Thesis Aims and Hypotheses**

The primary aim of this thesis is to examine the relationships between trunk function, offloading of the IT and health of the tissues overlying the IT in individuals with TSCI and NTSCI. Understanding the relationships between trunk function, offloading behaviour and health of weight bearing tissues may shed light on the potential need to develop rehabilitation programs targeting trunk function in order to potentially reduce the incidence of seated acquired pressure injuries in SCI.

The specific research question and the respective hypotheses which will be tested and answered throughout chapters 3-6 of the thesis include the following:

1) Chapter 3: The Exploration of Quantitative Ultrasound Imaging to Inform Skin Assessment

   - **Question:** Can we establish reliable measures to characterize geometric, grey scale and texture measures of tissues overlying the IT using ultrasound imaging?

   - **Hypothesis:** Tissue health measures in a sample of able bodied individuals will demonstrate high inter-trial reliability when using a single evaluator (coefficient of dependability >0.80)

2) Chapter 4: Trunk Strength and Function Using the Multidirectional Reach Test in Individuals with NTSCI

   - **Question:** How do measures of trunk function change over the course of rehabilitation in individuals with NTSCI?
• **Hypothesis**: Trunk function as measured by trunk strength and multidirectional reach distance will improve over the course of inpatient rehabilitation in patients with NTSCI

3) Chapter 5: Trunk function and ischial offloading in individuals with SCI.

  - **Question**: Is there a relationship between trunk function and ischial offloading in individuals with TSCI and NTSCI?

  - **Hypothesis**: There is a positive correlation between trunk function and ischial offloading in individuals with TSCI and NTSCI.

4) Chapter 6: The relationship between trunk function and ITH in individuals with SCI: an exploratory study

  - **Question 1**: Are there differences in the health of weight bearing tissues of individuals with TSCI and NTSCI compared to an able body cohort?

  - **Hypothesis 1**: Individuals with SCI will have reduced thickness of skin, subcutaneous tissue and muscle overlying the IT when compared with healthy controls.

  - **Question 2**: Is there a relationship between offloading behaviour and ITH in individuals with TSCI and NTSCI?

  - **Hypothesis 2**: There is a positive relationship between offloading behaviour and ITH (as measured by US imaging) in individuals with TSCI and NTSCI
Chapter 3 The Exploration of Quantitative Ultrasound Imaging to Inform Tissue Assessment

This chapter is a modified version of the following article, where modifications consist of changes in formatting:


To be submitted for publication
3.1 Abstract

Characterization of ischial tissue health (ITH) using standardized methods from diagnostic ultrasound (US) has not been established. The purpose of this study was to evaluate inter-participant and inter-trial reliability of thickness, gray scale and tissue texture measures from US images of tissues overlying the ischial tuberosity (IT). It provides recommendations for the number of images required to minimize the standard error of measurement (SEM) and calculates thickness and gray scale values close to the hypothetical true value. Brightness mode US images were collected on the dominant limb in the side lying position for ten healthy participants. Thickness and gray scale measures of skin, muscle and subcutaneous tissue were calculated using a customized MATLAB program. Generalizability theory was used to quantify indices of dependability and corresponding SEMs and Minimal Detectable Changes (MDC) with 90% Confidence Intervals. Participants (P) accounted for most of the total variance (75.56% to 94.78%). Coefficient of dependability (ϕ) for thickness and grey scale measures was greater than 0.80 when more than two were averaged. Coefficient of dependability (ϕ) for tissue texture measures was greater than 0.80 when more than four images were averaged. While methodological challenges exist in establishing tissue health measures, high reliability of quantifying tissue health is attainable between image captures by a single therapist on an individual participant.
3.2 Introduction

Diagnostic ultrasound is a safe, widely available, economical, efficient and non-invasive tool used to provide information regarding soft tissue integrity of the epidermis, dermis, subcutaneous tissue, muscle, tendons and joints (Schmid-Wendtner and Burgdorf 2005; Aoi et al., 2009, Quintavalle et al., 2006; Kanno et al., 2009). Brightness mode (B-mode) diagnostic ultrasound produces grey scale images (English et al., 2012), which enable visualization of skin thickness, muscle size and quality, orientation of blood vessels and progression of inflammation. Diagnostic ultrasound has been used to document soft tissue injury, assess wound healing, evaluate changes in scar tissue and examine the effect of atrophy secondary to steroid use (Rippon et al., 1998; Dyson et al., 2003) and diseased states including musculoskeletal and neuromuscular disorders (Dudley-Javoroski 2010; English et al., 2012; Thomaes et al., 2012). Tissue integrity can be characterized using gray scale analysis of the micropixels, which form ultrasound images (Moghimi et al. 2010). These findings suggest that diagnostic ultrasound may be a valuable tool to characterize “tissue health” in other disease states.

Using gray scale analysis of ultrasound images, each pixel is assigned a grey scale value ranging from 0 to 255, where 0 corresponds to black and 255 corresponds to white. The mean grey scale of the image can be quantified using the average grey scale of the pixels encompassed in a specific region of an image and defined as “echogenicity”. The frequency distribution of the grey scale values from all pixels can be interpreted using a histogram. Variance, symmetry, kurtosis and uniformity can be calculated from the data. Furthermore, the interrelation of the grey scale of each pixel or subgroup of pixels and its neighbouring pixels can be estimated in different orthogonal directions over a specific region of an image using a grey level co-occurrence matrix and expressed as the “contrast”, where 0 corresponds to a uniform image of equal grey scale throughout the image (Nadeau et al., 2016).

While ultrasound imaging does not replace histopathological examination of tissue, areas of tissue damage may be demonstrated by reduced ultrasound reflectance (hypoechogenicity) secondary to edema and changes to tissue architecture (Quintavalle et al. 2006). While high frequency ultrasound can be used to characterize soft tissue health in individuals to study the effect of injury, disease related changes and immobility, image quality, which is dependent on
the skill of the operator (Mercuri et al. 2007), probe placement, scanning technique and system parameter settings (Dudley-Javoroski et al. 2010) is integral in demonstrating its utility. Furthermore, there is literature demonstrating different applications for its use in tissue assessment (Reimers, Harder, Sax, 1998, Lal et al., 2002, Maurits et al., 2003, Porter Armstrong et al., 2013, Nato et al., 2014).

The reliability and validity of B-mode ultrasound has been established in estimating the size of skeletal muscles and has been compared with both computerized tomography (Thomaes et al., 2012) and magnetic resonance imaging (Miyatani et al., 2004; Ahtiainen et al., 2009), which are considered the “gold standards” (Thomaes et al., 2012; Ahtiainen et al., 2009). Cross-sectional area, volume and thickness of upper and lower limbs muscles have been evaluated in healthy individuals and individuals with neuromusculoskeletal disorders (English et al., 2012).

Echogenicity of the biceps tendon and supraspinatus tendon thickness in wheelchair users has also been evaluated to reflect edema (van Drongelen et al. 2007, Fournier et al., 2017). Skin, adipose and muscle thickness in individuals with spinal cord injury (Yalcin et al. 2013, Akins et al., 2016, Swaine et al., 2017), adipose tissue thickness of young adults (Leahy et al. 2012) and median nerve excursion in healthy individuals and in individuals with carpal tunnel syndrome (Paquette et al. 2015) have also been measured. The presence of edema and/or damage in the dermis, subepidermal and subcutaneous tissue identified from images acquired using high frequency (20 MHz) transducers has been used as an adjunct assessment approach along with clinical skin assessment overlying the heels and coccygeal areas in vascular surgery patients (Porter-Armstrong et al. 2013).

Assessing tissue integrity overlying the ischial tuberosity in healthy individuals could serve as a comparator for other populations or as a baseline in cases where tissue damage is suspected; however characterization of healthy tissue has not yet been established. The physiological changes identified with impending pressure injuries (Quintavalle et al., 2006) and the lack of quantification of buttock tissue health necessitates a study to examine whether standardized measures can be quantified using ultrasound imaging. The purposes of the present study were to i) evaluate the reliability of thickness and gray scale measures from ultrasound images of tissues overlying the ischial tuberosity, ii) provide recommendations for the number of images required to minimize the Standard Error of Measurement (SEM), and iii) obtain thickness and gray scale values that are close to the hypothetical value, which could be used as a comparisons with other
populations thereby informing tissue assessment. We anticipated that our protocol would be able to establish reliable ($\phi > 0.80$) and accurate measures (SEM $< 15\%$) for thickness, grey scale and texture measures of the tissue overlying the ischial tuberosity.

3.3 Materials and Methods

The study was approved by the Institutional Review Board at the University of Toronto. All testing procedures were performed at the Muscle Performance Lab at the University of Toronto. All participants provided informed consent to take part in the study.

3.3.1 Participants

Ten healthy participants (4 males), aged 23-69 (mean age $42.8 \pm 15.7$) years were recruited for the study by convenience sampling and evaluated at two time points, spaced sixty minutes apart. Participants were excluded from the study if they reported any history of prior injury or surgery of the hip, knee, or ankle, history of muscle disease (e.g. muscular dystrophy, polymyositis), or any skin conditions (e.g. dermatitis, psoriasis) to eliminate any confounding variables on ultrasound imaging.

3.3.2 Ultrasound Imaging Protocol

3.3.2.1 Ultrasound Device

A Linear Array B-Mode 12 MHz Ultrasound Transducer (GE LOGIQ-E Ultrasound system, GE Healthcare, WI, USA) was used to scan the tissue overlying the ischial tuberosity. Gain, depth
and time/gain compensation were standardized for each individual to ensure within-participant consistency in measures and to ensure optimal image quality. Although optimization of each participant could result in difference grey scale and tissue measures, the rationale was to simulate what would happen in the clinical setting.

3.3.2.2 Ultrasonographer

A physical therapist captured and recorded all ultrasound images. The physical therapist received 2 hours of training in ultrasonography by a physical therapy researcher with experience in performing ultrasound image acquisition and well published in the field of musculoskeletal ultrasound imaging. The physical therapist received training in identifying the placement of the ultrasound transducer to capture the region of interest and image optimization to distinguish the superficial fat and muscle layers in addition to the bone.

3.3.2.3 Image acquisition

Participants assumed the side lying position with the dominant leg uppermost as determined by the kicking leg, with the hip and knee flexed to 90° with a pillow between the knees to maintain neutral hip abduction/adduction and neutral internal/external rotation. A goniometer was used to ensure hip and knee flexion of 90°. Once the participant was placed in the scanning position, the ischial tuberosity was palpated and its perpendicular distance at mid-point from a line between the coccyx and greater trochanter was recorded using a tape measure. The midpoint of the line between the greater trochanter and coccyx to the ischial tuberosity was recorded to ensure consistent placement of the ultrasound probe between trials. Three longitudinal ultrasound images were captured for each participant on two distinct occasions separated by sixty minutes. Prior to each image being captured, the probe was removed and then reapplied over the same landmark. Care was taken during image capture to minimize tissue deformation under the probe. System settings on the ultrasound unit remained the same for the two ultrasound scanning
sessions for each participant. Two dimensional ultrasound images were captured by the GE system, and subsequently transferred in a DICOM format to an encrypted computer for analysis. The mean of three images was used to obtain group means and standard deviations.

### 3.3.2.4 Image Processing

The ultrasound images in DICOM format were imported to a customized image analysis software, using MATLAB Image Processing Toolbox (MATLAB 2013, Mathworks, USA) for 2D viewing and analysis. The ischial tuberosity was traced by the investigator using an image marker. The ischial tuberosity was identified as a curved hyperechoic structure with an anechoic bone shadow beneath (Pillen and van Alfen 2011). The investigator then outlined a well-defined area over the ischial tuberosity. Within each area overlying the ischial tuberosity, boundaries between the skin-subcutaneous tissue and subcutaneous tissue-muscle and the muscle-ischial tuberosity were selected manually using image markers. The skin was identified as a smooth hyperechoic layer with a clearly defined boundary. Subcutaneous tissue was identified as an area of low echoic intensity with echogenic boundaries of connective tissue and muscle was identified as an area of low echoic intensity with fascicular architecture surrounded by clearly defined boundaries as per Pillen and van Alfen (2011). Once all boundaries were identified, the image was partitioned into three main regions of interest (ROIs) by the MATLAB Image Processing Toolbox: skin, subcutaneous tissue and muscle. The investigator confirmed correct partitioning of boundaries and any errors in identifying boundaries were corrected. Geometric measures (mean and maximal skin, subcutaneous and muscle thickness, and depth of the ischial tuberosity), measurement related to gray scale analysis (echogenicity of the skin, subcutaneous tissue and muscle) and measurements related to the grey scale co-occurrence matrix in each ROI (i.e. contrast of the regions corresponding to skin, subcutaneous tissue and muscle) were extracted.
3.3.3 Statistical Analysis

In order to determine if the investigator identified boundaries consistently within images, intra-
class correlation coefficients (ICC(2,1)) with 95% Confidence Intervals were calculated from
repeated measurements of one image from each participant by the same rater.

SPSS Statistics (SPSS Statistics 23, IBM, USA) was used to obtain group means and standard
deviations for participants’ mean and maximal thickness, echogenicity and contrast of skin,
subcutaneous tissue and muscle. A Multivariate Analysis of Variance was used to determine if
significant differences existed between Time 1 and Time 2 in mean and maximal thickness,
echogenicity and contrast of skin, subcutaneous tissue and muscle using a p-value of 0.05.

For reliability analyses, a Generalizability Study (G-Study) using the GENOVA software
(Springer-Verlag, USA), was first conducted to compute the multiple sources of error in the
measurements including the participant (P), the ultrasound image (I) and the random errors
associated from the interaction effects between the participant and image (PI). Multiple sources
of errors in the measurements were expressed as a percentage of the total variance. Then,
coefficients of dependability (D-Study) were computed (Briesch et al., 2014) for each
measurement to determine the reliability when one or multiple images (i.e. mean of 2, 3, 4 or 5
images) were used. While only 3 images per participant were used for this study in the
calculation of the generalizability coefficient, the information gathered from the G-Study enables
one to calculate the variance and interaction components of more than one image by dividing the
variance by the number of images used in the calculation of the mean (Cardinet et al., 1976). The
following interpretation for reliability was used: $\phi < 0.50$ representing poor reliability, $0.50-
0.75$ representing moderate reliability and $\phi > 0.75$ representing good reliability (Portney and
Watkins, 2000).

Absolute Standard Error of Measurement (SEM) (expressed as the square root of the absolute
variance), Relative SEM (expressed as (SEM/overall mean) x 100) Absolute Mean Detectable
Change (Absolute MDC) using 90% Confidence Interval (expressed as $1.65 \times \text{SEM} \times \sqrt{2}$) and
Relative Mean Detectable Change (Relative MDC) using 90% Confidence Interval (expressed as
(Absolute MDC/overall mean) x 100) were calculated for all measures to determine the
dispersion of measurement error and spread of the data respectively. The SEM was used to
 quantify the accuracy of the measurements and to calculate confidence intervals around the measured variables. A higher SEM indicates low accuracy of the measurement, whereas a low SEM indicates a high level of accuracy. MDC enables one to determine the value that is required to establish that a change in measure is not due to chance (Gibney et al. 2010). Therefore, any value exceeding the MDC is considered to indicate a true change. A 90% Confidence Interval was selected to reflect the common standard used in physical therapy research (Haley and Fragala-Pinkham, 2006).

3.4 Results

Demographics of study participants are found in Table 3-1.

Table 3-1 Demographics of Study Participants

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<thead>
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<th>Count</th>
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<td>Sex (males/females)</td>
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<table>
<thead>
<tr>
<th>Mean ± SD</th>
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</thead>
<tbody>
<tr>
<td>Age (years)</td>
</tr>
<tr>
<td>Height (cm)</td>
</tr>
<tr>
<td>Weight (kg)</td>
</tr>
</tbody>
</table>
Intra-class correlation coefficients (ICC(2,1)) from repeated measurements on the same image by the same rater identified intraclass correlation coefficients between 0.902-0.999 (Table 3-2).

Table 3-2 Intra-Rater Reliability from Repeated Measurements on the Same Image by the Same Rater with 95% Confidence Intervals

<table>
<thead>
<tr>
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<th>95% Confidence Interval</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
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<td></td>
<td>Intraclass Correlation</td>
<td>Lower Bound</td>
<td>Upper Bound</td>
<td>Significance</td>
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</tbody>
</table>

A representative longitudinal ultrasound image overlying the ischial tuberosity is illustrated in Figure 3-1A and 3-1B. Table 3-3 summarizes the descriptive statistics of mean and maximal thickness, echogenicity and contrast of skin, subcutaneous tissue and muscle at the two time points. There were no significant differences between Time 1 and Time 2 for the mean and maximal thickness, echogenicity and contrast values at the skin, subcutaneous tissue and muscle layers and therefore data was pooled for Time 1 and Time 2 for the Generalizability and Dependability studies.
Figures 3-1A and 3-1B Ultrasound image of the tissue overlying the ischial tuberosity in one healthy participant (a). The same image is then processed (b) to partition the tissue into three different layers: including skin, subcutaneous tissue and muscle. The ischial tuberosity is indicated by a hyperechoic structure. The image reveals a homogenous pattern of reflection from the epidermis down to the ischial tuberosity. A clear muscle layer is identified, corresponding to the gluteus maximus muscle. Selective regions of interest were analyzed using MATLAB software to calculate mean and maximal thickness of skin, subcutaneous tissue, and muscle, depth of ischial tuberosity, echogenicity, and contrast.
Table 3-3 Mean and Standard Deviations of Thickness, Echogenicity and Contrast in Skin, Subcutaneous Tissue and Muscle over the Regions of Interest for Time 1 (n = 10), Time 2 (n = 10) and Overall (n = 20)

<table>
<thead>
<tr>
<th></th>
<th>Time 1 (mean ±SD)</th>
<th>Time 2 (mean ±SD)</th>
<th>Overall (mean ±SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum Thickness (mm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>2.63±0.46</td>
<td>2.64±0.46</td>
<td>2.64±0.45</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>9.24±3.07</td>
<td>9.89±3.50</td>
<td>9.56±3.22</td>
</tr>
<tr>
<td>Muscle</td>
<td>18.21±7.16</td>
<td>19.42±6.33</td>
<td>18.82±6.61</td>
</tr>
<tr>
<td><strong>Mean Thickness (mm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>2.33±0.40</td>
<td>2.38±0.41</td>
<td>2.36±0.40</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>8.20±3.25</td>
<td>8.77±3.68</td>
<td>8.48±3.94</td>
</tr>
<tr>
<td>Muscle</td>
<td>14.49±6.58</td>
<td>15.58±6.07</td>
<td>15.04±6.18</td>
</tr>
<tr>
<td><strong>Echogenicity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>91.79±6.18</td>
<td>87.23±6.31</td>
<td>89.51±6.51</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>75.68±13.55</td>
<td>70.99±13.38</td>
<td>73.33±13.32</td>
</tr>
<tr>
<td>Muscle</td>
<td>76.59±10.98</td>
<td>72.39±14.72</td>
<td>74.49±12.82</td>
</tr>
<tr>
<td><strong>Contrast</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>16.83±5.58</td>
<td>15.33±4.79</td>
<td>16.08±5.12</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>19.02±8.27</td>
<td>18.16±6.90</td>
<td>18.59±7.42</td>
</tr>
<tr>
<td>Muscle</td>
<td>11.16±4.55</td>
<td>11.56±4.23</td>
<td>11.36±4.28</td>
</tr>
</tbody>
</table>

*Echogenicity is quantified using a greyscale range from 0-255, where 0 = black, 255 = white
**Contrast is quantified at 0 = no contrast (image is completely homogeneous, all pixels have the same greyscale)

The thickest layer of tissue observed over the ischial tuberosity was the area occupied by muscle (mean 18.82 ± 6.61 mm) followed by subcutaneous tissue (mean 9.56 ± 3.22 mm). Higher echogenicity was observed in the area occupied by skin (89.51 ± 6.51) when compared with subcutaneous tissue (73.33 ± 13.32) and muscle (74.49 ± 12.82).
3.4.1 G-Study: Magnitude of Component Variances

The largest proportion of the total variance (75.56% to 94.78%) was associated with the participants (P), whereas the lowest proportion of the variance (≤ 0.20%) was attributed with the image (I). Participant-image interaction demonstrated that there were substantial interaction effects across all outcome measures, ranging from 5.22% to 33.03% (Table 3-4).

