Fractures at the Fortress: A Study of Fractures at the 18th Century Fortress of Louisbourg

by

Taylor Corbett

Honours Bachelor of Science, University of Toronto Mississauga, 2022

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

Master of Arts

in the Graduate Academic Unit of Anthropology

Supervisor: Amy Scott, PhD, Anthropology

Examining Board: Susan Blair, PhD, Anthropology
Tracy Betsinger, PhD, Anthropology
Jeremy Noble, PhD, Kinesiology

This thesis is accepted by the Dean of Graduate Studies

THE UNIVERSITY OF NEW BRUNSWICK

July 2024

© Taylor Corbett, July 2024

ABSTRACT

The study of fractures in bioarchaeology can provide valuable insights related to many aspects of the lived experience, from violence to changing social roles. As the investigation of fractures in bioarchaeology has developed, may studies have begun to use both macroscopic and microscopic approaches to provide a more holistic understanding of how and why fractures occurred. For this thesis project, 32 individuals from the Fortress of Louisbourg skeletal collection were macroscopically evaluated to understand fracture prevalence within this 18th century population. Fracture causes and physical impairment are also investigated to understand the effects these injuries may have had on the overall lived experience of these individuals. Additionally, this study is the first to explore the utility of micro-computed tomography (micro-CT) to assist with understanding fracture healing in a bioarchaeological context. Overall, this multifaceted approach allows for a comprehensive understanding of fractures and their impact on the individuals at the Fortress of Louisbourg.

DEDICATION

To my family, this one’s for you.

ACKNOWLEDGEMENTS

I would like to extend my sincerest gratitude to my supervisor, Dr. Amy Scott. Thank you for your extensive edits, constant encouragement, and all of your support throughout this thesis You have always pushed me to become better and I truly appreciate your dedication to ensuring I received so much experience through my time at UNB. A huge thank you to Dr. Andrew Nelson for his time, assistance, and access to resources to perform my microscopic imaging. I would also like to thank Dr. Greg Gavrin for providing his time and assistance to perform x-ray imaging. Thank you to the folks at Parks Canada for access to the skeletal material, and to Sarah MacInnes for last minute research support. Many thanks to the Roman Catholic Diocese of Antigonish and the Anglican Diocese of Nova Scotia and Prince Edward Island for providing access to the skeletal material permission to perform this research. I would like to say a warm thank you to Judy Babin for her continuous support and positive energy, you truly made my days in the Annex happier. I would like to extend my appreciation to Dr. Tracy Betsinger and Dr. Jeremy Noble for providing edits and valuable insights to my research. Thank you to Kelsey Kane for providing your time and photography skills to provide figures for this thesis. Additionally, thank you to my fellow graduate students for your unwavering support and friendship throughout this degree, we made it! Finally, a huge thank you to my family and friends who have been cheering me on, you all mean the world to me. This research was supported by a SSHRC CGS Master's Award and a SSHRC Partnership Development Grant (PDG # 890-2017-0049) (Dr. Amy Scott).

TABLE OF CONTENTS

ABSTRACT ..... **ii**
DEDICATION ..... **iii**
ACKNOWLEDGEMENTS ..... **iv**
TABLE OF CONTENTS ..... **v**
LIST OF TABLES ..... **viii**
LIST OF FIGURES ..... **ix**
LIST OF APPENDICIES ..... **x**
CHAPTER 1 – Introduction **1**
1.1 Background and Significance 1
1.2 Research Questions, Expected Results, and Objectives 3
1.3 Thesis Outline 5
CHAPTER 2 – Literature Review **7**
2.1 Introduction 7
2.2 Bone Composition, Growth, and Remodeling 7
2.2.1 Bone Cells, Composition and Remodeling 7
2.3 Skeletal Fractures and Bone Biomechanics 10
2.3.1 Wolff's Law and the Mechanostat 10
2.3.2 Biomechanics of Skeletal Fractures 11
2.3.3 Fracture Causes and Classification 14
2.3.4 Fracture Healing and Complications 16
2.3.5 Fracture Timing 19
2.4 Fractures in Bioarchaeology 20
2.4.1 Interpretive Approaches to Fractures 20
2.4.2 Methodological Approaches to Fractures 24
2.5 Fortress of Louisbourg 28
2.5.1 History 28
2.5.2 Fracture Risk and Medical Care 29
2.6 Conclusion 31
CHAPTER 3 – Materials and Methods **32**
3.1 Introduction 32
3.2 Access Permissions 32
3.3 Fortress of Louisbourg Skeletal Collection 33
3.3.1 The Block 3 Cemetery 33
3.3.2 The Rochefort Point Cemetery 34

3.3.3 The Ste. Marie Multiple Burial 34
3.3.4 Sample Inclusion Criteria 35
3.4 Macroscopic Fracture Assessment 36
3.5 Plain Radiograph Image Capture and Rendering 36
3.6 Microscopic Computed Tomography Imagining 39
3.6.1 Preliminary Nikon XT 225 ST Setup 39
3.6.2 Spatial Resolution and Projection Settings 39
3.6.3 Micro-CT Image Rendering 41
3.7 Microscopic Fracture Healing Assessment 44
3.8 Intraobserver Error 49
3.8 Conclusion 50
CHAPTER 4 – Results 51
4.1 Introduction 51
4.2 Population Sample 51
4.3 Intraobserver Error 53
4.4 Macroscopic Analysis 54
4.4.1 Fracture Prevalence and Location on the Body 54
4.4.2 Fracture Prevalence and Age 57
4.4.3 Fracture Data 58
4.5 Radiograph and Micro-CT Analysis 61
4.5.1 Imaging Subsample 61
4.5.2 Fracture Healing Assessment 62
4.6 Conclusion 64
CHAPTER 5 – Discussion 65
5.1 Introduction 65
5.2 Fracture Prevalence and Trends 65
5.2.1 Fracture Prevalence 65
5.2.2 Sex and Age Trends 69
5.3. Fracture Location on the Skeleton 71
5.4 Fracture Causes, Physical Impact, and Level of Healing 72
5.4.1 Ribs and Vertebrae 73
5.4.2 Lower Limb 77
5.4.3 Upper Limb 83
5.4.4 Cranium 87
5.5 Medical Care in the 18th Century 90
5.6 Microscopic Assessment of Rib Fracture Healing and Fracture Events 92
5.7 Study Limitations 96

5.8 Conclusion 98
CHAPTER 6 - Conclusion 100
6.1 Introduction 100
6.2 Revisiting the Research Questions and Expected Results 100
6.3 Future Research 104
6.4 Research Contributions 106
BIBLIOGRAPHY 107
APPENDIX A 130
APPENDIX B 135
CURRICULUM VITAE

LIST OF TABLES

CHAPTER 2 – Literature Review Tables
Table 2.1: Primary types of force that cause skeletal fractures.....13

CHAPTER 3 – Materials and Methods Tables
Table 3.1: Modified scoring descriptions for the assessment of fracture healing using radiographs and micro-CT 45
Table 3.2: Landis and Koch (1997) interpretation of the Kappa Statistic 49

CHAPTER 4 – Results Tables
Table 4.1: Block 3, Rochefort Point, and Ste. Marie sample summary and skeletal completeness percentage.....52
Table 4.2: Kappa statistic values for macroscopic, radiograph, and micro-CT assessments 53
Table 4.3: Detailed summary of fracture presence and location within the sample 55
Table 4.4: Independent sample t-test comparing mean number of fractures between each skeletal subsample.....56
Table 4.5: Independent samples t-test comparing number of fractures to fracture location on the left, right, and center of the body 57
Table 4.6: Independent samples t-test comparing average age at death to fracture presence in each subsample 58
Table 4.7: Summary of fracture type, healing, displacement, and reduction for all individuals.....60
Table 4.8: Summary of rib fractures for radiograph and micro-CT imaging 61
Table 4.9: Fracture healing scores for radiograph and micro-CT images.....63