Table 3-4 Magnitude of Variance Components Expressed as a Percentage of the Total Variance for Each Source of Variance (P = Participant, I = Image) and Interactions (PI = Interaction of Participant and Image) for All Measures. Data Obtained from the G-Study

<table>
<thead>
<tr>
<th></th>
<th>Participant (P)</th>
<th>Image (I)</th>
<th>PI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum Thickness</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>75.56</td>
<td>0.00</td>
<td>24.43</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>85.64</td>
<td>0.00</td>
<td>14.36</td>
</tr>
<tr>
<td>Muscle</td>
<td>89.77</td>
<td>0.00</td>
<td>20.23</td>
</tr>
<tr>
<td><strong>Mean Thickness</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>82.01</td>
<td>0.00</td>
<td>17.99</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>90.04</td>
<td>0.00</td>
<td>9.96</td>
</tr>
<tr>
<td>Muscle</td>
<td>91.48</td>
<td>0.00</td>
<td>8.52</td>
</tr>
<tr>
<td><strong>Echogenicity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>82.07</td>
<td>0.00</td>
<td>17.93</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>94.78</td>
<td>0.00</td>
<td>5.22</td>
</tr>
<tr>
<td>Muscle</td>
<td>87.15</td>
<td>0.00</td>
<td>12.85</td>
</tr>
<tr>
<td><strong>Contrast</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>66.97</td>
<td>0.00</td>
<td>33.03</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>87.91</td>
<td>0.20</td>
<td>11.89</td>
</tr>
<tr>
<td>Muscle</td>
<td>71.88</td>
<td>0.00</td>
<td>28.12</td>
</tr>
</tbody>
</table>
3.4.2 D-Study: Coefficients of Dependability, Inter-Trial and Inter Participant Reliability

The dependability coefficients (ϕ) for each region of tissue overlying the ischial tuberosity are represented in Table 3-5. Mean thickness measures reached good reliability across the three layers investigated, with the highest value reached for the muscle. Coefficients of dependability for mean thickness were lowest for the skin (0.820-0.932) and highest for the muscle (0.915-0.970). Measures for echogenicity and contrast were lowest for the skin (0.8210-0.932 and 0.670-0.859, respectively) and highest for the subcutaneous tissue (0.948-0.982, and 0.879-0.956, respectively).
Table 3.5 Inter-Trial Reliability (measured by Coefficient of Dependability $\phi$) Obtained for a Mixed D-Study Design with 1 Evaluator Using 1 Image, the Average of 2 Images, 3 Images, 4 Images and 5 Images for Thickness, Echogenicity and Contrast

<table>
<thead>
<tr>
<th></th>
<th>1 Image</th>
<th>2 Images</th>
<th>3 Images</th>
<th>4 Images</th>
<th>5 Images</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Thickness</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>0.756</td>
<td>0.861</td>
<td>0.903</td>
<td>0.925</td>
<td>0.939</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>0.856</td>
<td>0.923</td>
<td>0.947</td>
<td>0.960</td>
<td>0.968</td>
</tr>
<tr>
<td>Muscle</td>
<td>0.898</td>
<td>0.946</td>
<td>0.963</td>
<td>0.972</td>
<td>0.978</td>
</tr>
<tr>
<td>Mean Thickness</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>0.820</td>
<td>0.901</td>
<td>0.932</td>
<td>0.948</td>
<td>0.958</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>0.900</td>
<td>0.948</td>
<td>0.964</td>
<td>0.973</td>
<td>0.978</td>
</tr>
<tr>
<td>Muscle</td>
<td>0.915</td>
<td>0.956</td>
<td>0.970</td>
<td>0.977</td>
<td>0.982</td>
</tr>
<tr>
<td>Echogenicity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>0.821</td>
<td>0.902</td>
<td>0.932</td>
<td>0.948</td>
<td>0.958</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>0.948</td>
<td>0.973</td>
<td>0.982</td>
<td>0.986</td>
<td>0.989</td>
</tr>
<tr>
<td>Muscle</td>
<td>0.872</td>
<td>0.931</td>
<td>0.953</td>
<td>0.964</td>
<td>0.971</td>
</tr>
<tr>
<td>Contrast</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>0.670</td>
<td>0.802</td>
<td>0.859</td>
<td>0.890</td>
<td>0.910</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>0.879</td>
<td>0.936</td>
<td>0.956</td>
<td>0.967</td>
<td>0.973</td>
</tr>
<tr>
<td>Muscle</td>
<td>0.719</td>
<td>0.836</td>
<td>0.885</td>
<td>0.911</td>
<td>0.927</td>
</tr>
</tbody>
</table>

Of the three layers examined, relative SEM for thickness and echogenicity measures were lower in the skin when compared with subcutaneous tissue and muscle (Table 3-6). The skin yielded the lowest relative SEM for maximal and mean thickness and echogenicity measures (4.315-9.648, 3.633-8.124, 1.464-3.273) when compared with subcutaneous tissue (5.863-13.109,
5.757-12.872, 2.158-4.826) and muscle (4.958-11.086, 5.341-11.943, 2.660-5.947). With increasing number of images averaged, a decrease in the relative SEM was found for all measures.

Table 3-6 Relative Standard Error of Measurement (SEM-rel) in Thickness, Echogenicity and Contrast of Repeated Measures of Skin, Subcutaneous Tissue and Muscle Thickness

<table>
<thead>
<tr>
<th></th>
<th>Image 1</th>
<th>Image 2</th>
<th>Image 3</th>
<th>Image 4</th>
<th>Image 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum Thickness (mm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>9.65</td>
<td>6.82</td>
<td>5.57</td>
<td>4.82</td>
<td>4.32</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>13.15</td>
<td>9.27</td>
<td>7.57</td>
<td>6.56</td>
<td>5.86</td>
</tr>
<tr>
<td>Muscle</td>
<td>11.09</td>
<td>7.84</td>
<td>6.40</td>
<td>5.54</td>
<td>4.96</td>
</tr>
<tr>
<td><strong>Mean Thickness (mm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>8.12</td>
<td>5.74</td>
<td>4.69</td>
<td>4.06</td>
<td>3.63</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>12.87</td>
<td>9.10</td>
<td>7.43</td>
<td>6.44</td>
<td>5.76</td>
</tr>
<tr>
<td>Muscle</td>
<td>11.94</td>
<td>8.44</td>
<td>6.90</td>
<td>5.97</td>
<td>5.34</td>
</tr>
<tr>
<td><strong>Echogenicity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>3.27</td>
<td>2.32</td>
<td>1.89</td>
<td>1.64</td>
<td>1.46</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>4.83</td>
<td>3.41</td>
<td>2.79</td>
<td>2.41</td>
<td>2.16</td>
</tr>
<tr>
<td>Muscle</td>
<td>5.95</td>
<td>4.20</td>
<td>3.43</td>
<td>2.97</td>
<td>2.66</td>
</tr>
<tr>
<td><strong>Contrast</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>23.68</td>
<td>16.74</td>
<td>13.67</td>
<td>11.84</td>
<td>10.59</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>14.48</td>
<td>10.24</td>
<td>8.36</td>
<td>7.24</td>
<td>6.47</td>
</tr>
<tr>
<td>Muscle</td>
<td>22.18</td>
<td>15.68</td>
<td>12.80</td>
<td>11.09</td>
<td>9.92</td>
</tr>
</tbody>
</table>

Relative MDC using a 90% confidence interval for each variable is presented in Figure 3-2A – 3-2D. The figures depict the relative MDC required to establish that a change in measure on repeated testing is not attributed to chance variation based on the number of averaged images.
used to obtain that measure. The skin yielded the lowest MDC for maximal thickness (10.068-22.513), mean thickness (8.478-18.956) and echogenicity measures (3.416-7.638). With increasing number of images averaged, a decrease in the relative MDC was found. Relative MDC was less than 21% for maximal and mean thickness and echogenicity measures when averaging 3 or more images. Relative MDC was less than 25% for contrast measures when 5 images were averaged.

Figure 3-2A – 3-1D Summary of the Relative Mean Detectable Change with 90% Confidence Interval (MDC90%-rel) for Maximal and Mean Thickness, Echogenicity and Contrast of the skin, subcutaneous tissue and muscle. Reduction in MDC90%-rel is observed with increasing number of images averaged. Averaging three or more images reduces the MDC90%-rel to less than 21% for maximal and mean thickness measures of skin, subcutaneous and muscle (Figures 3-2a and 3-2b). For echogenicity measures (Figure 3-2c), only one image is required to obtain a MDC90%-rel of less than 15%. For contrast measures (Figure 3-2d), four images is required to obtain a MDC90%-rel of less than 20% for subcutaneous tissue only, whereas five images is required to obtain a MDC of 24.7% and 23.1% in skin and muscle tissue respectively.
3.5 Discussion

The purpose of this study was to determine the reliability of repeated ultrasound imaging over the ischial tuberosity and to determine the number of images required to obtain tissue thickness and gray scale values that exceeded an a-priori minimal detectable change for repeated tissue assessment overlying the ischial tuberosity.

Our study showed that the highest component of measurement variance was attributed to the participants themselves (66.97%-94.78%), with limited amount of variance attributed to the images (0 - 0.20%) and a minimal amount of variance attributed to the interaction effects of the participants and images (5.22%-33.03%). Several factors linked to participants can account for variance in skin, subcutaneous and muscle tissue thickness including Body Mass Index (BMI) (Gibney et al. 2010), sex (Lasagni and Seidanari, 1995), and age (Ikezoe et al., 2011, Narici et al., 2003). Additionally, system settings customized for each participant can contribute to the total variance that would be attributed to echogenicity and contrast measures. Our ability to determine which factors could contribute to thickness and grey scale measures of skin, subcutaneous tissue and muscle was limited by our sample size. Therefore, it is recommended that further studies explore how BMI, sex, age and system settings influence thickness, grey scale and texture measures of tissue overlying the IT.

The participant by image interaction effect suggests that the variance across images is affected by the participants. We attribute the participant by image interaction effect to be a function of both the device used and system settings used when acquiring ultrasound images. Obtaining quality images for each participant requires the use of a standardized protocol for probe placement, optimization of ultrasound system parameters (gain, depth, dynamic range and frequency) reported previously by Brant (2001). Pillen and Van Alfen (2011) recommend using standardized muscle ultrasound protocols with the same system settings for each individual. However, a standardized protocol with the same system settings for each participant may reduce the variance attributed to the interaction effects of participants and ultrasound settings at the expense of a potential optimal image quality. Obtaining optimal image quality in our study was
essential for identification of the delineation of the skin, subcutaneous and muscle tissue used in our analysis. Additionally, the choice of customization of system settings would best reflect what is done in clinical practice.

It is well established that ultrasound imaging is operator dependent (Szabo 2004) and obtaining high quality images requires experience (Larivière et al. 2013). During ultrasound scanning, the pressure applied while scanning will influence the amount of tissue deformation, which will affect quantification of tissue measures and image quality. We attempted to minimize measurement error by ensuring consistent placement and pressure of the ultrasound head, standardizing participant position and obtaining measurements over a well-defined ROI over the ischial tuberosity. We were unable to measure pressure exerted on the ultrasound transducer during scanning as our transducer is not instrumented for such. The use of an external reference marker system such as a scanning template and the application of standardized pressure using a dense foam cube during scanning may have further reduced this measurement error by minimizing tissue deformation. However, it is important to note that the use of a scanning template on the lumbar multifidus muscles (Larivière et al., 2013) and a dense foam cushion on the transverse abdominis muscles (Larivière et al., 2013) to standardize transducer orientation have been shown to have limited effect on improving reliability when the measurement protocol is precisely defined.

The present study has established that measures of skin, subcutaneous and muscle thickness demonstrate good inter-trial reliability ($\phi = 0.903 - 0.982$) in individuals between the ages of 23-69 when averaging three images. When more than four images were averaged for all gray scale measures of echogenicity and contrast, the coefficient of dependability demonstrated good reliability ($\phi > 0.8$) and with increasing number of images averaged to obtain thickness and gray scale measurements of skin, subcutaneous tissue and muscle, the coefficient of dependability increased. It is not surprising that the coefficient of dependability is lower for grey scale measurements compared with thickness measurements. Given that grey scale distribution measures incorporate variance in the calculations, the ability to discriminate changes in pixel properties is more challenging. For example, changes in tissue secondary to edema will result in a change of the mean grey scale of the pixel. The contrast measures will provide a numeric calculation that reflects the interrelation of the grey scale of each pixel or subgroup of pixels and
its neighbour in different orthogonal directions. The ability to discriminate these changes in tissue contrast is more challenging when compared with a single thickness measure.

Based on the findings of this study, we recommend that using a 90% Confidence Interval, at least three images should be averaged when the primary outcome measures are linked to geometric measures (e.g., thickness) and grey-scale measures (e.g., echogenicity), and that at least four images should be averaged whenever there is an interest to characterize texture within a ROI (e.g., contrast). On repeated imaging, at least three images are required in order to detect a minimal change of 21% for thickness and echogenicity, whereas at least 5 images are required to detect a minimal change of 25% for contrast measures. Determining the number of images that are required for each parameter to detect minimal change in the desired range needs to be established. Therefore, it may be prudent for researchers to determine which measures are required depending on the research question prior to image acquisition, so that the minimal number of images can be collected.

When measuring muscle thickness using ultrasonography, our study demonstrated a higher reliability for mean muscle thickness measures ($\phi = 0.820-0.915$) when compared with maximum thickness measures ($\phi = 0.756-0.896$). Our customized program enabled us to obtain mean thickness measures by averaging the values across the entire length of the region of interest. In order to obtain more reliable outcome measures in research and clinical practice, one would have to have a fundamental understanding of the pathology to determine if mean or maximum thickness is the better measure to use. Until this is addressed in each population, we suggest that both should be used.

Due to the small sample size, caution is advised when generalizing these results to a population of healthy adults. Based on the results of our study, an average of 3 images is required to detect a 21% difference in thickness measures in skin on repeated imaging for the same participant. Assuming a two-sided significance of 0.05, a power of 0.80, mean skin thickness of 2.64 mm and standard deviation of 0.45 mm, a total of 11 participants would be required to detect a significant difference beyond the minimal detectable change whenever thickness is selected as the main outcome measure for between group comparisons.

Our paradigm was constructed as a best-case scenario to be able to identify the structures of interest as participants were asked to maintain the side lying position for 30 minutes during data
collection. We scanned the buttock region of able-bodied individuals, in which interfaces between skin, subcutaneous tissue and muscle could be easily identified and used a customized image analysis program that provided a user-interface to enable manual detection of the boundaries of skin, subcutaneous tissue and muscle. The approach may not be as applicable for clinical situations where, for example multiple assessors are used and studies examining inter assessor variance are required. Furthermore individuals with neuromuscular disorders may be unable to maintain a prolonged side lying position to obtain quality images and interfaces may be more difficult to visualize due to atrophy or fat infiltration of skeletal muscle. However, this exploratory approach demonstrates proof of principle.