CHAPTER 5 – Discussion Tables
Table 5.1: Fracture/trauma prevalence across comparative populations 66

LIST OF FIGURES

CHAPTER 3 – Materials and Methods Figures

Figure 3.1: Radiograph image capture setup with rib bones placed on x-ray plate with the plural surface facing superiorly and balanced against x-ray foam to prevent movement 38
Figure 3.2: Sample mounted in plastic tube and secured using foam 40
Figure 3.3: Image rendering setup in Dragonfly 2023.2 demonstrating focus crosshair placement through the center of the fracture callus 44
Figure 3.4: Fracture healing flow chart for x-ray and micro-CT assessment of fracture healing (modified from Hufnagl 2005; Oryan et al. 2015; Salih et al. 2015; Tritella et al. 2020; Viero et al. 2021) 46
Figure 3.5: Fracture healing references images for radiographs stages 3-6 47
Figure 3.6: Fracture healing references images for micro-CT stages 3-6 48

CHAPTER 4 – Results Figures

Figure 4.1: Summary of fracture locations and number of individuals affected across all three subsamples 54
Figure 4.2: Average age at death compared to the number of fractures present within each individual 58

CHAPTER 5 – Discussion Figures

Figure 5.1: Butterfly fracture to the femur (red arrows) of Burial 85/2019 alongside the uninjured right limb for comparison. Note the proximal, lateral, and distal epiphyses are not shown 79
Figure 5.2: Location of femoral artery in relation to butterfly fracture on the left femur of Burial 85/2019 80
Figure 5.3: Comminuted fracture to the left tibia, fibula, and calcaneus (red arrows) of Burial 84/2019 alongside the uninjured right side for comparison 82
Figure 5.4: Location of the popliteal artery and its associated branches in relation to the comminuted fracture to the left lower limb of Burial 84/2019 83
Figure 5.5: Isolated fracture to the left radius (red arrow) of Burial 19 from Block 3, with the uninjured right radius for comparison (photo by Kelsey E. Kane) 85
Figure 5.6: Blunt force trauma impact points and radiating fractures on the posterior parietals of Burial 19 from the Block 3 cemetery. 88
Figure 5.7: Early signs of healing (red arrows) along the injury margins of the right side of the lambdoidal suture in Burial 19 from the Block 3 cemetery (photo by Kelsey E. Kane) 90
Figure 5.8: Fractures to the right 7th rib (red arrows) of Burial 77/2019 (photo by Kelsey E. Kane) 94
Figure 5.9: Right 7th rib fracture 1 (red arrows) of Burial 77/2019, A) macroscopic (photo by Kelsey E. Kane), B) radiograph, C) micro-CT 95
Figure 5.10: Right 7th rib fracture 2 (red arrows) of Burial 77/2019, A) macroscopic (photo by Kelsey E. Kane), B) radiograph, C) micro-CT 95

LIST OF APPENDICIES

APPENDIX A **130**
APPENDIX B **135**

CHAPTER 1 – Introduction

1.1 Background and Significance

The field of bioarchaeology provides an avenue to explore lived experiences in the past through the analysis of human skeletal remains (Agarwal 2016; Perry 2007; Zuckerman et al. 2014). One part of this narrative is the evaluation of trauma and the impact of trauma on the skeletal system. Physical trauma in bioarchaeology is conventionally understood as force applied to living tissues, resulting in injury (Blau 2017; Love and Wiersema 2016; Lovell 1997; Wedel and Galloway 2014). Fractures are a specific type of trauma that occur when enough force is applied to bone where it reaches the point of failure and breaks (Love and Wiersema 2016; Wedel and Galloway 2014).

The study of fractures in bioarchaeology mainly centers around understanding how and why fractures occurred within a specific population, informing interpretations of violence, occupation, illness, group conflict, accidental injury, and changing social roles (see Dittmar et al. 2021; Grauer and Roberts 1996; Judd and Roberts 1999; Lovell and Grauer 2019; Martin and Harrod 2015; Matos 2009; Milner et al. 2015; Šlaus et al. 2012; Wakely 1996). Identification of fractures and fracture healing can be conducted macroscopically (see Agnew and Justus 2014; Agnew et al. 2015; Khudaveryan et al. 2021; Łukasik et al. 2019; Milner et al. 2015; Tung 2007); however, in cases of advanced healing, microscopic assessment can provide additional information when macroscopic assessment alone becomes more challenging and less reliable (Al-Ayyoub and Al-Zghool 2013; Cappella and Cattaneo 2019; Cattaneo et al. 2010; Dittmar et al.

2021; Djurić et al. 2006; Grauer and Roberts 1996; Judd and Roberts 1998; Judd and Roberts 1999; Matos 2009; Pankowská et al. 2019; Šlaus et al. 2012; Viero et al. 2021). Ideally, research that integrates both a macroscopic and microscopic approach creates the most robust dataset on which to base bioarchaeological interpretations. Therefore, this thesis project will incorporate both macroscopic and microscopic methods to provide a holistic understanding of fractures and their impact on the individuals living at the 18th century Fortress of Louisbourg.

The Fortress of Louisbourg is a National Historic Site in Cape Breton, NS, that sees thousands of visitors annually, with historical interpreters who work to bring the past to life. The data and interpretations generated from this thesis project will directly contribute to what is known about medical care and injury, which can be used by interpreters to inform their portrayal of 18th century life and to share individual stories with visitors at the Fortress. Broadly, this research will provide robust data about fractures at the Fortress of Louisbourg by comparing three subsamples at the site. The Block 3 cemetery represents the earliest period of occupation, while the Rochefort Point cemetery represent the latest. The Saint Marie multiple burial represents a distinct period of occupation by the New Englanders in the winter of 1745. Comparing these three subsamples will provide data that has not yet been explored, generating unique perspectives on the impact of fractures (e.g., mobility issues, chance of reinjury, occupation, etc.) on the lived experience of these 18th century colonists. Additionally, this thesis project will produce comparative data about 18th century injuries which can be used for future research. Finally, this study will be the first to explore the utility of micro-computed tomography (micro-CT) to assist with understanding fracture healing in a bioarchaeological context. Overall, this thesis research represents an important step

forward in the bioarchaeological study of fractures, combining imaging methods, macroscopic assessments, and historical data to explore instances of skeletal fractures at the Fortress of Louisbourg.

1.2 Research Questions, Expected Results, and Objectives

The goal of this thesis is to conduct a robust study of skeletal fractures at the 18th century Fortress of Louisbourg and to evaluate the impact of this type of trauma on the lived experience, using both macroscopic and microscopic methods. The four primary research questions and expected results of this project are:

1. What is the prevalence of skeletal fractures at the Fortress of Louisbourg, and does this differ across subsamples?

   Given that the three subsamples represent distinct periods of occupation at Louisbourg, it is expected that there will be a difference in fracture prevalence. The Block 3 and Ste. Marie subsamples represent earlier occupation periods that differ socially and culturally from Rochefort Point, which may also be a driving factor behind any differences observed.

2. Does the type and severity of fractures differ within and between subsamples?

   Due to the distinct occupation periods represented by these subsamples, it is expected that the type and severity of fractures will differ, likely relating to the various activities and availability of medical care during the development

of this colonial town. As the Block 3 cemetery represents the earliest occupation, the lack of skilled tradespeople and medical care available may have resulted in more severe fractures than those seen in Ste. Marie or Rochefort Point.