3.6 Conclusion

This study is the first to report quantitative ultrasound imaging outcome measures characterizing the integrity of the tissue overlying the ischial tuberosity. Skin, subcutaneous and muscle thickness and gray scale contrast measures of the skin, subcutaneous tissue and muscle overlying the ischial tuberosity can be measured reliably in a sample of able-bodied individuals between the ages of 23 – 69 years, by the same rater on the same day. This method for longitudinal evaluation, may have some value in the clinical setting. Our methodology, repeated with a carefully determined sample could be a first step in establishing normative data for comparison with selected populations.
Chapter 4 Trunk Strength and Function Using the Multidirectional Reach Test in Individuals with Non-Traumatic Spinal Cord Injury

This chapter is a modified version of the following article, where modifications consist of changes in formatting:


A link to the published paper can be found at http://www.tandfonline.com/doi/full/10.1179/2045772314Y.0000000246
4.1 Abstract

Trunk control is essential to engage in activities of daily living. Measuring trunk strength and function in persons with Spinal Cord Injury (SCI) is difficult. Trunk function has not been studied in non-traumatic SCI (NTSCI). The purpose of this observational study was to characterize changes in trunk strength and seated functional reach in individuals with NTSCI during inpatient rehabilitation, to determine if trunk strength and seated reach differ between walkers and wheelchair users and to explore relationships between trunk and hip strength and multidirectional reach. This study was conducted at two SCI rehabilitation facilities using 32 sub-acute inpatients (mean age 48.0±15.4 years). Isometric strength of trunk and hip and function (Multidirectional Reach Test: MDRT) were assessed at admission and within 2 weeks of discharge. Analysis of variance was conducted for admission measures (MDRT, hip and trunk strength) between walkers and wheelchair users. Changes in MDRT, hip and trunk strength were evaluated using parametric and nonparametric statistics. The level of association between changes in values of MRDT and strength was also examined. Significant differences between walkers and wheelchair users were found for strength measures (P < 0.05) but not for MDRT. Left and right sided reaches increased in wheelchair users only (P < 0.05). Associations between changes in hip strength, trunk strength and reach distance were found (R = 0.67–0.73). In clinical settings, it is feasible and relevant to assess trunk and hip strength and MRDT. Future studies require strategies to increase the number of participants assessed, in order to inform clinicians about relevant rehabilitation interventions.
4.2 Introduction

Individuals with non-traumatic spinal cord injury (NTSCI) present as a unique population among the spinal cord population. NTSCI can result from multiple etiologies including vascular impairment, infection, malignant and benign tumours, spinal stenosis, transverse myelitis and syringomyelia. Due to the chronicity of the condition, the level of adaptation in response to the sensory and motor decline over time varies considerably among the different etiologies. Surgical intervention in NTSCI is considered when the neuropathology is progressing to life threatening levels and the decline in sensory and motor function can no longer meet that required for their daily needs. It is well documented that individuals with NTSCI are older, more likely to be female, to suffer from paraplegia, present with less physical disability on admission, require shorter term in-patient rehabilitation (Simmons et al., 2010, Cosar et al., 2010, New, Simmonds and Stevermuer 2010) and present with higher AIS scores than those with traumatic SCI. While individuals with NTSCI have a different etiology of disease, they have been reported to have similar levels of walking function at discharge as measured by FIM subscores (New, Simmonds and Stevermuer, 2010) and walking outcomes (Marinho et al., 2012). What is unclear is whether those with different mobility status at discharge have different neurological recovery in trunk function and a differing rehabilitation, e.g., length of stay.

Upright trunk stability is a necessary component in engaging in functional activities including feeding, dressing and transferring (Chen et al., 2003, Sprigle, Maurer and Holowka, 2007). Proprioceptive input in addition to adequate synergistic recruitment and force generating capabilities of the trunk, hip and lower extremity muscles is necessary to maintain adequate trunk stability (Gauthier et al., 2013). Furthermore, prior to the initiation of upper extremity activities in the sitting position, anticipatory activity of the erector spinae and abdominal muscles is required to stabilize the trunk (Tyler and Hasan, 1995).

There is increasing literature about trunk stability in SCI. However, most of the studies have focused on the traumatic SCI population and have been tested in the laboratory setting using kinematic or kinetic paradigms. In individuals with traumatic SCI, greater dynamic and static stability has been found in individuals with lower thoracic spinal cord injury when compared with those with high thoracic SCI (Chen et al., 2003, Sprigle, Maurer and Holowka, 2007).
Decreased ability to recruit the rectus abdominis, transverse abdominis, external and internal obliques, quadratus lumborum and erector spinae muscles may lead to compensatory strategies using the non-postural muscles including latissimus dorsi, trapezius, pectoralis major, neck, upper and lower extremity muscles (Chen et al., 2003, Larson et al., 2010). It has also been suggested that individuals following SCI develop a new central postural control process in the maintenance of sitting stability (Seelan et al., 1998). With increased trunk instability, the individual with SCI may engage in a posterior pelvic tilt and an increase in thoracolumbar kyphosis. These compensatory strategies increase the base of support thereby improving sitting balance (Triolo et al., 2013, Hobson et al., 1992) resulting in increased functional reach (Sprigle et al., 2003).

Hand-held dynamometry of the upper and lower extremity muscles has been shown to have high inter-rater (ICC = 0.86 – 0.97) and intra-rater (ICC = 0.89 – 0.97) reliability in individuals with neuropathic weakness (Kilmer et al., 1997). Strength testing using hand-held dynamometry of the upper extremity has also been evaluated in individuals with paraplegia and tetraplegia during the course of rehabilitation and up to 15 months post rehabilitation (Drolet et al., 1999). Drolet et al. (1999) found a high variability in upper extremity recovery, with improving upper extremity strength up to 15 months post rehabilitation. Not surprisingly, a greater variability in recovery was found for individuals with tetraplegia compared with paraplegia (Drolet et al., 1999). Assessment of trunk muscle strength in SCI has demonstrated high inter-rater (ICC 0.96 – 0.99) and high intra-rater (ICC 0.79 – 0.99) reliability and can be used to evaluate postural muscle strength (Bjerkefors, Carpenter and Thorstensson, 2007).

The seated Multidirectional Reach Test (MDRT) has been used by several researchers as a measure of postural control in individuals with SCI (Gauthier et al., 2013, Field-Fote and Ray, 2010) and older adults (Newton, 2001). The MDRT distance has been shown to be a reliable and valid indicator of stability limits in healthy community dwelling older adults (Newton, 2001) and individuals with SCI (Field-Fote and Ray, 2010). Concomitant measures during reach tests include centre of pressure (COP), limits of stability (Gauthier et al., 2013), time to contact the virtual stability boundary (Shin and Sosnoff, 2013), hand/wrist excursion (Field-Fote and Ray, 2010, Newton, 2001) and trunk excursion (Gauthier et al., 2013). Field-Fote & Ray (2010) found a significant correlation (r ≥ 0.70) between COP excursion and seated reach distance in the forward, backward and leftward reaching, using the wrist as the distal marker. Gauthier et al.
(2012) found that the overall stability index in the seated position was best predicted by anterior reaches, left posterior lateral reaches and right reaches ($R^2 = 0.98$, $P < 0.001$). However, these measures present some challenges in the clinical setting. Mainly, measuring COP excursion requires specialized laboratory equipment which limits its applicability, and using the wrist/hand as reference marker for reach distance is influenced by the ability to maintain upper extremity position and may overestimate or underestimate the contribution of the trunk.

To date, there are limited studies examining trunk function (strength and reach distance) in individuals with SCI (Chen et al., 2003, Gauthier et al., 2013, Larson et al., 2010, Field-Fote and Ray, 2010). Moreover, we were unable to find published studies that have documented changes in trunk function following NTSCI, differences between wheelchair users and walkers, and the relationship between trunk muscle strength and seated postural control. Understanding recovery of the trunk function in individuals with NTSCI during rehabilitation would enable clinicians to determine appropriate rehabilitation potential enabling timely intervention to achieve realistic rehabilitation goals and the duration of rehabilitation required to effect change in this population.

The first objective of this observational study was to characterize and follow trunk strength, hip strength and reach distance in individuals with NTSCI over the course of rehabilitation and to determine if there were differences between walkers and wheelchair users. The second objective of this study was to determine if a relationship existed between changes in trunk strength, hip strength and functional reach distance over the course of their rehabilitation program. It was also hypothesized that there would be a positive correlation between changes in trunk strength, hip strength and functional reach distance.

### 4.3 Materials and Methods

The current sub-study was part of a larger study ($N = 75$) investigating trunk recovery post traumatic or non-traumatic spinal cord injury. This sub-study was designed to determine if individuals with NTSCI who were walkers and wheelchair users presented with different seated
trunk function when admitted to inpatient rehabilitation, and to evaluate changes in trunk function following surgical spinal intervention.

### 4.3.1 Study Population

A sample of 32 patients admitted to inpatient rehabilitation with NTSCI affecting various vertebral levels was recruited from two rehabilitation hospitals. The subsample of the larger study comprised 42% of the population under study. Subjects from the larger study included sub-acute patients admitted for inpatient rehabilitation, aged 18 to 75 years with SCI between levels C5 to L1, either of traumatic or nontraumatic etiology and classified as having an AIS Score of A or B (able to sit and wheel independently) or AIS Score C or D (able to stand, walk). Subjects from the larger study who were AIS A and B groups, required the capability to maintain an unsupported sitting position for at least 30 seconds and to use a wheelchair as their primary source of mobility for more than two hours per day. For the AIS C and D groups, the participants were required to stand without any assistance for at least 30 seconds and to walk two minutes with walking aids and no assistants. Participants were required to present with an activity tolerance of at least 45 minutes when multiple rest periods were available. Subjects were excluded from the study if they had pathology to other parts of the nervous system other than the spinal cord (e.g., major head injury), additional musculoskeletal problems such as severe arthritis, history of deep vein thrombosis, cardiovascular, pulmonary and other comorbidities that would contraindicate the assessment, or could confound the results of the study.

The sample from the larger study represented the most incident demographics for tetraplegia (C5-C8), and paraplegia (T1-L1) for both groups. The subsample used in this analysis from the larger study included individuals with NTSCI only.

Screening for study participants was done by the research coordinator in consultation with the attending participant’s physician and a review of medical records by one of the co-investigators. All eligible participants that consented to be in the study were assessed if their data could be captured during the study timeframes for the admission (i.e., within two weeks of admission to
the rehabilitation unit) and discharge assessments (i.e., within two weeks prior to discharge from the rehabilitation unit).

The study was conducted at two rehabilitation hospitals: Institut de réadaptation Gingras-Lindsay-de-Montréal (IRGLM), Montreal, Quebec, Canada and at the University Health Network - Toronto Rehabilitation Institute, Toronto, Ontario, Canada. The study was approved by the Research Ethics Boards of both research facilities. All participants reviewed and signed the consent form prior to participating in the study.

4.3.2 Experimental Procedure

Subjects were tested over 2 assessment periods: at admission to the rehabilitation unit (Admission Assessment) and within two weeks prior to discharge (Discharge Assessment). Clinical measures comprised of maximal static strength of the trunk, upper and lower extremities, range of motion of the trunk, upper and lower extremities, spasticity using the Composite Spasticity Index (Levin and Hui-Chan., 1993) and the MDRT.

While enrolled in the study at both institutions, patients continued to receive the standard of rehabilitative care. Standard of care at the two sites was comprised of interdisciplinary patient customized rehabilitation based on the patient’s postural, mobility and functional status at admission in order to optimize physical and functional outcomes and minimize secondary complications. Customized rehabilitation changed throughout the course of rehabilitation as the patients’ needs changed.

4.3.2.1. Strength Measures of the Trunk and Hip Muscles

Maximum static torque generating capabilities were measured during trunk flexion, trunk extension, trunk side flexion, hip extension and flexion using a calibrated hand held dynamometer (microFET 2, Hoggan Health Industries, West Jordan, UT, USA). For each muscle
group tested, subjects performed three trials of 5 seconds, with a 30 second recovery period in between each trial.

Trunk strength measures were performed in the sitting position. At the Montreal site, a rigid frame was used to resist trunk strength assessments. At the Toronto site, resistance during trunk strength was provided manually by the research assistant. For trunk side flexion, the resistance was placed at the acromion. For trunk flexion, the resistance was placed at the upper part of the sternum, and for trunk extension, resistance was placed at the thoracic spine (level of the acromion). Stabilization of the lower limbs was provided with belts at the thighs and we ensured that the subject’s feet did not come off the ground. For all muscle groups assessed, the strength was expressed in Nm/kg of body mass and lever arm calculated from the center of the dynamometer and the greater trochanter.

Given the potential contribution of the hip flexors during trunk flexion measures, and hip extensors during trunk extension measures, hip flexion and extension strength was evaluated. Hip flexion and extension measures were performed while the participant was positioned most of the time in supine or side lying. During hip flexion, the hips and knees were placed at 90 degrees of flexion with the calves supported on a stool while hip extension was assessed with the hips in neutral position and the knees extended. For hip flexion and extension strength measurements, resistance was placed on the distal thigh.

For each movement, participants were instructed to produce a progressive contraction up to their maximal level of effort without pain. For all muscle groups assessed, the strength was expressed in Nm/kg of body mass with the lever arm calculated from the point of the axis of rotation of the hip joint to the point of resistance. As the difference between sides was not significant (P>0.05), the mean of three trials for the least affected side was used for analysis.

4.3.2.2 Seated Multidirectional Reach Distance

Subjects were asked to remain in a seated position on a height adjustable plinth without a backrest, with their hips, knees and ankles flexed at approximately 90 degrees and their feet
position planted symmetrically on the floor, with their popliteal fossa approximately 5 cm from the edge of the support surface. Using their preferred arm, subjects were asked to reach in one of six different directions (i.e., forward, back, left, right, forward right, forward left) in random order, towards a target at the level of their acromion, with their opposite hand remaining on their thigh. Subjects were instructed to reach as far towards the target at a self-selected velocity without losing their balance and not to stabilize their trunk with their hand before returning to their initial position. The subjects’ legs were not braced; however testing was stopped if the subjects’ feet came off the ground during MDRT to prevent compensatory movements. A passive marker was placed over the first thoracic vertebrae to allow one to measure the vertical and horizontal displacements between the initial and final trunk positions. These distances were recorded using a telemetric laser distance meter (Fluke 411D, Fluke Corporation, Everett, WA, USA) and the resultant displacement was calculated using the Pythagoras theory (Fig. 4-1). Due to the use of a laser pointer, subjects were provided with protective eyewear to avoid eye damage in the event that the participant looked into the laser. During all reaching tasks, a researcher associate supervised the participants closely to ensure optimal safety while the other research associate obtained the measurements. Subjects were provided with practice trials to acclimatize them to the testing procedure. In order to account for variations in trunk length, MDRT distance was expressed as a percentage of trunk length. The mean of three trials was used for analyses. The results are interpreted as the longer the displacement, the better seated reaching ability.
Figure 4-1 Representation of the Multidirectional Reach Test (MDRT). Using their preferred arm, subjects were asked to reach in one of six different directions (forward, back, left, right, forward right, forward left) in random order, towards a target at the level of their acromion, with their opposite hand remaining on their thigh.

4.3.4 Statistical Analysis

Descriptive statistics (means and standard deviations) were calculated for each of the subject demographics, trunk and hip strength measures and reach directions using IBM SPSS Software 22 (IBM Corporation, Armonk, New York, United States). A normality test of the data was conducted to determine if the data fit the normal distribution.

Subject demographics of walkers and wheelchair users were analyzed using independent t-tests to determine if walkers and wheelchair users were similar at admission.

Due to the examination of multiple variables, repeated measures analysis of variance (ANOVA) Test with a between group factor was conducted to determine for each outcomes (strength and
reach tests) whether the data differed between walkers and wheelchair users at admission. Where significance was found, multiple t-tests were conducted to determine if differences between groups were specific for each direction for strength and reach distance. Strength and MDRT data were tested separately to verify group difference at admission.

Repeated measures analysis of variance with a between group factor was conducted to determine if there were significant differences over time between walkers and wheelchair users. Where significant interaction effects occurred between the dependent variables of strength and reach distance and group, nonparametric statistics, Wilcoxon tests were used to assess the significant reach directions for each group comparing admission and discharge data.

Pearson product-moment correlation coefficients between trunk strength, hip strength and MDRT distances were calculated to determine if changes in trunk and hip strength were related to changes in MDRT distance.

### 4.4 Results

Subject demographics and clinical presentation can be found in Table 4-1. Data were analyzed for 32 individuals with NTSCI who underwent surgical intervention(s) including laminectomy with/without fusion and/or tumour resection. The number of participants in the subgroups of walkers and wheelchairs users was equal. There was no significant difference in demographics between the subgroups of walkers and wheelchair users (P > 0.05). Wheelchair users had longer rehabilitation length of stays; however the results were not significant. The greatest proportion of participants with NTSCI enrolled in the study had etiologies of tumours (n = 12) and myelopathy (n = 6). The remaining participants presented with abscess (n = 4), transverse myelitis (n = 3), myelopathy and abscess (n = 1), osteomyelitis (n = 1), osteoporosis (n=1), AV malformation (n = 1), cord compression (n = 1), cauda equina (n = 1) and spinal stenosis (n = 1).
<table>
<thead>
<tr>
<th></th>
<th>All Participants</th>
<th>Subgroup Walkers</th>
<th>Subgroup Wheelchair Users</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n = 32</td>
<td>n = 16</td>
<td>n = 16</td>
</tr>
<tr>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
</tr>
<tr>
<td>Age (years)</td>
<td>48.2 ± 15.2</td>
<td>46.6 ± 13.7</td>
<td>49.8 ± 16.8</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.73 ± 0.15</td>
<td>1.75 ± 0.12</td>
<td>1.71 ± 0.17</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>79.9 ± 18.2</td>
<td>79.3 ± 18.9</td>
<td>80.4 ± 18.1</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>26.5 ± 4.50</td>
<td>25.7 ± 4.70</td>
<td>27.4 ± 4.30</td>
</tr>
<tr>
<td>Day post-surgery at assessment 1</td>
<td>48.0 ± 30.4</td>
<td>47.7 ± 29.8</td>
<td>48.3 ± 32.0</td>
</tr>
<tr>
<td>Day post-surgery at assessment 2</td>
<td>88.6 ± 43.7</td>
<td>77.2 ± 45.6</td>
<td>98.7 ± 42.0</td>
</tr>
<tr>
<td>Rehab Length of stay (days)</td>
<td>61.9 ± 21.3</td>
<td>51.4 ± 19.2</td>
<td>72.4 ± 18.2</td>
</tr>
<tr>
<td>Sex (Females/males)</td>
<td>8/24</td>
<td>4/12</td>
<td>4/12</td>
</tr>
<tr>
<td>Handedness (R/L/A)</td>
<td>30/0/2</td>
<td>16/0/0</td>
<td>14/0/2</td>
</tr>
<tr>
<td>Level of Pathology (C/T/L/)</td>
<td>10/19/3</td>
<td>7/8/1</td>
<td>3/11/2</td>
</tr>
</tbody>
</table>
Not all participants enrolled in the study participated in both admission and discharge assessments and not all subjects assessed at admission and discharge were able to participate in the complete trunk strength, hip strength and/or MDRT testing protocol due to scheduling conflicts (n = 6), late recruitment (n = 3), voluntary withdrawal (n = 4), early discharge (n = 5), fatigue (n = 1), infection (n = 1) and decreased tolerance to assessment (n = 2). However, subjects’ ability to participate in all components of the testing did not vary based on subject demographics or clinical presentation.

4.4.1 Trunk and Hip Strength

Mean trunk strengths at admission for the composite group, walkers and wheelchair users are found in Table 4-2 and Figure 4-2. Mean trunk strength for the composite group at admission was highest in the extension direction followed by flexion. Walkers had significantly greater trunk and hip strength compared with wheelchair users at admission (P < 0.05). Post-hoc analysis using multiple t-tests found significant differences in trunk and hip strength in all directions between walkers and wheelchair users (P < 0.01).
Table 4-2 Means, Standard Deviations and Range of Trunk Strength in 4 Directions and Hip in Flexion and Extension at Admission and Discharge (Nm/kg) for All Participants and Subgroups

<table>
<thead>
<tr>
<th></th>
<th>All Participants</th>
<th>Subgroup Walkers</th>
<th>Subgroup Wheelchair users</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n = 32</td>
<td>n = 16</td>
<td>n = 16</td>
</tr>
<tr>
<td></td>
<td>Number</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Trunk Flexion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Admission</td>
<td>27</td>
<td>0.61</td>
<td>0.30</td>
</tr>
<tr>
<td>Discharge</td>
<td>19</td>
<td>0.61</td>
<td>0.30</td>
</tr>
<tr>
<td>Trunk Extension</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Admission</td>
<td>27</td>
<td>0.80</td>
<td>0.63</td>
</tr>
<tr>
<td>Discharge</td>
<td>19</td>
<td>0.91</td>
<td>0.77</td>
</tr>
<tr>
<td>Trunk Right Lat. Flex.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Admission</td>
<td>Discharge</td>
<td>Admission</td>
</tr>
<tr>
<td>---------------------</td>
<td>-----------</td>
<td>-----------</td>
<td>-----------</td>
</tr>
<tr>
<td><strong>Trunk Left Lat.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flex.</td>
<td>Admission</td>
<td>20 0.51  0.27 0.12-1.23</td>
<td>10 0.61  0.29 0.34-1.23</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>19 0.51  0.27 0.12-1.23</td>
<td>9 0.61  0.29 0.34-1.23</td>
</tr>
<tr>
<td><em><em>Hip Flex</em> (less affected)</em>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Admission</td>
<td>27 0.49  0.23 0.07-0.92</td>
<td>14 0.63  0.18 0.25-0.92</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>19 0.51  0.27 0.12-1.23</td>
<td>9 0.61  0.29 0.34-1.23</td>
</tr>
<tr>
<td><em><em>Hip Ext.</em> (less affected)</em>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Admission</td>
<td>27 0.49  0.23 0.07-0.92</td>
<td>14 0.63  0.18 0.25-0.92</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>19 0.51  0.27 0.12-1.23</td>
<td>9 0.61  0.29 0.34-1.23</td>
</tr>
</tbody>
</table>
Figure 4-2 Mean trunk strength (Nm/kg) for all participants (n = 27) at admission and for matched pairs of Walkers (n = 8) and Wheelchair Users (n = 9) at admission and discharge. Wheelchair users have lower trunk strength, particularly for extensors at admission and discharge than walkers.

Repeated measures analysis of variance demonstrated non-significant differences between walkers and wheelchair users with respect to change over time in trunk and hip strength.

### 4.4.2 Multidirectional Reach Distance

Mean reaches expressed in percentage of trunk length at admission for the composite group, walkers and wheelchair users are found in Table 4-3 and Figure 4-3. Mean reaches for the composite group at admission and discharge was highest in the forward reach direction. Significant differences in reaches at admission were found between walkers and wheelchair users (P < 0.05). Post-hoc t-test analyses revealed that left and right reaches were significantly greater in the walkers vs. wheelchair users (P < 0.02).
Table 4-3 Mean, Standard Deviation and Range of Multidirectional Reach Test (MDRT) in 6 Directions at Admission and Discharge (% of Trunk Length) for All Participants and Subgroups

<table>
<thead>
<tr>
<th>Direction</th>
<th>All Participants n = 32</th>
<th>Subgroup Walkers n = 16</th>
<th>Subgroup Wheelchair Users n = 16</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Front</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Admission</td>
<td>25</td>
<td>0.54</td>
<td>0.17</td>
</tr>
<tr>
<td>Discharge</td>
<td>19</td>
<td>0.68</td>
<td>0.18</td>
</tr>
<tr>
<td>Back</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Admission</td>
<td>22</td>
<td>0.34</td>
<td>0.10</td>
</tr>
<tr>
<td>Discharge</td>
<td>17</td>
<td>0.37</td>
<td>0.16</td>
</tr>
<tr>
<td>Left</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discharge</td>
<td>19</td>
<td>0.40</td>
<td>0.23</td>
</tr>
<tr>
<td>Right</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Admission</td>
<td>25</td>
<td>0.32</td>
<td>0.14</td>
</tr>
<tr>
<td>Discharge</td>
<td>19</td>
<td>0.40</td>
<td>0.15</td>
</tr>
<tr>
<td>45 degrees left</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Admission</td>
<td>24</td>
<td>0.40</td>
<td>0.17</td>
</tr>
<tr>
<td>Discharge</td>
<td>18</td>
<td>0.46</td>
<td>0.19</td>
</tr>
<tr>
<td>45 degrees right</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Admission</td>
<td>24</td>
<td>0.46</td>
<td>0.26</td>
</tr>
<tr>
<td>Discharge</td>
<td>18</td>
<td>0.56</td>
<td>0.23</td>
</tr>
</tbody>
</table>

45 degrees left
Repeated measures analysis of variance demonstrated a significant interaction effect of group (walkers vs. wheelchair users) and multidirectional reaches between admission and discharge. The analysis of variance revealed non-significant differences for changes in reach distance between admission and discharge in walkers while it was significant for wheelchair users. Thus we pursued with nonparametric statistics to determine the reaching directions that differed from admission to discharge with Wilcoxon tests in the wheelchair users. Differences between admission and discharge reach data in the wheelchair users (P < 0.05) were significant for right and left reach direction in the wheelchair users (P ≤ 0.05).

### 4.4.3 Relationship between MDRT and Muscle Strength

Figure 4-4 shows significant associations between the less affected hip flexion strength and right reach (R = 0.731), left lateral trunk flexion and right reach (R = 0.700), trunk extension strength and left reach (R = 0.735) and trunk flexion strength and left reach (R = 0.669). Walkers presented with a greater effect on the association when compared with wheelchair users.
Figure 4-4 Scatterplots showing significant (p = 0.01) association between changes in sitting Multidirectional Reach Test (MDRT) (% trunk length) for matched pairs of Walkers (blue diamonds) (n = 7) and wheelers (red squares) (n = 7) and hip or trunk strength changes.

4.5 Discussion

The purpose of this study was to characterize and follow trunk strength, hip strength and reach distance in individuals with NTSCI over the course of rehabilitation, to determine if there were differences between walkers and wheelchair users with respect to trunk and hip strength and reach distance, and to determine if a relationship existed between changes in trunk strength, hip strength and reach distance in individuals with NTSCI. This observational study is the first of its
kind to document the changes in trunk function following surgical intervention for NTSCI during rehabilitation.

We analyzed the NTSCI subjects separately, as the NTSCI population presented with various etiologies of non-incident SCI (i.e., oncology, cervical myelopathy, etc.). Participants presented with multiple levels of spinal pathology (C2-L4), different surgical intervention(s). Given that their history and course of their disease processes and health status prior to surgery was variable, they were considered to be a distinct SCI population.

We were not able to characterize these patients using the International Standards for Neurological Classification of Spinal Cord Injury with any degree of sensitivity based on the types of pathology of our participants. An alternative classification system for NTSCI has been suggested (New and Marshall, 2013), which considers the history of etiology and International Classification of Diseases coding. However this is not the current practice in Canada and therefore such data is not available in the health record coding. Therefore we elected to separate the participants into two mobility subpopulations (walkers and wheelchair users) for our analysis to address our question as we anticipated that they would show differences in trunk neuromotor capacity at admission to rehabilitation.

Assessment measures were scheduled around admission and discharge times to and from rehabilitation presenting challenges in the evaluation of both the impairments and functional limitations. Despite challenges in the evaluation of trunk function in individuals with NTSCI, we were able to demonstrate that walkers, not surprisingly had significantly greater trunk and hip strength than wheelchair users at admission for all directions measured.

Trunk strength has been evaluated minimally in individuals with SCI (Shin and Sosnoff, 2013, Ellaway et al., 2011) and there is a paucity of research on specific rehabilitation strategies for improving trunk control in these individuals. One study has demonstrated that with a 10-week kayak training protocol trunk stability improved in individuals with chronic paraplegia (Bjerkefors, Carpenter and Thorstensson, 2007). However, this was not with sub-acute post-operative study participants. Not surprisingly, our findings showed significant increase in trunk strength measures over the course of rehabilitation in patients with NTSCI in both walkers and wheelchair users.
Our study found significant differences in hip strength between walkers and wheelchair users at admission, however no significant differences for the magnitude of strength change between walkers and wheelchair users over the course of rehabilitation. Static strength of the ankle plantar flexors and dorsiflexor muscles has been related to ambulatory capacity in individuals with incomplete traumatic SCI (Ellaway et al., 2011). Reduction in knee extensor and ankle plantar flexion torque and reduced ability to generate instantaneous muscle strength has been found in individuals with chronic incomplete SCI when compared with healthy matched controls (Jayaraman et al., 2005). However there have not been previous studies measuring trunk and proximal lower limb musculature in NTSCI in the sub-acute phase so further studies with larger sample sizes are required to determine if proximal lower extremity strength changes in walkers and wheelchair users over the course of rehabilitation influences their mobility status and walking capacity.

We were able to demonstrate significant increases in sitting MDRT distance in the left and right directions between rehabilitation admission and discharge assessments for wheelchair users but not for walkers. We interpret that this increased difference may be related to having to reach in their extra-corporeal environment for all activities of daily living and that this group has optimized their performance through necessity/practice. Interestingly, the most dramatic increases in MDRT distance were found in the right direction. Fourteen of our 16 wheelchair users were right handed suggesting that, it may be possible to explore the interaction of trunk postural control, limb dominance, intensity of use and reach distance during recovery and rehabilitation particularly for those who will be required to reach from the sitting position for future activities if they do not recovery the ability to walk. Grangeon et al. (2012) suggest that individuals with SCI may use their dominant upper extremity for reaching more frequently while providing support through their non-dominant limb, thereby developing excellent seated stability with their dominant limb elevated.

Our study demonstrated that the changes in strength of the less affected hip and left trunk flexion strength were related to changes in right MDRT distance while the corresponding value of trunk extension strength was related to left MDRT distance. These findings are in contradiction with previous studies of Chen et al. (2003) that examined trunk flexion and extension strength as a predictor of dynamic sitting stability and found no relationship between strength and reach distance in individuals with paraplegia (Chen et al., 2003), however they did not measure hip
muscle strength. They did find that the injury level and trunk length were better predictors of functional reach explaining 43.5% of the variance hence we elected to normalize reach distance by trunk length. One would expect that the requirement to generate the forces to both stabilize the lower extremities and control trunk movement is necessary to maintain seated stability. A larger sample size with precise characterization of the site of pathology and neurological status would be important to explore these relationships and the changes post-surgery between level of pathology, injury and surgical intervention, lower limb motor scores, trunk strength and MDRT.

4.6 Study Limitations

We did not document or evaluate the specific rehabilitation interventions that would challenge trunk control sitting balance in our participants; therefore, we were unable to identify if any of our participants underwent specific trunk strengthening exercises. However, given our preliminary findings, the importance of understanding the relationships between trunk strength and rehabilitation interventions to facilitate the development of customized therapies for individual patients to improve sitting balance during functional activities becomes more paramount.

Our study measured MDRT distances in six directions and trunk strength in only four directions as our protocol did not evaluate the strength of the oblique muscles through assessment of resisted trunk flexion in cross flexion as some patients had postoperative restrictions for resisted testing in an oblique or rotational direction. As such, we were unable to assess correlations between MDRT distances in the 45 degrees to the left and 45 degrees to the right directions with strength of the oblique muscles. Future studies should investigate the contribution of the internal and external obliques to trunk stability during “rotational reaching”.

In addition, we did not conduct kinematic assessment of the trunk and lower extremity movement during the MDRT, and are therefore unable to comment on compensatory strategies of the pelvis used during the reaching task, nor establish if the trunk moved out of the primarily plane during testing. It has been established previously that individuals with poor trunk control
engage in a posterior pelvic tilt and show an increased thoracic kyphosis in sitting to increase their base of support (Triolo et al., 2013, Hobson and Tooms. 1992). Sprigle et al. (2003) demonstrated that with posterior pelvic tilt functional reach distance increased. This compensatory strategy may increase reach ability, due to posterior displacement of the centre of mass over the base of support, offsetting the anterior displacement of the centre of mass during forward reaching. Using 3D motion analysis in addition to electromyography of the trunk muscles (i.e., quadratus lumborum, external obliques, rectus abdominis) and lower extremity muscles (i.e., gluteus maximus) would help elucidate trunk posture during the reach task and determine if postural movement strategies or compensations change over the course of rehabilitation.

Our study was conducted using 32 individuals with NTSCI. Given the small n-values for the matched pairs of walkers and wheelchair users, we are unable to generalize our findings to the total sample of all individuals with NTSCI. Larger scale multi-site studies are recommended with implementation of strategies to reduce attrition of study participants and incorporate broader inclusion criteria.

4.7 Conclusion

This study demonstrated that monitoring changes in trunk and hip strength and reach distance is complex in individuals with NTSCI, particularly when multiple measures are being assessed and individuals are assessed at varying time points during their recovery post-surgery. Trunk and hip strength did not improve over the course of rehabilitation in both walkers and wheelchair users. MDRT distance in the right and left lateral directions improved over the course of in-patient rehabilitation for wheelchair users only. Measuring trunk control using static trunk strength and the MDRT in the right and left directions which were sensitive to changes over the course of 61 days of inpatient rehabilitation, appears to show promise as a clinical assessment approach to track changes and to demonstrate outcome.
Chapter 5 Trunk Function and Ischial Pressure Offloading in Individuals with Spinal Cord Injury

This chapter is a modified version of the following article, where modifications consist of changes in formatting:

A link to the published paper can be found at

5.1 Abstract

The purpose of this prospective cross-sectional study is to determine if there is a relationship between trunk function and offloading of the ischial tuberosities in individuals with Spinal Cord Injury (SCI). Fifteen non-ambulatory participants with complete or incomplete traumatic and non-traumatic SCI, American Spinal Injury Association Impairment Scale (AIS) Classification A-D attending in-patient sub-acute rehabilitation participated in this study. Isometric trunk strength using a hand held dynamometer, the ability to reach using the multidirectional reach test and offloading times of the ischial tuberosities using a customized pressure mat were assessed. Participants who were able to engage in the multidirectional reach test were defined as “Reachers”, whereas individuals who were unable to engage in the multidirectional reach test were defined as “Non-Reachers”. Trunk strength was significantly higher in Reachers compared to Non-Reachers (P < 0.05). Offloading times over the left and right ischial tuberosities were lower in Non-Reachers when compared with Reachers, however the results were statistically significant only for offloading over the right ischial tuberosity (P < 0.05). There was no correlation between trunk strength and pressure offloading times for both groups. Regardless of an individual’s ability to engage in a reaching task, participants with spinal cord injury spent more time offloading the left ischial tuberosity compared with the right ischial tuberosity. The study highlights the need to identify factors that may contribute to offloading behavior in individuals with spinal cord injury who lack sufficient trunk strength.
5.2 Introduction

Pressure injuries occur from prolonged unrelieved pressure (NPUAP, 2016) and are a costly medical complication leading to morbidity, reduced quality of life and possible mortality (Claudia et al., 2010). The estimate of pressure injuries in all Canadian healthcare settings is 26% (Woodbury and Houghton, 2004). The prevalence for pressure injuries in adults with spinal cord injury (SCI) has been reported to be up to 66% (Schubart, Hilgart and Lyder, 2008).

Preventative programs have been developed to mitigate the development of seated acquired pressure injuries, including regular skin checks, pressure offloading and proper seating assessment and prescription. Guidelines for pressure injury prevention include engaging in pressure relief every 15-30 minutes for a period of 30-120 seconds (Houghton and Campbell, 2013). Pressure offloading over the weight bearing surfaces has focused on spatial and temporal redistribution of pressure (Tung et al., 2015). However, there is inconsistency regarding the frequency and method of repositioning (Moore and Cowman, 2015) for the prevention of seated acquired pressure injuries. It has also been recommended that pressure relief frequency, length and type be customized for each individual with spinal cord injury using pressure mapping (Houghton and Campbell, 2013). Despite recommendations for pressure relief, patient adherence is low (Stockton and Parker, 2002).

There are multiple methods to engage in pressure relief for the individual with SCI. Depending on motor impairments, individuals who spend prolonged periods sitting in a wheelchair can engage in pressure relief through a push up, side lean, and forward lean. Furthermore, pressure offloading can occur under the ischial tuberosity during forward and cross body reaches with the greatest pressure offloading on the contralateral tuberosity of the reaching arm (Park, 1992, Chen et al., 2014). Individuals with SCI who lack adequate trunk or upper extremity function may be unable to engage in frequent offloading due to impaired neural control of the trunk and upper extremity muscles, reduced trunk and upper extremity strength and reduced sensory input (Seelan et al., 1997) and therefore may rely on wheelchair tilts or recline to engage in pressure offloading which have been found to be effective in reducing interface pressures over the ischial tuberosity (Park, 1992, Sprigle, Maurer and Sonenblum, 2010).
Pressure relief in individuals with SCI can be captured through several technologies including time loggers (Grip and Merbitz, 1986), interface mapping technologies (Brienza et al., 2001) and flexible pressure monitoring systems (Yip et al., 2009, Moreau-Gaudrey et al., 2006). Furthermore, there are several interventional strategies used to promote pressure relief including educational tools and pressure offloading reminding systems (Tung et al., 2015) to promote self-managed care. While trunk function is essential for engaging in daily activities including reaching and has been reported as a high priority for functional recovery in individuals with both tetraplegia and paraplegia (Anderson, 2004), individuals with SCI who are unable to engage in a functional reach, may also be unable to engage in effective ischial offloading.