3. Can micro-CT technology be used to assess fracture healing in bioarchaeological contexts?

    As micro-CT has been used in the field of forensic anthropology, it is expected that this technology will also be useful in determining fracture healing within a bioarcheological context. Given the increased detail on micro-CT images, it is expected that this method will provide additional details not visible on x-ray or macroscopically.

4. What is the physical impact of these fractures on the lived experience (e.g., mobility, reinjury, occupation, etc.)?

    Given that the subsamples represent distinct periods of occupation that differ socially and culturally, it is expect that there will be differences between the subsamples. Specifically, Block 3 and Ste. Marie represent periods where a proper hospital and adequate medical personnel were not yet established and as such, it is likely there will be more unhealed and/or poorly healed fractures (i.e., fractures that healed out of proper alignment) in comparison to Rochefort Point.

1.3 Thesis Outline

This thesis is divided into six chapters. The Introduction chapter has briefly discussed the importance of the study of fractures in bioarchaeology and outlines the research purpose and objectives of this thesis. Chapter 2 is the Literature Review which provides relevant background information on bone structure and biomechanics, as well as skeletal growth. An overview of the study of skeletal fractures in bioarchaeology, including macroscopic and microscopic methodologies will also be provided. The Literature Review will conclude with a brief history of the Fortress of Louisbourg to highlight 18th century life and the risk of fractures at this particular site. Chapter 3 will outline the materials and methods used for this thesis project, beginning with the permissions given to access the skeletal samples and inclusionary criteria. Chapter 3 will also review the steps for macroscopic assessment, as well as x-ray and micro-CT image capture and rendering. A detailed guide to assessing fracture healing will also be provided. Chapter 3 will conclude with a discussion of intra-observer error assessment. Chapter 4 summarizes the results of this thesis research, presenting the macroscopic fracture data trends and the assessment of fracture healing using both x-ray and micro-CT. Chapter 5 will discuss the results of this thesis, exploring the trends in fracture data using bioarchaeological, historical, and clinical literature. The beginning of this chapter will focus on fracture causes and the physical impacts fractures may have had on past individuals in the context of 18th century life. This will be followed by a discussion of fracturing healing assessment and what microscopic imaging can add to the overall interpretation of fractures. This chapter will conclude with an overview of the study limitations. Lastly, Chapter 6 will summarize the findings of this thesis in the context of

the previously stated research questions and provide potential avenues for future research, as well as the contributions of this research within the bioarchaeological discipline and research on skeletal fractures.

CHAPTER 2 – Literature Review

2.1 Introduction

This chapter is broken into four main sections to best explain the background and basis for this research. First, the basics of bone composition and function will be discussed, followed by the biomechanics of bone and skeletal fractures. The third section will review the interpretative and methodological approaches to the study of fractures in bioarchaeology, followed by a brief history of the Fortress of Louisbourg. Overall, these four sections will contextualize this project within the bioarchaeology discipline and highlight why it is significant in advancing fracture research.

2.2 Bone Composition, Growth, and Remodeling

2.2.1 Bone Cells, Composition and Remodeling

As an active living tissue, bone is made up of both organic and inorganic components. Collagen is the primary organic component of bone providing flexibility, whereas calcium hydroxyapatite is the main inorganic component of bone providing rigidity and strength (Wedel and Galloway 2014; White et al. 2011). At a basic level, bones in the adult skeleton can be divided into two different types – cortical and trabecular, each contributing to the overall structure and function of the skeleton in different ways (Florencio-Silva et al. 2015; White et al. 2011). Cortical bone is the dense, compact tissue on the external surface, while trabecular bone is the more porous and lightweight tissue found inside bone (Teti 2011; White et al. 2011). Functionally,

the cortical bone is protective, while the trabecular bone provides strength and flexibility to the skeleton (Teti 2011; Wedel and Galloway 2014; White et al. 2011).

Bone tissue itself is composed of four different types of cells: osteoblasts, osteoclasts, osteocytes, and bone lining cells (Florencio-Silva et al. 2015; Mohamed 2008; Teti 2011). Osteoblasts are the bone-forming cells that help create and mineralize bone (Hadjidakis and Androulakis 2006; Raggatt and Partridge 2010). In contrast, osteoclasts are the cells responsible for the resorption of old and/or damaged bone tissue (Florencio-Silva et al. 2015; Mohamed 2008). Bone lining cells reside on the surface of bone where neither formation nor destruction occurs and help regulate bone remodeling by separating osteoclasts from the bone matrix when necessary (Florencio-Silva et al. 2015; Mohamed 2008). Finally, osteocytes are the most abundant type of cell making up 90 to 95 percent of total bone composition and are former osteoblast cells that have both maintenance and sensory functions (Hadjidakis and Androulakis 2006; Schaffler and Kennedy 2012; Teti 2011). Despite their distinct functions, these primary bone cells work in tandem to build and maintain the skeleton, allowing it to change and adapt over time and repair itself in response to injury.

Throughout the life course, the skeleton undergoes regular maintenance to preserve the structural integrity and function of the skeletal system (Allen and Burr 2014; Hadjidakis and Androulakis 2006; Raggatt and Partridge 2010). Bone remodeling is the process by which the four different bone cells work in tandem to remove old and/or defective bone and replace it with new bone. For example, any small fractures or defects in the bone are removed and replaced with new bone (Hadjidakis and Androulakis 2006; Raggatt and Partridge 2010; Teti 2011). To begin this process, the osteocytes produce an activation signal that communicates to the other bone cells

(osteoblasts and osteoclasts) that remodeling needs to occur (Hadjidakis and Androulakis 2006; Raggatt and Partridge 2010). Next, the bone lining cells retract so the osteoclasts can begin resorbing the defective bone tissue (Allen and Burr 2014; Teti 2011). Once resorption is complete, the osteoblasts begin producing new bone tissue which becomes mineralized over time (Allen and Burr 2014). While mineralization is occurring, the bone lining cells resume their position until the remodeling cycle is activated again (Allen and Burr 2014; Hadjidakis and Androulakis 2006; Raggatt and Partridge 2010). The cycle of remodeling allows the body to maintain structural integrity over the life course and contributes to skeletal growth.

2.2.2 Skeletal Growth

There are two main types of skeletal growth in the body – intramembranous and endochondral ossification (Allen and Burr 2014; Cohen Jr. 2006; Gilbert 2000; Olsen et al. 2000; Provot and Schipani 2005; Teti 2011; Thompson et al. 2002; Tsang et al. 2014). Intramembranous ossification mainly occurs in utero through a process of directly converting mesenchymal tissue cells to bone. This type of growth occurs with the flat bones of the cranium and select post-cranial elements (i.e., clavicle and scapula) (Allen and Burr 2014; Gilbert 2000; Teti 2011; White et al. 2011). With intramembranous ossification, mesenchymal tissue cells differentiate into osteoblast cells to start creating bone within a pre-bone membrane called osteoid until growth is complete (Cohen Jr. 2006; Thompson et al. 2002). In contrast, endochondral ossification begins within a cartilage matrix both in utero and after birth and is the primary mechanism of growth for the majority of the bones within the body including the long bones (e.g., femur) and short bones (e.g., metacarpals) (Allen and Burr 2014; Olsen et al.