The seated reach test, measured by trunk excursion during forward, backward and lateral reaches has been found to be highly reliable ($r \geq 0.71$) in individuals with motor incomplete SCI and also related to seated centre of pressure excursion (Field-Fote and Ray, 2013). The seated reach test has been used as a surrogate measure of trunk function when sophisticated electromyography (EMG), kinematic and kinetic data are not available to determine trunk control ability for offloading in individuals with SCI. The purpose of this study was to measure temporal pressure offloading and to explore the relationship between trunk function and pressure offloading in individuals with Traumatic and Non-Traumatic SCI. We used the seated reach test and trunk strength as indices of trunk function. Participants were classified by their ability to engage in the reaching task without losing their balance as “Reachers”. Those participants who were unable to engage in the reaching task and demonstrated a protective mechanism (i.e. moving their arm) to prevent them from losing their balance or demonstrated a loss of balance were defined as “Non-Reachers”. We hypothesized that in individuals with SCI, reaching ability and trunk strength would correlate with pressure offloading of the ischial tuberosities.
5.3 Materials and Methods

5.3.1 Participants with Spinal Cord Injury

Twenty non-ambulatory participants with complete or incomplete traumatic and non-traumatic SCI, American Spinal Injury Association Impairment Scale (AIS) classification A-D were recruited for the study by convenience sampling. Eligible participants were approached by a central recruiter at the sub-acute rehabilitation hospital where they were receiving inpatient rehabilitation at which time they were advised of the nature, purpose, risks and benefits of the study. Participants who were medically stable, participating in in-patient rehabilitation and using a wheelchair as their primary means of mobility for at least two hours per day were eligible to participate. Participants were excluded from the study if they presented with an existing pressure injury, significant musculoskeletal conditions (e.g. inflammatory arthritis), impaired neurological status affecting their sitting balance due to conditions other than SCI (e.g. Parkinson’s disease) or documented brain injury impacting their ability to follow instructions. All participants provided informed consent to participate in the study, which was approved by the hospital Institutional Review Board.

5.3.2 Evaluation of Trunk Function

5.3.2.1 Trunk strength

Trunk strength testing was conducted as per the method reported by Larson et al. (2010). Testing was done by an experienced physical therapist (SG) with training and expertise in muscle strength testing in individuals with SCI. A hand held dynamometer (MicroFet, Hoggan Health, 3653 W 1987 S #7, Salt Lake City, Utah, 84104, USA) was used to assess isometric trunk strength in the forward flexion, extension and lateral flexion directions in random order. The lever arm was determined from the point of resistance to the iliac crest (for flexion and extension
strength) or the greater trochanter (for lateral flexion strength). The participant was instructed to push “as much as you can” into the dynamometer and hold this position for five seconds in order to obtain a maximum voluntary isometric contraction. The peak force was recorded in Newtons (N) for three contractions and the mean of three peak force measures was multiplied by the lever arm to convert the value into newton meters (Nm).

5.3.2.2 Multidirectional Reach Test (MDRT)

Multidirectional reach testing was conducted according to the method as described in Gabison et al. (2014). Participants were asked to remain in the same seated position as during the trunk strength testing. Participants were asked to reach in one of six different directions (forward, back, left, right, forward right, forward left) in random order towards a target situated at the level of their acromion, with their opposite hand across their chest. Participants were instructed to reach using their preferred arm as far towards the target without losing their balance. A passive marker was placed over the T1 vertebrae and the vertical and horizontal displacements were recorded using a telemetric laser distance meter (Fluke 411D, Fluke Corporation, 6920 Seaway Blvd., Everett, Washington, 98203, USA). The resultant displacement was calculated using the Pythagoras theory. Participants were monitored during this task to prevent them from falling or losing their balance. Participants were required to demonstrate the ability to reach in all six directions to be classified as “Reachers”. Participants who were unable to engage in reaching in all six directions were classified as “Non-Reachers”.

5.3.2.3 Evaluation of Pressure Offloading During Sitting

A pressure mat, “SensiMAT™” (SensiMAT Systems, 910 Rowntree Dairy Road, Unit 13, Woodbridge, Ontario, L4L 5W5, Canada) with six (43.7 mm by 43.7 mm, 0.55 mm thick) standard force sensors (actuation force 0.1 N, force sensitivity 0.1-10.0² N) was placed under the participants’ wheelchair cushions. To ensure that the SensiMAT™ would capture offloading
behavior under the wheelchair cushion, we ensured that the size of the SensiMAT™ corresponded to the same size of the wheelchair cushion for each individual, in order to make certain that the pressure sensors were within the participant’s weight bearing area. The SensiMAT™ sampled offloading from each of the six sensors at a sampling rate of 1 Hz. Analog signals were collected using an iPhone via Bluetooth link and subsequently transferred to a secure server via Wi-Fi (Fig. 5-1). Analog signals were processed with MATLAB Version R2013a (MATLAB, Mathworks, 1 Apple Hill Drive, Ntkc, MA., 01760-2098, USA) to capture pressure offloading duration. Offloading behaviour was characterized when the pressure sensors registered a force equivalent in value to that when no pressure was applied for a minimum of at least 2 seconds (s). The feasibility of capturing offloading behavior using the SensiMAT™ was pilot tested on 10 individuals without SCI and one individual with SCI prior to the study (Appendix A2) to ensure that the characterization of offloading could be described as demonstrated in Figure 5-1.
Participants were instructed to engage in their usual activities over a two-hour period while sitting during the time that pressure offloading behavior was collected. Activity logs were completed by each participant to capture the activities they participated in for the duration of the data collection period. Activity logs were used to detect the duration of prolonged offloading, which occurred when the participants were not in their wheelchairs (i.e. during transfers). SensiMAT™ data were compared with activity logs to confirm offloading activities that should
not be included in the sitting analysis. Due to the participants’ differences in sitting durations, cumulative pressure offloading time data were converted to seconds per hour (s/hour).

Testing for trunk function and pressure offloading were conducted on two separate days.

### 5.3.2 Data Analysis

SPSS Version 23 (SPSS, IBM Analytics, 233 S Wacker Dr., 11th Fl., Chicago, Illinois, 60606-63007, USA) was used for data analysis. An Analysis of Variance (ANOVA) was conducted to compare demographic data between the Reachers and Non-Reachers. Chi-Square Analysis was conducted to determine if AIS classifications were significantly different between Reachers and Non-Reachers. The Shapiro Wilk test was used to assess for normalcy for trunk strength measures and offloading durations. Since the data was not normally distributed, the Mann-Whitney U Test was used to determine significance between the Reachers and Non-Reachers with respect to trunk strength and pressure offloading times. Spearman’s Rank Correlation Coefficients were computed to determine if there were associations between trunk strength and pressure offloading times. Correlation coefficients were interpreted according to the following criteria: kappa = 0.21-0.40 representing fair correlation, kappa = 0.41-0.60 representing moderate correlation, kappa = 0.61-0.80 representing good correlation, and kappa > 0.81 representing very good correlation (Altman, 1991).

Participants with missing data were excluded in the full analysis.

### 5.4 Results

Of the 20 participants who were recruited for the study, one participant dropped out due to the required time commitment for the study. Two participants were deemed as ineligible to participate in the study due to their progression to an ambulatory status following recruitment into the study. Seventeen participants had trunk strength entered for analysis. SensiMAT™ data
was lost from two participants due to technical difficulties. As such, data from 15 participants were entered into the full analysis.

5.4.1 Participants’ Demographics and Clinical Status

Table 5-1 presents the demographic and clinical characteristics of the Reachers and Non-Reachers. All participants were right hand dominant. Six individuals were manual wheelchair users in the Reachers group whereas seven individuals were manual wheelchair users in the Non-Reachers group. Statistical analysis revealed that Reachers and Non-Reachers were similar with respect to age, height and weight. AIS classifications were not significantly different between Reachers and Non-Reachers.
Table 5-1 Patient Characteristics

<table>
<thead>
<tr>
<th>ID</th>
<th>Age (yrs)</th>
<th>Sex</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>AIS Score</th>
<th>Injury Level</th>
<th>T/NT</th>
<th>WC</th>
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<tbody>
<tr>
<td>17</td>
<td>39</td>
<td>M</td>
<td>152</td>
<td>104.5</td>
<td>A</td>
<td>C7</td>
<td>Traumatic</td>
<td>EL</td>
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<td>2</td>
<td>48</td>
<td>F</td>
<td>172</td>
<td>77.0</td>
<td>A</td>
<td>T11</td>
<td>Traumatic</td>
<td>MA</td>
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<td>L3</td>
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<td>M</td>
<td>182</td>
<td>72.7</td>
<td>B</td>
<td>T10</td>
<td>Traumatic</td>
<td>MA</td>
</tr>
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<td>15</td>
<td>53</td>
<td>M</td>
<td>180</td>
<td>82.0</td>
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<td>M</td>
<td>175</td>
<td>84.5</td>
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<td>EL</td>
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<td>78</td>
<td>F</td>
<td>157</td>
<td>68.0</td>
<td>D</td>
<td>C6</td>
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<td>MA</td>
</tr>
</tbody>
</table>

**Mean** 46.5 - 169 76.3 - - - 

**SD** 20.9 - 10.7 16.1 - - - 

Non-Reachers
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</tr>
<tr>
<td><strong>SD</strong></td>
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</table>
5.4.2 Trunk strength

Figure 5-2 presents the trunk strength results for the Reachers and Non-Reachers. Left sided trunk flexion strength was highest in both the Reachers and Non-Reachers. Right sided trunk strength was lowest in both the Reachers and Non-Reachers. Between group comparisons revealed that trunk strength was higher in Reachers when compared with Non-Reachers. The Mann-Whitney U test demonstrated that significant differences existed between Reachers and Non-Reachers for all trunk strength measures ($P < 0.05$).
Figure 5.2 Mean isometric trunk strength (expressed as Nm) with 95% Confidence Intervals for Reachers (n = 8) and Non-Reachers (n = 9). Non-Reachers demonstrated significantly lower trunk strength for all directions (P < 0.05). Trunk extension strength was the highest in the Reachers whereas trunk LS Flexion strength was highest in the Non-Reachers (RS = Right Side, LS = Left Side).

5.4.3 Pressure offloading

Figure 5-3 presents the pressure offloading results for the Reachers and Non-Reachers. In general, Reachers spent more time offloading over the left and right ischial tuberosities than
Non-Reachers (94.40 s/hour and 34.35 s/hour vs. 18.25 s/hour and 6.85 s/hour respectively). However, significant differences existed between the Reachers and Non-Reachers for offloading only for the right ischial tuberosity (P = 0.029). While offloading for the left ischial tuberosity was lower in Non-Reachers than Reachers, the results did not reach significance (P = 0.232).

![Mean Pressure Offloading in Reachers and Non-Reachers](image)

**Figure 5-3** Mean offloading times (expressed as s/hour) with 95% Confidence Intervals for Reachers (n = 7) and Non-Reachers (n = 8). The right ischial tuberosity was offloaded less than the left ischial tuberosity in both Reachers and Non-Reachers. Non-Reachers spent less time offloading the right and left ischial tuberosities compared with Reachers however the results were significant only for the right ischial tuberosity (P < 0.05).
5.4.4 Relationship between trunk strength and pressure offloading

There were no significant correlations found between isometric trunk strength (flexion, extension, and lateral flexion) and pressure offloading duration of the right and left ischial tuberosities (Spearman’s Rank Correlation: 0.083-0.434, P = 0.134-0.769).

5.5 Discussion

This study demonstrated that ischial offloading could be assessed in individuals with SCI using SensiMAT™ technology in a paradigm when individuals with SCI were performing normal daily activities. Although data were collected over a two hour period, no participants developed a pressure ulcer during this period or the course of the study despite the fact that offloading frequency and duration were less than best practice recommendations (Houghton and Campbell, 2013) suggesting that pressure relief may not be the only contributing factor in the maintenance of tissue health. Other factors need to be monitored longitudinally.

Trunk strength was significantly lower in Non-Reachers compared with Reachers. Individuals with SCI, who were unable to engage in a reaching task, had significantly lower trunk strength in all directions. In earlier work we demonstrated that trunk strength was significantly lower in wheelchair users compared to walkers in individuals with SCI (Gabison et al., 2014), however, trunk strength was not characterized in wheelchair users in relationship to reaching ability. Given that trunk muscle activation is required to maintain trunk stability during perturbed sitting (Masani et al 2009), it is likely that reduced trunk muscle strength may preclude an individual’s ability to reach and generate reactive compensatory balance strategies through the activation of trunk muscles, which are required when the centre of mass is displaced beyond the base of support. This study adds to the current literature by characterizing trunk strength in wheelchair users, however additional studies using EMG may help shed light on the required generation of muscle forces and synergies to maintain upright stability in wheelchair users with varying reaching abilities and the relationship to offloading behaviours.
Because the ability to reach while sitting and maintain upright stability involves synergistic trunk muscle activity, individuals with SCI who present with sensorimotor impairments of the upper and lower extremities and trunk muscles, which are dependent on both the injury level and completeness of the injury (New, Simmonds and Stevermuer, 2010), will use different offloading strategies. Furthermore, individuals with Traumatic SCI demonstrate lower Functional Independent Measures Scores than those with Non-Traumatic SCI suggesting greater disability in individuals with Traumatic SCI (New, Simmonds and Stevermuer, 2010, Ones et al., 2009). Shin and Sosnoff (2013) demonstrated that individuals with high Traumatic SCI (T10 and above) exhibited smaller “functional” boundaries in sitting compared with individuals with low SCI (T11-L4), suggesting that there may be varying degrees of reaching ability depending on injury level. In addition, Chen et al. (2003) found that individuals with low thoracic SCI demonstrated greater dynamic seated stability than those individual with a high-level thoracic SCI. Earlier Seelan et al. (1997) noted that individuals with high thoracic injury tend to rely on their latissiumus dorsi, lower fibres of trapezius, pectoralis major, and serratus anterior and high thoracic parts of their erector spinae, while able-bodied individuals rely more on their erector spinae for seated stability, also suggesting that trunk muscle activation depends on level of injury. Based on Shin and Sosnoff’s (2013) work, we decided to use T10 as the threshold as we expected this level would be a neurological level of injury that might explain some of the variance.

Although due to our sample size we could not examine injury level, AIS impairment scale and etiology of SCI as variables to account for reaching ability, when considering seated stability and injury level, four of the eight Reachers in our study had injury levels at or below T10 whereas only two of nine participants in the Non-Reachers group had an injury at the level of T10 or lower. Three Reachers had a Non-Traumatic SCI whereas only one of the Non-Reachers sustained a Non-Traumatic SCI. Participant ID18 was unable to engage in a reaching task despite an incomplete Non-Traumatic injury at the level of T11 and two of the participants (ID14 and ID16) were able to engage in a reaching task despite incomplete Non-Traumatic injuries at C5 and C6, suggesting that while an injury level of T10 may characterize those who can perform a reach vs. those who are unable to, the completeness and nature of the injury must be considered in the context of injury level. These differences in the etiology of SCI (i.e. traumatic and non-traumatic SCI) and time course of pathology could not be factored into our analysis due to our
limited sample size. Furthermore, data on participants were collected post SCI, hence their pre-injury reaching profile was not assessed which could influence their post-injury reaching status. Ideally, a larger sample would have enabled us to stratify participants by injury level and etiology and would have allowed us to explore further the relationship between injury level, etiology, reaching ability and offloading behaviour.

We did however stratify the participants into two groups based on their reaching ability as we expected that individuals who would be unable to engage in a reaching task would also present with reduced pressure offloading times in comparison to those who could engage in reaching tasks. Interestingly participants in this study engaged in pressure offloading over their left ischial tuberosity approximately 50% longer than their right ischial tuberosity. Although Reachers spent more time offloading compared to Non-Reachers, the results showed significance only for the right side. All participants were right hand dominant, suggesting that reaching dominance might play a role in offloading. Our findings are in agreement with Grangeon et al. (2012) who suggested that individuals with SCI may prefer to reach with their dominant limb, and while reaching, use their non-dominant limb for support. Consequently, individuals with SCI may prefer to reach towards their dominant side when engaging in daily activities (Park, 1992), thereby offloading their non-dominant side making it plausible that non-dominant limb support also relates to side offloading. Offloading the right ischial tuberosity would have required participants to reach towards their non-dominant (left) side, obviously a more difficult task for Non-Reachers as they were unable to reach without losing their balance. We recommend further studies using a larger sample size to determine if and how the ability to engage and dominance in reaching tasks has an effect on offloading times for both the left and right ischial tuberosities.

In previous work we demonstrated a relationship between right-sided trunk strength and left reach distance (Gabison et al., 2014), however pressure offloading was not assessed during the reaching task. Cabanas-Valdes, Cuchi and Bagur-Clafat (2013) demonstrated that trunk training exercises improve both trunk performance and dynamic sitting balance in individuals post stroke. However, in SCI, where trunk strength is usually reduced bilaterally, particularly for those with complete injuries, the bilateral reduced trunk strength may preclude an individual’s ability to reach and offload the ischial tuberosity when sitting, while attempting to maintain functional sitting balance. Our data suggest that the greatest variability of trunk strength occurred with left side flexion in both Reachers and Non-Reachers as indicated by the largest confidence intervals.
At present, we are unable to explain these findings and suggest that future studies examine potential contributors of both trunk strength and hand dominance. Understanding the interrelationships might elucidate whether there is a need to target rehabilitation programs that address functional reaching for specific individuals who may be unable to engage in pressure offloading as suggested by Chen et al. (2003). Given that we could not demonstrate that trunk strength was correlated with offloading times, further studies, with a larger sample using specific thoracic levels and degrees of completeness of injury may be required to explore if and how trunk stability, reaching ability and pressure offloading behaviours are related. Examining the trunk musculature during various pressure offloading paradigms e.g. forward or side leans as well as reaching alone, may shed light on the influence on offloading behaviours during different functional activities.

As our study did not examine the trajectories of either trunk or arm movement during pressure offloading while participants engaged in their daily activities, we are unable to determine the method of offloading that participants used to engage in pressure relief. Additionally, we did not consider upper limb function, which could potentially influence offloading behavior. Three of the Reachers and one Non-Reacher simultaneously offloaded both ischial tuberosities, which could be achieved by a forward lean or vertical lift. Future studies in carefully designed cohorts of individuals with SCI should capture video monitoring or kinematics of the trunk and upper extremities and motor scores of the upper extremities to characterize the relationship between trunk kinematics, arm kinematics and strength, and pressure offloading in the laboratory setting and during various functional daily activities.

We defined full offloading as pressure relief. However, the offloading process can be broken down into three distinct phases: offloading (where the tissue is offloading), offloaded (the tissue is completely offloaded) and reloading (the tissue is reloaded as the individual returns to the loaded condition). It is documented that seated functional movements facilitate the redistribution of pressure and increase circulation to weight bearing surfaces (Sonenblum et al., 2014) suggesting that during the offloading process, ischemic tissues are re-perfused. Further studies should examine if partial offloading is significant between Reachers and Non-Reachers.
Recently Tederko et al. (2015) demonstrated that increased wheelchair footrest height increases pressure under the ischial tuberosity. As we did not account for footrest height during our study we do not know how it influences our findings. Future studies should examine if footrest height has an effect on the degree of our technological approach to monitor offloading.

5.6 Conclusions

Although the results of the study demonstrated that those who were able to reach offloaded their right ischial tuberosity more than those who were unable to reach, there was not a significant correlation between isometric trunk strength and ischial offloading. If reaching is an important factor for offloading, assessing reaching abilities and the corresponding trunk muscle activation patterns becomes paramount before targeted rehabilitation strategies for offloading pressure can be designed. We have demonstrated that the SensiMAT™ technology is capable of tracking the pressures over the ischial tuberosities for prolonged periods of time and during different activities. The data acquired are a first step in establishing a baseline for patient specific customized training for pressure offloading during the course of their rehabilitation. The participants in our study did not develop pressure ulcers during the sub-acute rehabilitation phase even though we could not demonstrate adherence to best practice recommendations for pressure offloading. These findings are consistent with what has been reported in the literature suggesting other factors that contribute to pressure ulcer development should be explored during the rehabilitation phase.
Chapter 6 The Relationship between Pressure Offloading and Ischial Tissue Health in Individuals with Spinal Cord Injury: An Exploratory Study

This chapter is a modified version of the following article, where modifications consist of changes in formatting:

Gabison S., Mathur, S., Nussbaum, E.L., Popovic, M.R., Verrier M.C. The relationship between pressure offloading and ischial tissue health in individuals with spinal cord injury: an exploratory study

This article will be submitted for publication to the Journal of Spinal Cord Medicine
6.1 Abstract

The purpose of this exploratory prospective cross-sectional study was to compare thickness and texture measures of tissue overlying the ischial region in able-bodied (AB) cohort vs. individuals with Spinal Cord Injury (SCI) and to determine if there is a relationship between offloading of the ischial tuberosities (IT) and tissue health in individuals with SCI. The study was undertaken in a university setting and rehabilitation hospital. An AB cohort of 10 individuals and 15 non-ambulatory participants with complete or incomplete traumatic and non-traumatic SCI, American Spinal Injury Association Impairment Scale (AIS) Classification A-D participated in the study. Thickness and texture measurements from ultrasound images over the IT in AB and SCI cohorts, and pressure offloading of the IT using a customized pressure mat in SCI cohort were measured. The area occupied by muscle was significantly greater in the SCI when compared with AB cohort. The area occupied by muscle in SCI appeared to lose the striated appearance and was more echogenic. There was no correlation between offloading times and thickness measurements of skin, subcutaneous tissue and muscle. Changes in soft tissues overlying the ischial tuberosity occur following SCI, corresponding to loss of striated appearance and increased thickness of the area occupied the muscle. Further studies using a larger sample size are recommended to establish if thickness and tissue texture differ between individuals with SCI who engage in pressure relief vs. those who do not.
6.2 Introduction

According to the National Pressure Ulcer Advisory Panel (NPUAP), a pressure injury (PI) is a localized area of injury to the skin and/or underlying tissue over a bony prominence, as a result of pressure, or pressure in combination with shear (NPUAP, 2016). It has been suggested that external pressure is the primary reason why PIs develop (Thomas, 2010) and can occur within two hours of immobility (Bansal et al., 2005). More recently, deep tissue injury (DTI), which occurs under intact skin in the deeper tissue including muscle and subcutaneous tissue as a result of pressure, has been recognized as a form of PI (NPUAP, 2016, Geffen, 2007). In DTI, edema accumulates in the deep tissue, which migrates up to the skin surface (Quintavalle et al., 2006). PIs are a costly medical complication in individuals with spinal cord injury (SCI). It is estimated that 1.3 to 3 million individuals in the United States have a PI (Lyder, 2003), costing the American health care system $2.2 - $3.6 billion annually for hospital acquired PIs alone (Beckrich and Aronovitch, 1999). The impact of PIs on the individual with SCI is significant affecting not only work productivity, but also quality of life (Spilsbury et al., 2007).

The ischial tuberosity (IT), a bony prominence, is the major weight bearing bone underlying the buttock tissue and is considered to bear the mechanical stresses during sitting (Makhsous et al., 2011). The tissues overlying the IT including the gluteus maximus, subcutaneous tissue and skin, undergo compressive forces during sitting. Wu and Bogie (2013) suggest that the gluteus maximus muscle overlying the IT provides cushioning for the subcutaneous tissue and skin. Varying degrees of stiffness and viscoelasticity of tissues, including those overlying the IT lead to different responses of the tissues during applied loads. Stiffness of tissue can serve as a protective factor, while viscoelastic tissues are more sensitive to applied loads. The greater stiffness of skin when compared with adipose tissue and muscle enables it to withstand greater compressive forces without injury (Van Loocke, Lyons and Simms, 2008, Thorfinn et al., 2009). Adipose tissue is comparable to incompressible fluid, in contrast to muscle, which is more viscoelastic (Van Loocke, Lyons and Simms, 2008), suggesting that muscle may be more sensitive to applied loads compared with adipose tissue. While Lyder and Ayello (2008) recommend that maintaining the external pressure over human tissue below the average capillary
pressure of 32 mmHg may reduce the development of a PI, the different responses of the tissues to applied loads can result in different outcomes.

Reenalda et al. (2009) and Linder-Ganz et al. (2007) demonstrated that AB individuals engage in weight shifting every 6-8 minutes, which interestingly is below best practice recommendations for individuals with SCI who are advised to engage in pressure relief every 15 minutes (Stockton and Parker, 2002). Difficulty unloading soft tissues over the IT due to immobility, such as that which occurs following SCI, can result in prolonged soft tissue deformation (Makhsous et al., 2011), damage of the epidermal and dermal layers (Leveque et al. 2002) and increased risk of a PI secondary to ischemia and reperfusion damage (Kottner et al., 2015). In addition to inability to offload weight bearing surfaces, structural changes in skin, subcutaneous tissue and muscles following SCI further increase the risk of developing seated acquired PIs.

Following an SCI, the skin undergoes an adaptive process, which can be described as disuse adaptation (Gefen, 2014). Individuals with SCI have shown to have up to 25% less thickness of skin over the ischium and sacrum (Makhsous et al., 2008, Yalcin et al., 2013) when compared to AB individuals. Additionally, malnutrition, dehydration, increased collagen catabolism (Claus-Walker and Halstead, 1982, Vaziri et al., 1992, Stover et al., 1980), reduced fibroblastic activity and microvascular changes in the skin (Gefen, 2014) can result in reduced collagen formation (Yalcin et al., 2013). Due to the protective nature of skin (Dealey, 2009) and its minimal response to strain when compared with muscle and adipose tissue (Luboz et al., 2014) it is possible that reduced skin thickness and reduced collagen content may predispose individuals with SCI to develop a PI in response to prolonged loading when compared to AB individuals.

Following SCI, morphological changes in muscles below the level of injury occur within 4 weeks post injury (Carsda, Cisari and Invernizie, 2013) including atrophy (Giangregorio and McCartney, 2006), fat infiltration (Carsda, Cisari and Invernizie, 2013), reduced number of slow oxidative fibres (Linder-Ganz et al., 2008) and a greater proportion of low-density muscle tissue (Wu and Bogie, 2013). The gluteus maximus muscle following SCI demonstrates non-uniform atrophy, with the greatest atrophy occurring over the IT (Wu and Bogie, 2013). In addition, micro and macrovascular changes (Gefen, 2014) secondary to reduced sympathetic nervous system activity, reduce the protective vasodilatatory response of muscle to prolonged
pressure (Jan et al., 2010), and thereby reduce oxidative capacity, and diminishes the ability of the muscle to remove accumulated metabolites (Kim et al., 2012, Bogie and Triolo, 2003) further compromising tissue health. The severity of changes in muscle post SCI are dependent on the level of injury and time since injury (Giangregorio and McCartney, 2006). The changes in the muscle following SCI can further compromise tissue health when the tissue is subjected to applied loads during sitting.

Changes in the physical properties of skin, subcutaneous tissue and muscle in individuals with neurological disorders can be captured using ultrasound imaging (Pillen et al., 2008). The advantage of using ultrasound imaging is its portability, minimal invasiveness and low cost while providing real time imaging at the bedside (Lucas et al., 2014). High frequency ultrasound has been used to detect dermal and subdermal edema in individuals at high risk for the development of PIs (Quintavalle et al., 2006, Lucas et al., 2014). Ultrasound imaging can be used to document tissue healing through the appearance of changes in tissue homogeneity and regularity (Rippon et al., 1998), the appearance of ill-defined layered structures and the presence of hypoechoic areas (Yalcin et al., 2013). While these methods have employed subjective interpretation of the ultrasound images, quantification of changes in texture of the tissue overlying the IT, which can be obtained from grey scale measures including pixel intensity (i.e. echogenicity) and homogeneity (i.e. contrast) has not been established in individuals with SCI.

Increased dermal edema results in separation of collagen bundles, which appear as areas of reduced echogenicity. The presence of dermal water has been related with magnetic resonance imaging (Gniadecka and Quistorff, 1996). Measures obtained in regions of interest (ROI) from ultrasound images such as echogenicity and contrast may be useful in quantifying tissue texture (Theodiris and Koutroubas, 2003, Molinari et al., 2015, Wu et al., 1992) and collagen content (Moghimi, Baygi and Torkman, 2011). The number of low echogenic pixels in relation to total pixels can be used to quantify the low echogenic component of the ultrasound image (Gniadecka and Quistorff, 1996). Therefore, obtaining more detailed measures from ultrasound images may provide additional insight into tissue texture in response to applied loads, rather than reliance on subjective interpretation from visual inspection of ultrasound images.
While it has been well documented that intrinsic factors may also contribute to the development of PI including altered neurogenic control of circulation, poor oxygen, nutrient availability and vasoactive medication (Marin, Nixon and Gorecki, 2013), the relationships between pressure offloading and any potential changes in tissue properties identified with ultrasound imaging have not been explored. The objectives of this study were to: 1) explore relative tissue thickness of skin, subcutaneous and muscle tissue overlying the IT in individuals with SCI in comparison to AB cohort using high frequency ultrasound, and 2) determine if pressure offloading was related to thickness of skin, subcutaneous tissue and muscle in individuals with SCI. The need to evaluate tissue properties in individuals with differing offloading abilities is important when considering rehabilitation strategies to mitigate the development of seated acquired PIs following SCI.

6.3 Materials and Methods

6.3.1. Study design

This cross-sectional study used a single-visit, single-evaluator, observational design.

Data were collected from the able-bodied (AB) cohort at the Muscle Function & Performance Laboratory at the University of Toronto, Department of Physical Therapy. Toronto, Canada. Data on individuals with SCI were collected at Toronto Rehabilitation Institute - UHN, Lyndhurst Centre, Toronto, Canada, a rehabilitation hospital serving individuals with both traumatic and non-traumatic SCI. The study was approved by the institutional review boards of both settings. Informed consent was obtained from each participant prior to their participation in the study.
6.3.2 Participants

6.3.2.1. Able-bodied Individuals

Ten healthy men (n = 4) and women (n = 6) between the ages of 18 to 70 participated in the study. Subjects were excluded from the study if they reported any history of joint injury or surgery of the knee, ankle, shoulder or elbow, history of muscle disease (e.g. muscular dystrophy), skin conditions (e.g. dermatitis, psoriasis) or history of inflammatory muscle disease (e.g. polymyositis).

6.3.2.2 Individuals with Spinal Cord Injury

Fifteen men (n = 12) and women (n = 3) with SCI participated in the study. Inclusion criteria included participants 18 years of age and older with complete or incomplete, traumatic or non-traumatic SCI, etiology classified as AIS A to D. Participants had to be medically stable and participating in in-patient rehabilitation and had to be using their wheelchair as the primary means of mobility for at least 2 hours per day to be included in the study. Individuals with significant musculoskeletal conditions, impaired neurological status affecting sitting balance other than those due to their injury, an existing PI or a documented brain injury were excluded from the study.

6.3.3 Pressure Offloading

Pressure offloading of the IT was captured for the individuals with SCI as described in Gabison et al. (2017). A customized 0.95 cm thick pressure mat “SensiMAT” (SensiMat Systems, Canada) was placed under the wheelchair cushion. The SensiMAT contained 6 square force sensitive resistors, each measuring 43.7 mm in diameter, with an actuation force of 0.1 N and
force sensitivity of 0.1-10.0^2 N. Data from each of the force sensors were collected at a sampling rate of 1 Hz. Data from the sensors were transferred to an iPhone using Bluetooth technology and then uploaded to a secure server through WiFi. Analog signals from each sensor were processed using MATLAB (Mathworks, USA) to capture offloading times (in seconds) under each of the six sensors. Offloading was defined as a period of time during which the two rear pressure sensors registered a force equivalent in value to that when no pressure was applied for a minimum of at least 2 seconds (s).

Each IT was examined separately. Individuals who engaged in offloading of the IT less than 1% of the time were categorized as “Loaders”, whereas those who engaged in offloading of the IT more than 1% of the time were characterized as “Offloaders”. We chose a 1% cutoff, which corresponds to 36 seconds in a one-hour period, which is similar to the corresponding minimal offloading duration recommended of 30-seconds (Houghton and Campbell, 2013). Although this threshold is well below the recommendations for offloading every 15 minutes, a study by Sonenblum and Sprigle, (2016) demonstrated that the majority of individuals with SCI do not engage in the recommended weight-shifting schedule.

While capturing pressure offloading times, each individual used their own wheelchair and wheelchair cushion and engaged in their usual activities of daily living, including participating in their routine rehabilitation program. Data were collected for a minimum of 2-hours. Given that sitting duration varied for each participant depending on their rehabilitation schedule, offloading times were expressed as a percentage of their total sitting times and only when the subjects were sitting in their wheelchair.

6.3.4 Ultrasound Imaging

For the AB cohort, a Linear Array B-Mode 8 - 13 MHz Ultrasound Transducer (GE LOGIQ-E Ultrasound system, GE Healthcare, USA) was used to scan the tissue overlying the ITs. For the individuals with SCI, a linear array B-Mode 6-18 MHz Ultrasound Transducer (Siemens Acuson S2000 Ultrasound System, Siemens Healthcare, Germany) was used.
Three transverse ultrasound images of individuals with SCI and the AB cohort were collected over both ITs in the side lying position, with the participants’ hips and knees placed in 90 degrees of flexion and with their hip in the neutral abduction/adduction and internal/external rotation positions using a pillow between the knees. To ensure consistent placement of the ultrasound probe during repeated image acquisition, the distance between the greater trochanter and the coccyx was measured and recorded. A perpendicular distance from the line drawn between the greater trochanter and coccyx to the IT was measured and recorded and used for repeated probe placement.

For each ultrasound image, the frequency, gain and focus were adjusted to obtain optimal image quality. Images were exported into a customized program using the Imaging Processing Toolbox of MATLAB (Mathworks, Natick, MA, USA). The same individual who acquired the images outlined the regions of interest (ROI) corresponding to skin, subcutaneous tissue and muscle through visual examination of each image. Each region of interest varied per participant depending on the depth of the IT. For each region of interest, mean thickness, echogenicity and contrast were computed and adjusted as a percentage of total thickness of tissue overlying the IT.

**6.3.5 Data Analysis**

Due to different ultrasound image capture for both cohorts, only thickness measures were used for analysis.

SPSS Statistics (SPSS Statistics 23, IBM, USA) was used for statistical analysis. The Shapiro Wilk Test was used to assess for normality for the demographic data. An Analysis of Variance was conducted to determine if demographic variables were significantly different between the AB cohort and the individuals with SCI. The Shapiro Wilk Test was used to assess for normality of pressure offloading and ultrasound measures. Medians and interquartile ranges were calculated for mean thickness of skin, subcutaneous tissue and muscle for both the left and right ITs in AB and SCI individuals. Spearman’s rank order correlations were used to determine the relationship between percent of offloading time and ultrasound measures. Using the criteria of Altman (1991) correlation coefficients were interpreted according to the following criteria: $r =$
0.21-0.40 representing poor correlation, \( r = 0.41-0.60 \) representing moderate correlation, and \( r = 0.61-0.80 \) representing good correlation, and \( r > 0.81 \) representing very good correlation.

### 6.4 Results

Demographics of the AB individuals and individuals with SCI are reported in Table 6-1. Characteristics of individuals with SCI are reported in Table 6-2. Analysis of Variance revealed that demographic variables were not statistically different between able-bodied individuals and individuals with SCI.

**Table 6-1 Demographics of Able-Bodied Individuals and Individuals with SCI**

<table>
<thead>
<tr>
<th></th>
<th>Able-bodied Individuals (n = 10)</th>
<th>Individuals with SCI (n=15)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
</tr>
<tr>
<td>Males/Females</td>
<td>4/6</td>
<td>12/3</td>
</tr>
<tr>
<td>Age (years)</td>
<td>42.8 ± 16.3</td>
<td>42.7 ± 17.2</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>173.4 ± 6.0</td>
<td>172.9 ± 6.2</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>71.3 ± 12.5</td>
<td>73.1 ± 12.0</td>
</tr>
</tbody>
</table>
### Table 6-2 Characteristics of Individuals with SCI

<table>
<thead>
<tr>
<th>ID</th>
<th>Demographics</th>
<th>Injury Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sex (M/F)</td>
<td>Age</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>53</td>
</tr>
<tr>
<td>12</td>
<td>M</td>
<td>35</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
<td>25</td>
</tr>
<tr>
<td>1</td>
<td>M</td>
<td>36</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>25</td>
</tr>
<tr>
<td>10</td>
<td>M</td>
<td>32</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>48</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>52</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>44</td>
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<tr>
<td>11</td>
<td>M</td>
<td>50</td>
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<td>15</td>
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<td>53</td>
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<td>6</td>
<td>M</td>
<td>21</td>
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<td>9</td>
<td>F</td>
<td>16</td>
</tr>
<tr>
<td>14</td>
<td>M</td>
<td>65</td>
</tr>
<tr>
<td>16</td>
<td>F</td>
<td>78</td>
</tr>
</tbody>
</table>

| Mean ± SD / Count | 12/3 | 42.7±17.2 | 172.9±6.2 | 73.1±12.0 | 126.2±99.7 | C4-T12 | 12/3 | 8/5/0/2 |
6.4.1 Ischial Tissue Health: Able-bodied vs. SCI Individuals

Figure 6-1A represents a typical image obtained from the tissue overlying the IT in an AB individual. Figure 6-1B represents the outlined ROI corresponding to skin (S), subcutaneous tissue (SC) and muscle (M) from the same image.