2000; Provot and Schipani 2005). With endochondral growth, mesenchymal tissue cells are converted into cartilage cells (i.e., chondrocytes) that build a simple template for the bone (Allen and Burr 2014; Gilbert 2000). Once the template is complete, primary ossification occurs at the center of the cartilage template where chondrocytes become osteoblasts and begin building the shaft of a bone (Gilbert 200; Provot and Schipani 2005; Tsang et al. 2014). Secondary ossification occurs in a similar fashion but at each end of the cartilage model where osteoblasts create the proximal and distal ends of each bone (i.e., epiphyses), which will fuse to the shaft as growth continues (Allen and Burr 2014; Gilbert 2000; Provot and Schipani 2005). While both growth processes are part of normal bone maturation, intramembranous and endochondral ossification are particularly important in the process of bone healing (Allen and Burr 2014; Olsen et al. 2000).

2.3 Skeletal Fractures and Bone Biomechanics

2.3.1 Wolff's Law and the Mechanostat

Wolff's Law states that bone adapts and remodels based on the amount of mechanical loading placed on it by adding strength and density when demands are higher, while maintaining a state of homeostasis when extra strength is not needed (Chen et al. 2010; Frost 1990; Ruff et al. 2006; Wang et al. 2019). Overall, bone architecture will change to meet the functional requirements of the specific muscles placing stress on the bone when in frequent use. While Wolff's Law has been generally accepted, it has been critiqued and improved upon over time, notably by Dr. Harold Frost who introduced the concept of the mechanostat (Frost 1990; Frost 1994; Ruff et al.

2006). The mechanostat is a biomechanical model that explains the skeletal response to mechanical loading required for habitual activities and is based on individual need (Frost 1990; Frost 1994). For example, a body builder will have a higher bone density due to the repeated force applied to their bones, in comparison to someone who does not go to the gym; however, that does not mean that the non-body builder's bone mass will decline and be unable to support their weight (Frost 1990; Frost 1994). Understanding Wolff's law and how bone adapts to mechanical stress is relevant to understanding the biomechanics behind fracture processes and how bone changes in response to injury.

2.3.2 Biomechanics of Skeletal Fractures

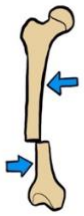
A skeletal fracture is a break or discontinuity in the bone that occurs because of force applied to the tissue (Bigham-Sadegh and Oryan 2015; Love and Wiersema 2016; Wedel and Galloway 2014). The biomechanics of bone fracturing is explained through two main mathematical models: Young's Modulus of Elasticity and stress-strain curves (Beaupied et al. 2007; Frankel et al. 2016; L'Abeé et al. 2021; Wedel and Galloway 2014). Young's Modulus of Elasticity is used to evaluate the strength and stiffness of a material with known stress and rate of loading, (i.e., the relative speed of force) (Beaupied et al. 2007; Frankel et al. 2016; Gupta and Zioupos 2008; L'Abeé et al. 2021). For this model, strength is the amount of energy that a material (bone) can absorb until deformation occurs, and stress is assessed by forced divided over the surface area (see Beaupied et al. 2007; L'Abeé et al. 2021; Oryan et al. 2015). Because bone is a dynamic material made up of both organic and inorganic components providing strength and flexibility, there is a threshold that allows small amounts of adaptation and deformation

before a break will occur (Hart et al. 2017; Oryan et al. 2015; Zimmermann and Ritchie 2015). Essentially, Young's Modulus measures how much energy a bone can absorb before this deformation occurs. Stress-strain curves are used to measure from the point of resistance to where deformation begins, to the point of failure and where the bone ultimately breaks (Hart et al. 2017; Oryan et al. 2015; L'Abeé et al. 2021; Wedel and Galloway 2014). The combination of Young's Modulus of Elasticity and stress-strain curves helps explain why fractures occur at certain thresholds. For example, the femur is important in supporting obligate bipedalism in humans, and as such has a higher threshold than smaller bones in the body (e.g., fingers and toes) which have evolved for different functions (Arun and Jadhav 2016; van der Meulen et al. 2001) and therefore, have a different threshold.

The energy-absorbing capacity of different bones is important when understanding the amount of force required to cause a fracture (Gupta and Zioupos 2008; Turner 2002). How and why a fracture occurs is also dependent on the type and amount of force applied to the tissue (Frankel et al. 2016; Gupta and Zioupos 2008; Wedel and Galloway 2014). The main types of force resulting in bone fractures are compression, tension, rotation, shearing, and bending (see Table 2.1), which affect how a bone fractures (Boyd 2018; Hart et al. 2017; L'Abeé et al. 2021; Wedel and Galloway 2014). Additionally, force can be applied at a high or low velocity (i.e., the rate and direction of movement of an object) which also affects how the bone will fracture (see Boyd 2018; Hart et al. 2017; L'Abeé et al. 2021). For example, falling from a great height or having an arm trapped by heavy machinery can both result in fractures; however, the type and amount of force, as well as velocity, will impact the skeleton differently in these circumstances and result in different fractures. Understanding the

types of force and the impact they have on fracture severity is important in understanding how an injury occurred and the functional impact these fractures may have had on the individual (Abrahamyan 2017; Frankel et al. 2016; Lovell 1997).

Table 2.1: Primary types of force that cause skeletal fractures

Type of Force	Description	Visual Representation
Compression	Crushing or impaction force applied in the axial direction	
Tension	Pulling away of the bone along the long axis	
Rotation	Twisting or rotation of the bone around its axis	
Shearing	Two opposing forces acting perpendicular to the diaphysis	
Bending	Force applied perpendicular to the long axis of a bone	

(modified from Wedel and Galloway 2014)

2.3.3 Fracture Causes and Classification

Fractures are categorized as complete where the break extends across the thickness of the bone, or incomplete if it does not (Boyd 2018; Love and Wiersema 2016; Wedel and Galloway 2014). Additionally, fractures are classified as open or compound when the fractured ends of the bone breach the skin, or as closed when the surrounding soft tissues remain intact (Wedel and Galloway 2014; Love and Wiersema 2016; Oryan et al. 2015). Compound fractures are particularly dangerous as the perforation of the skin increases the risk of bacterial infiltration causing infection, which can have life-threatening consequences (Matos et al. 2015; Zalavras et al. 2005). Fractures are also categorized as displaced, where the bone is no longer in typical alignment, or non-displaced, where the bone remains in its typical alignment (Wedel and Galloway 2014). The level of displacement is a helpful indicator of the amount of force applied to the bone and consequently the severity of the injury. For example, displaced fractures often occur due to extensive force being applied to the bone which can result in mobility issues and a prolonged healing period in comparison to non-displaced injuries (Matos et al. 2015; Murray et al. 2013; Wedel and Galloway 2014; Zalavras et al. 2005).

Skeletal fractures can arise from a number of circumstances, including direct and indirect trauma, biomechanical stress, and pathological conditions (Dirkmaat 2012; Gupta and Zioupos 2008; Lovell 1997; Lundon et al. 1999; Oryan et al. 2015). Direct trauma refers to a fracture that occurs at the point of impact, while indirect trauma refers to fractures that occur outside the point of impact (Dirkmaat 2012; Lovell 1997). For example, a gunshot wound will have direct trauma at the point where the bullet hits the bone, and indirect trauma around the entry and exit wounds due to the dissipation of

force in the surrounding bone (Dirkmaat 2012). Excess biomechanical stress/loading is where the application of force over a period of time ultimately causes the bone to fail and break, typically from repetitive motions (Oryan et al. 2015; Gupta and Zioupos 2008; Lundon et al. 1999; Yuasa et al. 2017). For example, elite athletes put continuous stress on their bones from doing repetitive motions over an extended period, which can lead to fractures (see Lundon et al. 1999; Yuasa et al. 2017). While Wolff's Law argues that bone will strengthen in response to activity, the frequency and force applied to the bone tissue can exceed the threshold in which bone can successfully adapt. Essentially, the stress on the bone can cause fracturing while the skeleton is still working to lay down extra bone to support the level of activity being undertaken. Additionally, underlying pathological conditions, such as cancer or osteoporosis, can lead to fractures as the bone may become weak and vulnerable to spontaneous fracturing or minor trauma (Dijkstra et al. 1997; Lovell 1997; Tanaka et al. 2012; Turner 2002). For example, osteoporosis ultimately results in bone fragility through the deterioration of bone tissue and low bone mass (Sànchez-Riera et al. 2010; Turner 2002). More specifically, osteoporosis increases the risk fracturing to regions of the skeleton that experience increased biomechanical loading such as the pelvis, femoral neck, and vertebral bodies which can all lead to loss of mobility and additional complications (Sànchez-Riera et al. 2010; Warriner et al. 2011). Overall, understanding the types of fractures and how they occur helps to guide interpretations of how fractures may heal and the impact they can have on individual lived experiences.