Figure 6-1A and 6-1B Ultrasound image of tissues overlying the ischial tuberosity (IT) obtained from able-bodied individual. The unprocessed image (A) is visualized on the left. The image on the right (B) depicts the selected regions of interest analyzed. S = skin, SC = subcutaneous tissue, M = muscle. Frequency, gain and depth were adjusted for each participant to optimize image quality. The skin is depicted as an area with hyperechoic lines, parallel to the skin surface, with a clear delineated border separating the subcutaneous tissue. The subcutaneous tissue is identified as a low echoic intensity area with echogenic regions corresponding to the connective tissue. The lower boundary of the subcutaneous tissue is separated by a clearly identified reflective fascial layer overlying the muscle. The region of muscle corresponds to the area where fascicular architecture is visible. The depth of the IT is measured at approximately 2.75 cm.
Figures 6-2A and 6-2B depict a typical image obtained from the tissue overlying the IT in an individual with SCI. The area corresponding to the muscle demonstrates reduced identification of the fascial planes as indicated by the lack of a clearly delineated striated pattern. Reduced contrast of the muscle is identified by the appearance of more uniform grey scale intensity throughout the region occupied by muscle.

Figure 6-2A and 6-2B Unprocessed ultrasound image over the left ischial tuberosity in one individual with spinal cord injury (A) with regions of interest outlined in processed image (B). Frequency, gain and depth were adjusted for each participant to optimize image acquisition. The image reveals a homogenous pattern of ultrasound reflection in the skin and muscle region. The region of subcutaneous tissue is illustrated through regions of hypoechoic tissue separated by hyperechoic bands. The ischial tuberosity is identified by the presence of a hyperechoic area. The depth of the IT is measured at approximately 4.0 cm.
The thickest layer overlying the IT in both AB and SCI cohorts was the muscle (38.06 - 74.89%), followed by the subcutaneous tissue (17.33 - 51.38%) and skin layer (4.53 - 16.63%) (Table 6-3). In both AB and SCI cohorts, the lowest contrast was seen in the muscle (median: 9.81 and 6.32 respectively). The echogenicity in the AB cohort was highest in the skin (median 92.02), followed by subcutaneous tissue (median 74.87) and muscle (median 72.99). The echogenicity in the SCI cohort was similar in the skin and subcutaneous tissue (median 59.31 and 59.93, respectively) and lower in the muscle (median 54.64).

Statistical analyses revealed that mean thickness of skin, subcutaneous tissue and muscle were not normally distributed for both groups (P < 0.05).
Table 6-3 Ultrasound Measurements Over the Right Ischial Tuberosity of Able-Bodied Individuals and Individuals with Spinal Cord Injury

<table>
<thead>
<tr>
<th></th>
<th>Able-Bodied Individuals</th>
<th>Individuals with SCI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median</td>
<td>IQR</td>
</tr>
<tr>
<td><strong>Mean Thickness (mm)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>2.32</td>
<td>2.04-2.70</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>8.30</td>
<td>5.89-10.18</td>
</tr>
<tr>
<td>Muscle†</td>
<td>12.93</td>
<td>9.33-15.84</td>
</tr>
<tr>
<td><strong>Percentage Thickness</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>10.15</td>
<td>8.00-11.52</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>35.34</td>
<td>21.48-29.39</td>
</tr>
<tr>
<td>Muscle</td>
<td>54.13</td>
<td>42.61-66.33</td>
</tr>
<tr>
<td><strong>Contrast</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>18.73</td>
<td>11.60-19.99</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>17.14</td>
<td>11.98-22.95</td>
</tr>
<tr>
<td>Muscle</td>
<td>9.81</td>
<td>6.45-13.08</td>
</tr>
<tr>
<td><strong>Echogenicity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>92.02</td>
<td>86.01-95.66</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>74.87</td>
<td>66.44-83.65</td>
</tr>
<tr>
<td>Muscle</td>
<td>72.99</td>
<td>61.42-85.14</td>
</tr>
</tbody>
</table>

†Denotes significance
6.4.1.1 Skin

The thickness of the skin overlying the IT in individuals with SCI (median = 2.19 mm, range: 2.03 – 2.52 mm) did not differ significantly when compared with the able-bodied individuals (median = 2.32 mm, range: 1.69 - 3.00 mm), (U = 68.0, z = -0.388, P = 0.723).

6.4.1.2 Subcutaneous Tissue

Subcutaneous tissue thickness in individuals with SCI (median = 8.15 mm) did not differ significantly from able-bodied individuals (median = 8.31 mm), (U = 67.0, z = -0.555, P = 0.683).

6.4.1.3 Muscle

The thickness of the region corresponding to muscle in individuals with SCI (median = 18.62 mm) differed significantly from able-bodied individuals (median = 12.93 mm), (U = 30.5, z = -2.469, P = 0.012).

6.4.2 Comparison of Tissue Health Between Loaders vs. Offloaders in SCI Cohort

Table 6-4 presents the mean thickness, echogenicity and contrast measures of the Loaders and Offloaders. Individuals with SCI offloaded differently for the right and left ITs. Seven individuals offloaded the left IT, whereas 4 individuals offloaded their right IT. Thickness of the skin, subcutaneous tissue and muscle overlying the left IT was greater in the Loaders when compared to Offloaders (Figure 6-3), whereas thickness of the skin and muscle over the right IT
was greater in the Loaders compared with Offloaders (Figure 6-4). Less contrast was seen in the Loaders compared with the Offloaders for both the left and right ITs (Table 6-4). Echogenicity was greater in the Loaders compared with the Offloaders in the skin, subcutaneous tissue and muscle over the left IT, whereas greater echogenicity was observed over the right IT only in the muscle (Figure 6-5).

There was no significant correlation between pressure offloading duration and thickness, measures of skin, subcutaneous tissue and muscle (r: -0.023 – 0.445, p: 0.096-0.934) (Table 6-5).
Figure 6-3 Boxplots of mean thickness of skin, subcutaneous tissue and muscle over the left IT in Loaders vs. Offloaders. The whiskers correspond to the 10th and 90th percentiles. The 1st and 3rd quartiles denote the borders of the box. The median is represented by a horizontal line inside the box. Outliers are denoted in circles. Mean thickness of skin was lowest in Loaders and Offloaders, whereas the area corresponding to muscle was the greatest in Loaders and Offloaders.
Figure 6-4 Boxplots of mean thickness of skin, subcutaneous tissue and muscle over the right IT in Loaders vs. Offloaders. The whiskers correspond to the 10th and 90th percentiles. The 1st and 3rd quartiles denote the borders of the box. The median is represented by a horizontal line inside the box. Outliers are denoted in circles. Mean thickness of skin was lowest in Loaders and Offloaders, whereas the area corresponding to muscle was the greatest in Loaders and Offloaders.
<table>
<thead>
<tr>
<th>Table 6-4 Ultrasound Measures of Offloaders and Loaders in Individuals with Spinal Cord Injury for the Left and Right Ischial Tuberosities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Ischial Tuberosity</td>
</tr>
<tr>
<td>Offloaders (n = 7)</td>
</tr>
<tr>
<td>Mean Thickness (mm)</td>
</tr>
<tr>
<td>Skin</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
</tr>
<tr>
<td>Contrast</td>
</tr>
<tr>
<td>Skin</td>
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<tr>
<td>Subcutaneous Tissue</td>
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<tr>
<td>Echogenicity</td>
</tr>
<tr>
<td>Skin</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
</tr>
<tr>
<td>Muscle</td>
</tr>
</tbody>
</table>
Figure 6-5 BoXPLOTS of median echogenicity of skin, subcutaneous tissue and muscle over the right IT in Loaders vs. Offloaders. Echogenicity was higher in the skin when compared with subcutaneous tissue and muscle in the Offloaders. The whiskers correspond to the 10th and 90th percentiles. The 1st and 3rd quartiles denote the borders of the box. The median is represented by a horizontal line inside the box. Outliers are denoted in circles. Echogenicity was higher in the loaders of muscle.
Table 6-5 Correlation Coefficients and corresponding p-values (in brackets) between thickness, echogenicity and contrast and percent of offloading time.

<table>
<thead>
<tr>
<th></th>
<th>Offloading Left IT (% sitting time) (n = 15)</th>
<th>Offloading Right IT (% sitting time) (n = 15)</th>
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</thead>
<tbody>
<tr>
<td><strong>Mean Thickness</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>-0.093 (0.742)</td>
<td>-0.143 (0.612)</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>-0.279 (0.524)</td>
<td>-0.036 (0.899)</td>
</tr>
<tr>
<td>Muscle</td>
<td>0.445 (0.096)</td>
<td>0.364 (0.182)</td>
</tr>
<tr>
<td><strong>Echogenicity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>0.023 (0.934)</td>
<td>0.157 (0.576)</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>0.113 (0.689)</td>
<td>0.061 (0.830)</td>
</tr>
<tr>
<td>Muscle</td>
<td>-0.259 (0.351)</td>
<td>0.043 (0.879)</td>
</tr>
<tr>
<td><strong>Contrast</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>0.388 (0.153)</td>
<td>0.305 (0.271)</td>
</tr>
<tr>
<td>Subcutaneous Tissue</td>
<td>0.352 (0.198)</td>
<td>0.339 (0.216)</td>
</tr>
<tr>
<td>Muscle</td>
<td>0.468 (0.079)</td>
<td>0.050 (0.860)</td>
</tr>
</tbody>
</table>
6.5 Discussion

Our study demonstrated that although thickness of skin and subcutaneous tissue was not significantly different between AB and individuals with SCI, the area occupied by muscle overlying the IT was significantly greater in individuals with SCI compared to the AB cohort. On visual inspection, clearly defined striations were not visible in the region occupied by muscle in individuals with SCI and the region occupied by muscle appeared more homogenous. It is possible that the loss of striated pattern in the muscle can be attributed to changes in the fascicular architecture as tissues are subject to stress and strain as shear forces are imparted on tissue during transitional movements. Additionally, the challenge in identifying clearly defined borders separating subcutaneous tissue from muscle when compared with the able-bodied cohort may have contributed to the increased muscle thickness observed in individuals with SCI.

Our thickness measures of muscle were lower in the AB cohort and individuals with SCI when compared with previous studies. Wu et al (2013) and Sonenblum et al (2015) found atrophy of the gluteus muscle while Wu et al (2013) using CT contrast, found fat infiltration of gluteus muscle post SCI. Using ultrasound, we were unable to assess the percentage of fat in the muscle and therefore are unable to describe the extent of atrophy vs. fat infiltration of the gluteus maximus muscle in individuals with SCI which could potentially confound the tissue thickness measures. While our cohorts did not differ with respect to height and weight, it is possible that participants with SCI had extensive fat infiltration of gluteus maximus giving the appearance of a homogeneous hyperechoic pattern with an overall larger area occupied by muscle. Given that muscle is more compressible than fat and is more sensitive to tissue deformation with prolonged loading (Van Loocke, Lyons and Simms, 2008), it is not surprising that the region corresponding to muscle appeared to be more homogeneous. It would be interesting to investigate using MRI or CT, if following SCI, fat infiltration of muscle provides a protective mechanism from the bony IT by providing the cushioning needed for the overlying tissue. A longitudinal evaluation of a cohort of individuals with SCI would help explore the nature of changes in echogenicity, atrophy and fat infiltration and their respective relationships to total tissue volume and development of PIs.
Our findings of subcutaneous thickness measures are in contrast to Sonenblum et al.’s study (2015) which examined the soft tissues over the IT in AB individuals and individuals with SCI. Sonenblum et al. (2015) found that thickness measures of unloaded subcutaneous tissue varied between 8 - 59 mm in AB individuals and 6 - 30 mm in individuals with SCI. Our study found that subcutaneous tissue in AB individuals and individuals with SCI to be much smaller than reported by Sonenblum et al. (2015), measuring 4.21 - 15.0 mm in the AB cohort and 4.0-13.0 mm in the SCI cohort. In contrast, thickness of the muscle was found to be greater in both our AB and SCI cohorts compared to Sonenblum et al.’s (2015) study. These differences are not surprising given that Sonenblum et al.’s (2015) experimental paradigm of an unloaded condition comprised individuals sitting on a customized cushion in which an opening in the cushion over the IT was created as participants sat in an MRI. Muscle and subcutaneous deformation occurs over the IT during loaded conditions in healthy individuals and individuals with SCI (Linder-Ganz et al., 2007, Makhsous et al., 2011, Al-Dirini et al., 2015). Al-Dirini et al (2015) found in healthy individuals, that during a loaded condition, greater deformation of the muscle overlying the IT occurred when compared with subcutaneous tissue. It is uncertain as to what deformation of the tissue, if any, occurred in Sonenblum’s study during their experimental paradigm. Participants in our study lay in a side lying position while ultrasound measurements were obtained, minimizing any potential compression or distortion of tissue. Since muscle is more compressible than fat, it is possible that the pressure redistribution during Sonenblum’s unloaded paradigm, in which participants lay on a cushion with an opening over the IT may have resulted in changes in 3D anatomy, and hence overall recorded thickness measures in subcutaneous tissue and muscle which would not have been captured in our study as a result of the side lying, unloaded position.

Previous investigators have used texture analysis to characterize tissue composition, however it has not been used to characterize tissue over the ITs in people with SCI. Studies have investigated the presence of hypoechoic lesions under the skin in individuals at risk of developing PIs (Porter-Armstrong et al., 2013, Quintavalle et al., 2006) using subjective observation. This study was the first of its kind to quantify texture in the tissues overlying the ITs using echogenicity and contrast measures. These measures could potentially be captured longitudinally in individuals at risk for the developmental of DTI. Additionally, texture analysis could be used in conjunction with histological evaluation. For example, Lal et al. (2002) found
texture analysis to correlate with histological evaluation of blood, lipid, fibromuscular and calcium composition in carotid plaques. To date, no studies have compared histological evaluation of tissues and texture analysis of tissues overlying the IT in humans. Correlating ultrasound grey scale measures with histological evaluation would provide additional insight into the changes in tissue properties that could potentially be detected using ultrasound imaging.

Our study examined tissue health using an ultrasound imaging paradigm and its relationship to pressure offloading behavior in individuals with SCI. We could not determine if tissue texture measures between our Loaders and Offloaders were significant due to our small sample size and customization of system settings for each participant. Additionally, we could not compare our texture measures with any other established ischial tissue texture measures. Using the differences in skin thickness measures between able bodied individuals and individuals with spinal cord injury from Yalcin et al.’s study (2013), with a significance level of 0.05, we estimated that we would require 11 participants in each group to obtain a power of 0.80. Further studies using larger sample size, longer offloading times, in conjunction with additional tissue health measures are recommended.

6.6 Limitations

Although our experimental paradigm captured offloading behavior at one point in time, we expected that the behavioural patterns exhibited during the data collection period would be representative of behavioural patterns in the natural environment. We could not confirm if the offloading behavior exhibited during our data collection period was representative of the typical behavior of offloading of participants in our study. Further studies, using longer periods of sitting time over multiple days, should be undertaken in order to increase the generalizability of the results to individuals with SCI.

Subcutaneous adipose tissue thickness is influenced by gender and body mass index (Ludescher et al., 2011). Due to our small sample size, we could not determine if there were any sex differences with respect to tissue measurements over the IT. Further studies using a larger
sample size would be able to elucidate differences in tissue properties between sexes and its potential effect on tissue health.

There are several documented methods for evaluation of tissue health in healthy controls including measuring local transcutaneous oxygen levels (TcPO₂) (Kim et al., 2012, Thorfinn et al., 2009), transcutaneous tissue carbon dioxide (TcPCO₂), sweat lactate, urea (Knight et al., 2001), erythema (Serup and Agner, 1990, Setaro and Sparavigna, 2002, Barnett and Ablarde, 1995), skin temperature (Kottner et al., 2015) and hydration (Scheel-Sailer et al., 2015). Kottner et al (2015) found increases in erythema and skin temperature over the sacrum and heels in healthy controls sustaining a supine posture, however, they did not study the ischial region. Few studies have examined markers of tissue health in individuals with PI or SCI (Barnett and Ablarde, 1995, Bogie, Nuseibeh and Bader, 1995, Bogie and Triolo, 2003, Andersen and Karlsmark, 2008, Wu et al., 2013, Thorfinn et al., 2002). Assessing tissue vascularity, skin redness and temperature and its relationship to loading/offloading in individuals with SCI may provide the opportunity to explore any potential differences between those that engage in pressure relief vs. those who do not.

6.7 Conclusions

This study is the first of its kind to explore differences in tissues overlying the IT and taking into consideration loading/offloading behavior in the natural environment. Additionally, the relationship between offloading duration and tissue thickness, grey scale and texture measures were explored in individuals with SCI. Following individuals with SCI longitudinally and evaluating tissue measures acquired through ultrasound imaging while monitoring for the development of PI is recommended to establish a potential threshold for thickness, grey scale and texture measures that can potentially be used to predict PIs. Understanding the implications of offloading to tissue properties may enable the development of customized rehabilitation programs for at risk individuals whose changes in tissue properties may be more pronounced.
Chapter 7 Concluding Summary, Unifying Discussion and Future Directions
7.1 Concluding Summary

The tissue overlying the ischial tuberosity (IT) was selected as the focus of this study as this is a region with a high prevalence of PIs in wheelchair users (Sezer, Akkus, and Ugurlo, 2015). Individuals with SCI were selected as the target population due to resultant paralysis and weakness of the muscles in addition to sensory deficits below the level of injury (Nas et al., 2015). Motor weakness and sensory deficits decrease the ability to maintain upright stability including sitting and reaching, tasks required to engage in performing offloading behaviour (Cabana-Valdés et al., 2013). Furthermore, individuals with SCI demonstrate changes in tissue properties overlying the IT (Bogie, Nuseibeh and Bader, 1995) including reduced ability to maintain adequate circulation while sitting, and despite their ability to engage in offloading behaviours, do not do so at the recommended frequency (Sonenblum, 2016). The rationale to use the SCI population to test the hypotheses was warranted given the combination of diminished capacity of the neuromuscular system, physiological changes in tissue properties and behavioural challenges in individuals with SCI.