2.3.4 Fracture Healing and Complications

Fracture healing is a complex process involving soft tissue repair, bone formation, removal, and remodeling (Bigham-Sadegh and Oryan 2015; Einhorn and Gerstenfeld 2015; Ghiasi et al. 2017; Little et al. 2007; Marsell and Einhorn 2011; Oryan et al. 2015; Schindeler et al. 2008). Primary fracture healing begins with intramembranous ossification where the osteoblast cells put down a layer of osteoid to initiate the repair and connect the fractured pieces of bone (Bigham-Sadegh and Oryan 2015; Marsell and Einhorn 2011; Oryan et al. 2015; Thompson et al. 2002). However, it is important to note that primary fracture repair can only occur if the bone fragments can successfully be rejoined and immobilized, which can be achieved through placing a cast on the injury or through operative intervention where the fractured ends are held together by medical screws and plates (Marsell and Einhorn 2011). In instances where the fractured ends cannot be immobilized and reduced to their original alignment, secondary healing occurs.

Secondary healing is more common, especially in the archaeological record, in cases where the fracture is not completely immobilized and aligned (Claes et al. 2012; Ghiasi et al. 2017; Oryan et al. 2015; Schindeler et al. 2008). Secondary healing is divided into three phases: inflammation, repair, and remodeling (Bigham-Sadegh and Oryan 2015; Claes et al. 2012; Little et al. 2007). Inflammation occurs due to movement between the fractured ends of a bone which damage the surrounding tissues such as nerves and blood vessels and cause swelling in the area (Claes et al. 2012; Little et al. 2007). During this phase, a hematoma forms around the fracture site which is composed of blood vessels and blood marrow cells (Bigham-Sadegh and Oryan 2015; Little et al.

2007). Hematoma formation typically lasts three to seven days and signals the release of growth hormones that stimulate healing and bone production (Claes et al. 2012; Schindeler et al. 2008). The repair stage of secondary fracture healing begins with the conversion of the hematoma into granulation tissue which is a combination of connective tissue and blood vessels that work to close the fracture gap (Bigham-Sadegh and Oryan 2015; Ghiasi et al. 2017; Marsell and Einhorn 2011). The granulation tissue contains mesenchymal cells that become chondrocytes and osteoblasts which facilitates both endochondral and intramembranous ossification (Bigham-Sadegh and Oryan 2015; Ghiasi et al. 2017; Marsell and Einhorn 2011). The chondrocytes come together around the fracture, encasing both ends and the fracture gap in a fibrocartilaginous capsule (i.e., callus), which provides support and stability to the fracture approximately seven to nine days after the initial injury (see Bigham-Sadegh and Oryan 2015; Marsell and Einhorn 2011). During the final repair stage in secondary fracture healing, the soft cartilaginous callus is replaced by bone through the process of endochondral ossification (Ghiasi et al. 2017; Oryan et al. 2015; Schindeler et al. 2008). Specifically, the chondrocytes are converted into osteoblasts that work to quickly lay down woven bone, creating a hard callus with more stability than the cartilaginous callus (Claes et al. 2012; Schindeler et al. 2008). If there is sufficient immobilization provided by the woven bone hard callus, intramembranous ossification can then occur (Claes et al. 2012; Schindeler et al. 2008). The transition from cartilage to bone callus occurs approximately two weeks after the initial fracture and is followed by bone remodeling (Marsell and Einhorn 2011). During the remodeling phase, the osteoclasts resorb the woven bone so the osteoblasts can replace it with lamellar bone, which has a more organized structure and is mechanically stronger (Bigham-Sadegh and Oryan 2015; Claes et al. 2012; Schindeler et al. 2008).

The process of remodeling can take up to six to eight years for a fracture to no longer affect biomechanical strength and to become invisible macroscopically and microscopically (Bigham-Sadegh and Oryan 2015; Marsell and Einhorn 2011).

Unfortunately, fracture healing can be negatively impacted by complications including infection, tissue necrosis, nerve damage, and misalignment (Bigham-Sadegh and Oryan 2015; Boyd 2018; Claes et al. 2012; Einhorn and Gerstenfeld 2015; Ghiasi et al. 2017). If the fracture is open, bacteria may enter the bloodstream leading to slower healing as the body is working to heal both the fracture and infection simultaneously (Claes et al. 2012; Wedel and Galloway 2014). One example of this is osteomyelitis, which is inflammation and eventual necrosis of the bone tissue through bacteria entering the body, likely through a soft tissue injury that can occur with open fractures (Fritz and McDonald 2008; Jorge et al. 2010; Roberts & Manchester 2007). Similarly, if a fracture is displaced and/or open, the blood vessels may be damaged and/or blocked so that blood cannot reach the damaged tissue, leading to tissue death which can have serious health consequences up to and including sepsis and/or death (Ghiasi et al. 2017; McKay et al. 2001). Depending on the location of the fracture, the damaged blood vessels may result in excessive bleeding, which can ultimately lead to death. For example, femoral fractures may rupture the femoral artery and/or its associated branches, resulting in potentially life-threatening hemorrhage (Krishna et al. 2022). Similarly, the nerves around the fracture may be damaged, which can affect mobility and increase the chance of infection and reinjury due to limited and/or absence of sensation when in use (McKay et al. 2001). In cases where a fracture is not immobilized properly through either medical intervention such as a cast/surgery or bedrest, the fracture may not heal in proper alignment which can prolong the healing process and lead to lasting mobility

issues, permanent disability, and/or osteoarthritis (Boyd 2018; Ehlinger et al. 2020; Marsell and Einhorn 2011; Lovell 2016).

2.3.5 Fracture Timing

When studying skeletal fractures, it is also important to consider when a fracture occurred (Blau 2017; Kemp 2016; L'Abbé et al. 2021; Ribeiro et al. 2020; Scheirs et al. 2018; Wieberg and Wescott 2008; Wedel and Galloway 2014). Antemortem fractures occur before death and are mainly identified by signs of healing (i.e., a callus or new bone formation around the injury site) (Blau 2017; L'Abbé et al. 2021; Wedel and Galloway 2014). Postmortem fractures occur after death and are identified by the lack of healing, inconsistent staining at the fracture margins, and a jagged appearance (see Kemp 2016; L'Abbé et al. 2021; Wieberg and Wescott 2008). Perimortem fractures occur at or around the time of death, when bone is still biomechanically fresh (i.e., responds as living bone) (see Ribeiro et al. 2020; Scheirs et al. 2018). Perimortem fractures may have more smoothed straight edges around the fracture margins, as well as consistent staining with an identifiable fracture pattern (i.e., transverse, comminuted, oblique, etc.) (Ribeiro et al. 2020; Scheirs et al. 2018; Wedel and Galloway 2014). The determination of fracture timing is extremely important when assessing the circumstances surrounding the injury and its significance, especially in bioarchaeological research when using fracture analysis to interpret the lived experience.

2.4 Fractures in Bioarchaeology

2.4.1 Interpretive Approaches to Fractures

Physical trauma is the second most common pathology in bioarchaeology which helps to inform what we know about violence, occupation, illness, group conflict, accidental injury, and changing social roles in past populations (see Dittmar et al. 2021; Grauer and Roberts 1996; Judd and Roberts 1999; Lovell and Grauer 2019; Martin and Harrod 2015; Matos 2009; Milner et al. 2015; Šlaus et al. 2012; Wakely 1996). Most commonly, bioarchaeologists study trauma and use this information to create possible interpretations for how and why fractures are present within a skeletal population (see Agnew et al 2015; Dittmar et al. 2021; Grauer and Roberts 1996; Martin and Harrod 2015; Šlaus et al. 2012; Tung 2007). Interpretations of trauma have highlighted the importance of understanding the context in which fractures occur, including the use of historical data and skeletal data for a particular site/group (see Agarwal 2016; Brickley and Smith 2006; Dittmar et al. 2021; Grauer and Roberts 1996; Matos 2009; Mant 2019; Mant et al. 2020; Milner et al. 2015).

With the broad applications of trauma research in bioarchaeology, it is important to highlight the role fractures play in the interpretation of the lived experience. Evidence of fractures have been widely used in investigations of violence in bioarchaeology, including interpersonal violence, conflict/warfare, abuse, and punishment (see Brickley and Smith 2006; Cagigao 2009; Khudaveryan et al. 2021; Łukasik et al. 2019; Mant et al. 2020; Martin and Harrod 2015; Pankowská et al. 2019; Šlaus et al. 2012; Tung 2007). Martin and Harrod (2015) outline the complexities of defining injuries resulting from violence in the past, emphasizing that the term *violence* will have varied meanings

across cultures. Injuries most characteristic of violence include sharp force/projectile trauma, fractures to the cranial vault, and parry fractures (generally an isolated fracture to of forearm) (see Khudaveryan et al. 2021; Łukasik et al. 2019; Pankowská et al. 2019; Šlaus et al. 2012). Injury patterns, location and type of trauma, as well as historical information should all be considered when attributing specific fractures to violence (Łukasik et al. 2019; Mant et al. 2020; Martin and Harrod 2015; Pankowská et al. 2019; Šlaus et al. 2012). For example, Łukasik and colleagues (2019), investigated a mass burial in Poland with individuals believed to have been killed during the 17th century Swedish invasion. While historical records stated that women and children were spared during the attack, both female and non-adult individuals were found alongside male individuals with perimortem injuries consistent with interpersonal violence, highlighting the importance of skeletal evidence to inform and potentially verify or dispute aspects of the historical record (Łukasik et al. 2019).

Additionally, fractures are often used as a proxy to understand the risk of accidental and occupational injury, as well as social, cultural, and political roles within a society (see Agnew and Justus 2014; Agnew et al. 2015; Brickley 2006; Dittmar et al. 2021; Djurić et al. 2006; Grauer and Roberts 1996; Judd and Roberts 1999; Milner et al. 2015). Accidental injury is typically associated with falls, indirect trauma, and accidents (i.e., vehicular accidents) (see Agnew et al. 2015; Dittmar et al. 2021; Grauer and Roberts 1996; Judd and Roberts 1999). Fractures attributed to occupation typically overlap with accidental injuries and are most frequently observed in individuals who participate in labour-intensive activities (see Agnew and Justus 2014; Agnew et al. 2015; Dittmar et al. 2021; Judd and Roberts 1999). Sex-based differences in accidental and occupational trauma have also been assessed in various populations, with males

typically having increased fracture prevalence, whereas female fractures are attributed to accidental injury (see Agnew and Justus 2014; Dittmar et al. 2021; Judd and Roberts 1999; Milner et al. 2015). For example, males typically conducted the more labour-intensive aspects of farming in medieval England, such as plowing and herding, while females typically tended to the garden and household chores, which is reflected in the fracture patterns as observed by Judd and Roberts (1999). An additional study from medieval Cambridge by Dittmar and colleagues (2021) produced similar findings in a more urban environment. Females were found to have injuries consistent with falls, such as evidence of a twisted ankle; however, the authors also argue females with multiple fracture could indicate interpersonal violence and/or labour-intensive occupations and not just accidents (see Dittmar et al. 2021). Further, males at this site had a much higher prevalence of fractures than females, which is consistent with social divisions of labour in medieval Cambridge (see Dittmar et al. 2021).

Fractures also provide a unique avenue to examine disease, illness, and medical practices in past populations (see Brickley 2006; Djurić et al. 2006; Grauer and Roberts 1996; Judd and Roberts 1998; Licata et al. 2019; Mant 2020; Matos 2009). Many diseases, such as cancer or osteoporosis, can affect bone density and increase the risk of fracturing (Brickley 2006; Judd and Roberts 1998; Matos 2009; Sànchez-Riera et al. 2010; Turner 2002). Thus, it is crucial to examine the entire skeleton and incorporate historical information about diseases in specific geographical and temporal locations when examining fractures. One example comes from Matos (2009) reporting multiple individuals with rib fractures that may be the result of coughing injuries due to pulmonary tuberculosis. Additionally, Judd and Roberts (1998) compared the prevalence of fractures between individuals from a leprosy hospital cemetery to other non-leprosy

cemeteries in Britian. The authors found that there was an increased fracture frequency at the leprosy hospital, which may have been due to the loss of sensation from nerve damage and/or ocular impairment that can occur during lepromatous and tuberculoid leprosy (Judd and Roberts 1998).

Inferring medical practices from fractures is also an area of investigation that relies heavily on antemortem healed fractures and the historical record. Using hospital records from the poorer districts of London, Mant (2020) concluded that medical practitioners were able to treat fractures successfully and combined the records and skeletal observations to understand the frequency and distribution of fractures. Research surrounding injury healing has also provided important insights into medical treatment of fractures in the past (Djurić et al. 2006; Grauer and Roberts 1996; Licata et al. 2019). Specifically, Djuríc and colleagues (2006) noted that many healed fractures were misaligned, which could have led to impairment and mobility issues. The lack of post-injury care is consistent with the known medical care, or lack thereof, in rural Serbia at that time. In contrast, Grauer and Roberts (1996) and Licata and colleagues (2019) noted that most of the fractures they identified were in proper alignment, indicating that reduction (i.e., realignment) and immobilization of the fracture likely occurred, suggesting the presence of at least some form of medical care. Ultimately, this holistic approach allows bioarchaeologists to bridge the gap between skeletal observations and historical data to better interpret the lived experience.