The study first set out to establish that IT health could be quantified in able-bodied individuals using thickness, grey scale and texture analysis. The study also set out to determine how many images were required to obtain thickness, grey scale and texture measures from ultrasound images. A reliability study obtaining thickness, grey scale and texture measures using ultrasound imaging had not been previously undertaken in tissues over the IT. Additionally, the use of quantitative texture measures of tissues overlying the IT had not been previously undertaken in able-bodied individuals. Using a cohort of able-bodied individuals, it was discovered that participants accounted for most of the variance for both thickness and texture measures. Two images were required to extract thickness and grey scale measures, and four images were required to extract tissue texture measures with a high degree of reliability in healthy participants when using a single evaluator, on a single day, in healthy participants. The ability to use grey scale and texture analysis in tissues overlying the IT provided an additional dimension beyond thickness measures and subjective ratings scales of changes in tissue properties in individuals at risk for the development of seated acquired PIs. Furthermore, the ability to measures texture in tissues overlying the IT, has the potential for longitudinal evaluation of tissue health. The next
study explored if tissue health measures would be different between individuals with SCI and an able-bodied cohort.

When comparing IT health of individuals with SCI to able-bodied individuals, it was discovered that the area corresponding to muscle overlying the IT in individuals with SCI was significantly thicker by approximately 50% when compared with the able-bodied cohort. Additionally, the region corresponding to the muscle appeared to lose the distinctive striated pattern and appeared to be more hypechogenic when compared with the able-bodied individuals. The increased thickness of the area corresponding to muscle in SCI was surprising given the reported muscle wasting below the level of injury following SCI (Giangregorio and McCartney, 2006). However this muscle wasting could be potentially explained by fat infiltration of the muscle and corresponding edema due to prolonged loading (Harrow and Mayrovitz, 2014). The loss of striated pattern in which the connective tissue is otherwise visible in muscle, could potentially be explained by mechanical trauma that muscle may be subjected to as a result of compression and or shearing forces that would occur in wheelchair users during transfers. Additionally, although no statistical analysis was conducted for tissue texture measures between able-bodied and SCI cohorts, greater contrast of the subcutaneous tissue was identified in individuals with SCI compared with the able-bodied cohort suggesting less homogeneity in the tissue. The greater contrast in subcutaneous tissue made it more challenging to partition the subcutaneous tissue from the underlying muscle when compared with the able-bodied cohort, which may contribute to tissue thickness. More detailed imaging such as MRI in conjunction with echogenicity and texture measurement may be able to elucidate potential contributions to the increased thickness of the tissue corresponding to the muscle and the potential morphological changes observed in the SCI population.

The second study examined potential surrogate measures of trunk function in individuals with non-traumatic SCI (NTSCI). The study was undertaken to better understand how trunk strength, trunk range of motion and the ability to reach in individuals with SCI changes over time and based on etiologies of SCI. Individuals with SCI who were able to ambulate had greater trunk strength than wheelchair users who did not ambulate. Wheelchair users improved their trunk flexion (0.05 Nm/kg), extension (0.14 Nm/kg), as well as right (0.08 Nm/kg) and left (0.06 Nm/kg) lateral flexion strengths between admission and discharge from subacute rehabilitation. However these findings were not statistically significant. When individuals with NTSCI and
their ability to reach were examined, it was demonstrated that there were significant differences between walkers and wheelchair users in their ability to reach in the right (0.38 vs. 0.25 % trunk length) and left directions (0.45 vs. 0.23 % trunk length) at their admission to the subacute rehabilitation (P < 0.05). These findings suggest that the multidirectional reach test and trunk strength measures may be potential surrogate measures of trunk function. They also suggest that it is warranted to further examine if reaching ability has any influence on the ability to offload the IT as well as what are typical locations where seated acquired PIs develop in individuals who are wheelchair users.

The third study was undertaken to understand the role of trunk strength and multidirectional reach test (MDRT) on offloading behaviour. Thus a cohort of individuals with traumatic SCI (TSCI) and NTSCI were evaluated on their trunk strength, MDRT and their offloading behaviour. It was demonstrated that those who could engage in a MDRT and defined as “Reachers” would engage in offloading their right and left buttocks more than those who could not engage in a MDRT (“Non-Reachers”) (34.35 s/hour and 94.40 s/hour vs. 6.85 s/hour and 18.25 s/hour respectively) however the results were only significantly different for the right side. Trunk strength was significantly greater in Reachers compared with Non-Reachers in all directions (P < 0.05). These findings suggest that the participants, all who were right-handed, were offloading their right buttock by reaching towards the non-dominant side, potentially a more challenging task. It was also postulated that greater time would be spent offloading the left buttock, due to all participants being right handed and using their dominant arm to engage in activities of daily living by reaching towards their right (dominant) side. However, the methods of offloading employed by the participants could not be confirmed, as supporting kinematic data were not collected. The relationship between offloading on the thickness or texture of the tissues overlying the IT was explored, leading to the fourth and final experiment, which examined the relationship between ischial offloading and tissue health in individuals with SCI.

Due to the small sample size, only descriptive statistics were used to examine the difference in tissue properties between individuals who would offload their ITs vs. those who did not (i.e. “Offloaders” vs. “Loaders”). It was demonstrated that in individuals with SCI, the region corresponding to the muscle demonstrated a trend for higher echogenicity in Loaders compared with Offloaders. Higher echogenicity observed in Loaders, corresponds with increased reflectance of sound waves suggesting a more dense tissue. Additionally the skin, subcutaneous
tissue and muscle were more homogeneous in Loaders compared with Offloaders, suggesting a loss of differentiation of tissues within each region of interest. The increased echogenicity and homogeneity in muscle could reflect changes in the muscle corresponding to fat infiltration. The increase in homogeneity in the subcutaneous tissue and skin observed in the Loaders compared with the Offloaders could potentially reflect a reduced composition of dense connective tissue. However, there was no relationship between total offloading time and any of the thickness or texture measures of skin, subcutaneous tissue and muscle which was not surprising given the minimal offloading time of the left and right buttocks.

7.2 Unifying Discussion

This thesis was presented in a multiple paper format, which provided a comprehensive discussion at the end of each chapter (Sections 3.5, 4.5, 5.5 and 6.5). To avoid duplication, the unifying discussion will focus on two main themes: the importance of consideration of trunk function in offloading behaviour to prevent seated acquired pressure injuries and the need to consider controlled loading as a construct in the maintenance of tissue health, rather than examining periods of sustained offloading to maintain tissue health.

7.2.1 Trunk Function, Offloading Behaviour and Tissue Health

Traditionally, pressure offloading and skin inspection have been the focus of preventing seated acquired PIs in individuals with SCI (Houghton and Campbell, 2013). Pressure mapping which measures interface pressure, has been used to identify areas under the seated surface prone to injury. The most suitable seating surface is then prescribed and strategies are recommended for the individual to engage in offloading behaviours. Individuals with SCI, who may be unable to physically engage in offloading through a forward lean, push up or side lean, may rely on wheelchair tilt and recline to offload weight-bearing tissues. Individuals with SCI are also educated on the importance of regular skin inspections. Educational programs during hospitalization that incorporate PI prevention have been shown to increase PI knowledge (Garber
et al., 2002, Brace and Schubart, 2010) which was retained up to 24 months following discharge (Garber et al., 2002). Additional tools such as sensory substitution devices, which provide sensory cues to non-affected regions to cue offloading, have been evaluated in healthy controls and found to be feasible to implement (Moreau-Gaudry et al., 2006) but have not yet been tested in SCI.

Despite many preventative strategies for the development of PI, the prevalence of PI remains high, and many of the strategies are considered passive in nature and do not incorporate trunk function in promoting offloading. Identifying the gap in knowledge with respect to trunk function in the promotion of offloading, Wu et al. (2013) investigated simultaneous gluteal and trunk muscular stimulation to change seated position and alter tissue health over the ischia and sacrum. Wu et al (2013) found that in individuals with SCI who predominantly sat on their sacrum (identified as “sacral sitters”), electrical stimulation of the gluteal and trunk muscles decreased mean sacral interface pressure. Additionally, increased transcutaneous oxygen tension under the ischial region was found suggesting alterations in interface pressure and improvement in perfusion with gluteal and trunk stimulation. It would be interesting to conduct similar experiments for the IT area.

The role of the trunk and its relationship to offloading the weight bearing surfaces and its effect on ischial tissue health cannot be overlooked. We were able to demonstrate that offloading behaviour is related to the ability of the individuals with SCI to engage in reaching task measured using a MDRT. We were also able to examine participants by their offloading behaviour, and examined potential differences in thickness, echogenicity and contrast measures of tissue overlying the IT in an attempt to highlight potential relationships between trunk function and its effect on the health of weight-bearing tissue. We were limited with our ability to analyze differences in tissue properties between Loaders and Offloaders due to our small sample size, however found a trend for lower contrast of skin, subcutaneous tissue and muscle, and a trend for higher echogenicity of muscle in Loaders. The trend for higher echogenicity in muscle could correspond to potential effects of shearing and compressive forces and disruption of connective tissue in muscle, which is more susceptible to mechanical stress than subcutaneous fat and skin. Disruption of the fascial layers in muscle would reduce the striated pattern normally observed, leading to a more homogeneous appearance reflected by lower contrast measures but this would need to be tested in future experiments.
Trunk strength was shown to be significantly greater in those who could reach vs. those who could not, and those who could reach, were able to spend significantly more time offloading the both ITs, however the results were significant only for the right IT. Should the individuals with SCI have the potential to improve trunk function, and the ultimate goal is to maintain tissue health through offloading, further studies should examine simultaneous reaching and offloading behaviour, and develop if applicable, rehabilitation strategies incorporating the trunk to engage in offloading to improve reaching.

### 7.2.2 Mechanical Stimuli and Its Effect on Tissue Health

It is well known that when mechanical stimuli are applied to tissue in animal models, they have the potential to change tissue (McHenry and Shields, 2014). Bone (Rubin et al., 2001), fat (Maddalozzo et al., 2009, Rubin et al., 2007), muscle (Ceccarelli et al., 2012, Xie et al., 2008) and neural tissue (Raju et al., 2011) respond to mechanical stimuli. Additionally, an optimal balance of mechanical stress is required to promote cell proliferation, while minimizing cell damage in bone (Rubin et al., 2001), fat (Maddalozzo et al., 2008, Rubin et al., 2007), muscle (Ceccarelli et al., 2012, Xie et al., 2008) and neural tissue (Raju et al., 2011). For example, a plethora of research supports loss of bone in astronauts exposed to microgravity conditions, while overloading muscle causes muscle to increase in size, illustrating the importance of mechanical stimuli on the maintenance of bone and muscle health.

Risk factors for the development of PI in individuals with SCI have been examined within the context of the acute care and rehabilitation settings (Gélis et al., 2008) however they have not taken into consideration the potential effect of the application of mechanical stimuli to maintain tissue health. Rather, the focus has been on preventing PI by promoting offloading and removing mechanical stress on tissue. The use of alternating wheelchair cushions, which provides cycling offloading of the seated weight bearing surfaces, have had positive influences on markers of tissue health (Wu and Bogie, 2014). Additionally, electrical stimulation of the gluteal muscles improved pressure redistribution and circulation (Bogie, 2008, Bogie, Wang and Triolo, 2006, van Londen et al., 2008). Therefore, one could suggest that mechanical stimulation, not just the
construct of offloading should be considered in the context of maintaining health of the tissue overlying the IT.

Given that some loading may be required to maintain tissue health, and that reactive hyperaemia occurs following unloading of loaded tissue (Sterner et al., 2014), it is possible that the approach that should be considered for the tissues overlying the IT is the cycling of loading/offloading, and the optimal mechanical stimuli, whether it be vibration or compressive forces and their potential to maintain tissue health rather than duration of offloading time.

While unrelieved pressure is a cause of PIs, it becomes important for the rehabilitation team to consider all potential factors that contribute to offloading behavior and ischial tissue health in this population. Engaging the client in the context of a behavioural strategy to promote offloading, while emphasizing restoration of trunk function in those that have the capacity may reduce the development of seated acquired PIs.

### 7.3 Future Directions

The findings of this work have resulted in additional questions that warrant further investigation in advancing PI research in order to develop appropriate rehabilitation strategies to mitigate the development of seated acquired PIs. A future study should be undertaken to examine the influence of providing an educational tool regarding PIs, and its relationship of changing offloading behaviour and tissue health in individuals with SCI and other at risk populations. Additionally, the use of other methods to evaluate tissue health, including simple approaches such as examining skin temperature and more complex investigations including near infrared spectroscopy could provide additional insight into physiological effects of loading, rather than just the gross anatomical changes that would be captured using ultrasound imaging.
7.3.1. Methods to Evaluate Tissue Health

The concept of tissue health is not new and is not only considered in the context of tissues overlying weight-bearing surfaces. For example, tissue health has been examined in the context of tumours, burns (Fletcher et al., 2015), white matter of the brain (Ryu et al., 2016) and titanium implants in dentistry (van Brakel et al., 2010). Additional markers of tissue health including tissue oxygen levels (Bogie and Triolo, 2003, Knight et al., 2001), carbon dioxide levels (Knight et al., 2001), laser doppler fluxmetry (Schubert and Fagrel, 1991), spectroscopy (Hagisawa et al., 1994), thermography, bacteria colonization (van Brakel et al., 2010), and blood markers such as triglycerides and glucose (Ryu et al., 2016) have been utilized to provide more detailed information regarding tissue properties that would not be captured using ultrasound imaging. Whether these are suited for examining tissue health over the IT in individuals with SCI remains to be explored.

If the goal is to capture the effect of offloading and tissue health, measures that would capture perfusion, oxygen uptake and by-products of metabolism during loading would enable the investigation of a more thorough understanding of the relationship between loading and tissue health. For example by-products of metabolism collected from sweat lactate during loading could provide additional details regarding the metabolic status of the tissue during the loaded condition (Knight et al., 2001). Skin redness captured during loading could provide information regarding perfusion while oxygen saturation and carbon dioxide tension during the loaded condition would provide information regarding oxygen uptake and utilization.

7.3.2. Technology to Effect Offloading Behaviour During Sitting

Technology has been integrated into health care with the potential of decreasing health care costs, and improving the efficiency and quality of health care delivery (Wang and Huang, 2012), with the ultimate goal of effecting behavior change by engaging clients and their families and caregivers in healthy behaviours. Technology has been used to treat a variety of medical conditions including childhood obesity (Schoffman et al., 2013), smoking cessation (Abroms et
al, 2011), diabetes, anti-coagulation therapy, depression, breast cancer, medication management (Denizard-Thompson et al., 2012) and promoting knowledge uptake for cardiac patients (Vawdrey et al., 2011). Technologies in health care can be administered in a variety of ways including the provision of Apps and the provision of customized technologies used to cue individuals on certain behaviours. Apps provide a suitable method of health information due to their portability, ease of use, low cost and large number of individuals who use smart phones (Sipior and Ward, 2014). The challenge to date is that there are minimal studies implementing and evaluating technology in PI prevention during real-time prolonged sitting.

Our clinical research team has developed a mobile iPad application, (“Pressure Ulcer Target”), which will provide patients with “on the go knowledge”. This iPad App has been developed taking into consideration that individuals with SCI need to know preventative strategies to combat PI development given their sensorimotor impairments. The iPad App, “Pressure Ulcer Target” and SensiMat™ (as described in Chapters 5 and 6) could be provided to patients for education regarding PI prevention, weight shifting strategies, and will enable real time monitoring of weight shifting behaviours in individuals with SCI. Further development of the device using designed algorithms to provide real time cueing to patients regarding timing for weight shifting behaviours will be based on pressure levels from the different skin areas taking into account the anthropometric characteristics and skin integrity of the individual patient.

Given that none of our participants developed a PI during the course of the study, the need to evaluate individuals with SCI longitudinally to determine the time course of changes in tissue properties following SCI is of paramount importance. The incidence of PIs is high, and increases with time following SCI and has been reported to vary between 15-30% during the chronic phase (Gélis et al., 2009). Therefore, it becomes relevant to determine at what time period do changes in tissue properties manifest, which then increase the risk of developing a seated acquired PI. Further studies should include a temporal study evaluating a cohort of individuals with SCI longitudinally using multiple assessments that measure not only tissue properties but trunk function and pressure offloading and determine which individuals develop PI so that the appropriate rehabilitation strategies that prevent PIs can be designed.
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Dear Sharon Gabison on Behalf of the University of Toronto,

Material requested: Figures 1-4, Tables 1-2, and Figure 4 in
Trunk strength and function using the multidirectional reach distance in individuals with
non-traumatic spinal cord injury
http://doi.org/10.1179/2045772314Y.0000000246

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Appendix

A1 – Abstract – Toronto Rehabilitation Institute Research Day November 2013

Can We Reliably Characterize Weight Shifting Behaviour Using a ‘Smart’ Pressure Mat? Gabison, S, Verrier, MC, Nussbaum, EN, Popovic, MR, Mathur, S., Mravyan, D., Mann, W. Rehabilitation Engineering Lab, SCI Mobility Lab and Muscle Performance Lab, University of Toronto, Toronto Rehabilitation Institute, Lyndhurst Centre, 520 Sutherland Drive, Toronto, Ontario, M4G 3V9, Canada.

Purpose/Rationale: To characterize weight-shifting behaviours during prescribed wheelchair activities using a ‘Smart’ Pressure Mat and activity log. Relevance: Individuals with Spinal Cord Injury (SCI) are advised to engage in weight shifting behaviours every 15 minutes to prevent skin breakdown, however, real time monitoring of weight shifting behaviours is limited.

Materials and Methods: Eight healthy individuals, mean age 25.6 years participated. Subjects were instructed to sit in a wheelchair over a period of three hours. A ‘Smart’ Pressure Mat “SensiMat”, with six 1.5” square standard force sensors was placed under the wheelchair cushion. Subjects were asked to engage in their daily activities, complete an activity log, and engage in one of three 2-minute weight shifting behaviors every 10-minutes. Analysis: Signal output from each sensor was low pass filtered and averaged using MATLAB program and compared with activity logs. Descriptive statistics were calculated using SPSS. Results: The SensiMat™ was able to discriminate three weight-shifting behaviours over a period of 3 hours. Rear offloading was demonstrated during forward trunk lean. Left sensor offloading was demonstrated during right trunk lean. Right sensor offloading was demonstrated during left trunk lean. Conclusion: Weight shifting characteristics can be reliably quantified using a ‘Smart’ Pressure Mapping during dynamic activities, however challenges exist in standardizing data collection and signal processing. The SensiMat™ has the potential to be used in the SCI population to teach and monitor weight-shifting behaviours during dynamic activities and evaluate the effect of educational interventions in the prevention of seated acquired pressure ulcers.