It is evident that fractures can provide a wealth of information about the lived experience, but it is important to acknowledge the limitations of these interpretations (see Djurić et al. 2006; Dittmar et al. 2021; Grauer and Roberts 1996; Pankowská et al. 2019; Šlaus et al. 2012; Wakely 1996). First, the fragmentary nature of skeletal remains

at many bioarchaeological sites makes it difficult to assess fractures as individual skeletons may be incomplete, making comparisons between populations difficult (Djurić et al. 2006; Dittmar et al. 2021; Grauer and Roberts 1996). Some studies use a preservation threshold to help mitigate this issue; however, this can create sample bias (Dittmar et al. 2021; Milner et al. 2015). Why and how fractures occur is also a complex process that rarely yields one definitive answer. While the injury patterns, frequency, and available historical data can be used to make inferences about the mechanism of fractures, it is equally important to provide differential diagnoses for the observed injuries. For example, Wakely (1996) studied two individuals from a British cemetery documented to have succumbed to interpersonal violence; however, the fractures identified could not be solely attributed to violence, as they were also consistent with the fracture patterns associated with falls or labour-intensive occupations. Additionally, the presence of parry fractures (isolated fracture to the ulnar shaft) versus colles fractures (distal radial fracture) are often used to distinguish between violent and accidental injuries; however, these are not absolute, as these fractures can result from a variety of circumstances (see Pankowská et al. 2019; Šlaus et al. 2012).

2.4.2 Methodological Approaches to Fractures

Identification of fractures and fracture healing can be conducted both macroscopically and microscopically. Macroscopic assessments use the visual presence of a discontinuity in the bone, irregular bone shape, and evidence of healing such as a bony callus to diagnose a fracture (Bigham-Sadegh and Oryan 2015; Ghiasi et al. 2017; Marsell and Einhorn 2011). When detected, fracture location, type (if possible),

evidence of healing, alignment, and the timing of injury should all be recorded to allow further analysis and comparison within and between samples (Brickley 2006; Dittmar et al. 2021; Grauer and Roberts 1996).

Many studies solely use macroscopic assessments to discuss fracture prevalence and the potential impacts of these injuries on the lived experience (see Agnew and Justus 2014; Agnew et al. 2015; Khudaveryan et al. 2021; Łukasik et al. 2019; Milner et al. 2015; Tung 2007). However, there are limitations to these types of macroscopic assessments, including determining fracture type. For example, during healing, the assessment of fracture type and stage of healing can be obscured by the development of the bony callus; therefore, limiting interpretations of how an injury may have occurred (Milner et al. 2015; Tung 2007). Additionally, preservation and post-mortem damage to the skeleton can impede fracture visualization by obscuring the callus or fracture margins, which can impede interpretations when the internal bone structure cannot be visualized. Fractures that are healed and no longer clearly visible to the naked eye may also be missed through macroscopic assessment alone, creating additional bias and interpretive limitations (Milner et al. 2015; Tung 2007).

Due to some of these longstanding limitations of macroscopic fracture assessments, there has been a substantial amount of research in both bioarchaeology and forensic anthropology to integrate microscopic methods of analysis such as bone histology, x-ray, and micro-computed tomography (micro-CT) (see Al-Ayyoub and Al-Zghool 2013; Cappella and Cattaneo 2019; Cattaneo et al. 2010; Dittmar et al. 2021; Djurić et al. 2006; Grauer and Roberts 1996; Judd and Roberts 1998; Judd and Roberts 1999; Matos 2009; Pankowská et al. 2019; Šlaus et al. 2012; Viero et al. 2021). Bone histology is the examination of bone under a microscope and is considered by some to

be the most accurate way to identify fracture healing (see Cappella and Cattaneo 2019; Cattaneo et al. 2010; Viero et al. 2021). Researchers can differentiate among bone cells and precursors cells such as chondrocytes to identify the stage of fracture healing; however, bone histology is a destructive method of analysis and generally not ideal in bioarchaeological samples (Cappella and Cattaneo 2019; Cattaneo et al. 2010). Non-destructive methods such as x-ray and micro-CT imaging have been used in place of bone histology as both produce a similar level of detail but are minimally invasive (Al-Ayyoub and Al-Zghool 2013; Conlogue et al. 2020; Dittmar et al. 2021; Grauer and. Roberts 1996; Joshi and Singh 2020; Khudaverdyan et al. 2021; Ross and Juarez 2016; Viero et al. 2021).

X-ray imaging produces a two-dimensional (2D) radiograph that allows visualization of the internal architecture of bone (see Allen and Burr 2014; Dittmar et al. 2021; Hadjidakis and Androulakis 2006; Raggatt and Partridge 2010). This is accomplished through the process of photons (light particles) passing through the bone to the photon detector beyond the focus of the subject, creating the radiograph (Conlogue et al. 2020; Hendrix 2002; Joshi and Singh 2020; Martz et al. 2016). The visualization of the bone is dependent on the principle of attenuation, which explains how the trajectory of the photons is affected by the material they are passing through (Buzug 2008; Conlogue et al. 2020). This is determined largely by the density of the subject, which is especially helpful in visualizing fractures due to the differing densities in woven and lamellar bone (Allen and Burr 2014; de Boer et al. 2015; Hadjidakis and Androulakis 2006; Raggatt and Partridge 2010). Many bioarchaeological studies use x-ray in combination with macroscopic techniques to better visualize healing and fracture type (see Dittmar et al. 2021; Djurić et al. 2006; Grauer and Roberts 1996; Judd and

Roberts 1998; Judd and Roberts 1999; Matos 2009; Šlaus et al. 2012). For example, Dittmar and colleagues (2021) use radiographs in combination with macroscopic assessment to better understand the types of fractures present, sex-related differences in fractures, and fracture frequency. X-ray technology is also widely accessible and relatively cost-effective; however, due to the limited capabilities of x-ray technology, the image produced can be of a lower quality where all structures may not be captured (Conlogue et al. 2020; Flohr et al. 2015; Viero et al. 2021). Therefore, micro-CT technology is one proposed solution as it takes a high-quality image that can better visualize the density differences of bone, allowing for a more accurate differentiation between woven and lamellar bone (Viero et al. 2021).

Micro-CT imaging takes a large number of 2D x-ray images, and through image rendering software, combines those 2D images into a 3D model of the bone (Boerckel et al. 2014; Buzug 2008; Molino et al. 2020). The high-resolution 3D model allows for visualization of bone microstructures, such as woven and lamellar new bone formation and cortical canals, which are not visible on 2D x-ray images (Bouxsein et al. 2010; Jiang et al. 2005; Rühli et al. 2007; Viero et al. 2021). Micro-CT technology is also better suited to smaller bones, as the smaller surface area allows more detail to be captured (Conlogue et al. 2020; Flohr et al. 2015; Hassett 2018). Micro-CT has been used in bioarchaeology to examine bone bioerosion, trauma, entheseal changes, and paleopathological conditions such as dental disease, osteomalacia, and Paget's disease (see Berthon et al. 2016; Booth et al. 2016; Flohr et al. 2015; Mandl et al. 2022; Wade et al. 2011; Welsh et al. 2020). Recently, micro-CT has been proposed as a new avenue to study fracture healing of rib bones in forensic anthropology (see Viero et al. 2021). Specifically, Viero and colleagues (2021) conducted a study to ascertain the advantages

of micro-CT technology in fracture healing assessment, comparing x-ray and micro-CT images to assess visualization differences between the two technologies. Their findings suggest that through micro-CT imaging, researchers are better able to classify stages of healing, as the images produced are clearer and the differences between the soft and hard tissue calluses can be better identified through distinct structural organization and density (Viero et al. 2021). Despite micro-CT being an extremely useful tool, it may be less accessible than x-ray analysis as there are few machines worldwide (Conlogue et al. 2020; Flohr et al. 2015). Additionally, it takes longer to produce an image due to the level of detail being captured. The higher cost of micro-CT analysis may also be prohibitive (Conlogue et al. 2020; Flohr et al. 2015). However, the quality of images produced through micro-CT analysis far exceeds those produced from x-ray, making it an ideal tool when examining fracture-specific changes in bone architecture (Viero et al. 2021). Overall, the macroscopic and microscopic methods of fracture assessment in bioarchaeology and forensic anthropology have developed over time, providing a variety of methods to support fracture research.

2.5 Fortress of Louisbourg

2.5.1 History

The Fortress of Louisbourg, located on Cape Breton Island, NS, was an 18th century French colony and is now a National Historic Site of Canada. The Fortress of Louisbourg is on the traditional land of the Mi'kmaq peoples, first colonized by the French in 1713 (Johnston 2001). At this time, Louisbourg was one of the largest French colonies in North America, occupied between 1713 and 1758, and was home to

approximately 10,000 inhabitants towards the end of its occupation (Johnston 1984). Despite its short history, the Fortress of Louisbourg experienced unrest and multiple administrative changes. During early French settlement, Louisbourg grew into a major economic and trade hub, as well as a military center (Johnston 2001). Louisbourg underwent two periods of siege in its history, the first in 1745 and the second in 1758. In 1745, Louisbourg quickly capitulated to a New Englander force which occupied the Fortress for four years before it was surrendered back to the French in 1749 (Johnston 2001). The Fortress of Louisbourg was under siege again in 1758 when the French and British declared war on one another, ultimately leading to the final downfall of this coastal community and its eventual abandonment (Johnston 2001).

2.5.2 Fracture Risk and Medical Care

Based on the history of Louisbourg, there were likely many instances of trauma resulting in fractures. Hoad (1972) states that according to surgeons' reports, broken limbs were among the most common injuries reported at Louisbourg, especially among the soldiers. The Fortress was largely a military community, with soldiers training and working around the town (McLennan 1918; Pitcher 2014). Military life and training presented many opportunities for trauma to occur, with intense physical training and interpersonal violence that may have led to broken bones (Johnston 2001; Thomson 1996). Many other occupations at Louisbourg were also labour intensive. For example, many individuals worked on the maintenance and repair of the fortification walls which was a dangerous and exhausting occupation (Greer 1997; Hoad 1972; Johnston 2001; Pitcher 2014; Thomson 1996). Reports of injuries sustained from fortification

maintenance and repair indicate that some individuals were maimed and/or left with permanent mobility issues due to bone fractures (Pitcher 2014). Additionally, many individuals indulged in the excessive consumption of alcohol increasing the risk of accidental and/or violence-related injuries due to inebriation (Johnston 1981; Johnston 2002).

When fractures occurred at Louisbourg, some individuals may have sought out medical care. Medicine at Louisbourg was mainly practiced by The Brothers of Charity of St. John of God (Johnston 1984). The Brothers were called to Louisbourg to begin setting up a hospital and providing care for its citizens, as they already had experience running hospitals in France, Italy, Spain, and Saint Pierre and Miquelon (Johnston 2001). After their arrival in 1719, the Brothers operated in a small temporary hospital off the north shore for almost a decade; however, incidences of neglect were often reported (Johnston 1981). Around 1730, the Hôpital du Roi ("King's Hospital") was built, and more surgeons began arriving, adding to the medical capabilities at the Fortress (Johnston 1984; Thomson 1996). While the introduction of a larger hospital and more surgeons was certainly an improvement, the unsanitary conditions and limited medical personnel and supplies made it difficult to treat patients effectively (Johnston 1981). Overall, it is clear medical practice was difficult, which may have led to complications for individuals with fractures. Based on the numerous risks of fractures and rich historical records, Louisbourg is an ideal location to research fractures in an effort to better understand how and why fractures occurred within this population, and the medical attention individuals may have received.

2.6 Conclusion

This literature review focused on the cellular and biomechanical responses of bone to fracturing and the intricacies of bone healing. Additionally, this chapter highlighted the different interpretive and methodological approaches to the study of fractures in bioarchaeology. Understanding the fracture process and methods of assessment will directly inform this thesis research and aid in the understanding of 18th century medical care and the lived experience of those at the Fortress of Louisbourg.

CHAPTER 3 – Materials and Methods

3.1 Introduction

This chapter will begin by reviewing the access permissions to the Fortress of Louisbourg Skeletal Collection, followed by a discussion of the sample. Next, will be a review of all macroscopic methods to assess age, sex, and fracture presence in the sample. Additionally, this chapter will review the standards and procedures for radiographic and micro-computed tomography (micro-CT) image capture and rendering. Finally, this chapter will provide an overview of the scoring system that was used to assess fracture healing.

3.2 Access Permissions

Permission to access these skeletal remains and complete this research was granted by Dr. Amy Scott and the University of New Brunswick (UNB), Parks Canada, the Catholic Dioceses of Antigonish, and the Anglican Diocese of Nova Scotia and Prince Edward Island as outlined in the Parks Canada Management Directive for Human Remains, Cemeteries and Burial Grounds. Additionally, the ongoing excavations on Rochefort Point have been supported by the local Mi'kmaq Chiefs and Lindsay Marshall, the Indigenous Liaison for the Parks Canada Cape Breton Field Unit. All macroscopic assessment took place in the UNB Bioarchaeological Research and Teaching (BART) Laboratory and selected rib bones were temporarily transported to the Museum of Ontario Archaeology and Western University in London, Ontario (ON), for micro-CT analysis under the supervision of Dr. Andrew Nelson. The selected skeletal

remains were also temporarily transported to St. Joseph's Hospital in London, ON, under the supervision of Dr. Greg Garvin and Dr. Andrew Nelson for radiographic imaging.

During micro-CT scanning, all image data were stored on two computers at the Museum of Ontario Archaeology. Once scanning was complete, the radiographs were deleted from the museum computers and transferred to a secure file server (via FileZilla software application) for image rendering at Western University. After image rendering was complete, the files were transferred to a password protected external hard drive and removed from the secure server. Radiographs from St. Joseph's Hospital were exported to a CD disc and transferred to the external hard drive. The skeletal remains and external hard drive were returned to the UNB BART laboratory once data collection was complete. Necessary precautions were taken during data collection to ensure the safe and ethical handling of all skeletal remains and image data.

3.3 Fortress of Louisbourg Skeletal Collection

3.3.1 The Block 3 Cemetery

The Block 3 cemetery was the first formal cemetery at Louisbourg, established by the first French settlers in 1713 (Johnston 2001; Moore 1974). In 1723, the cemetery was closed, and the individuals buried in the Block 3 cemetery were relocated to Block 34 so the area could be converted into residential homes (Johnston 1984). However, during excavations in the 1960s when the Fortress was being reconstructed as a National Historic Site of Canada, it was discovered that not all individuals had been relocated to

Block 34. The remaining individuals were exhumed at this time and stored on site until 2017 when they were transferred to the UNB BART laboratory.

3.3.2 The Rochefort Point Cemetery

The Rochefort Point cemetery was the largest documented cemetery at Louisbourg, established around 1738 by the French and was in use until the site was abandoned in the 1760s (Johnston 1984). This cemetery was also used by the New Englander garrison after the 1745 siege, and again by the French in 1748 when they returned to the site; however, at this time it may have been mainly used for soldier interments (Johnston 1984). It is also possible that other groups (e.g., Basque) used the Rochefort Point cemetery; however, written documentation of its use is scant. Systematic excavation of the Rochefort Point cemetery began in 2017 through the UNB Bioarchaeological Field School in response to ongoing costal erosion. Since 2017, over 200 burials have been excavated from Rochefort Point, and are temporarily curated in the UNB BART laboratory.

3.3.3 The Ste. Marie Multiple Burial

The Ste. Marie property was located on Rochefort Point directly east of the Rochefort Point cemetery boundary and was burned and levelled at the time of the first siege (Dunham 2017; Parish 2007). In 2006 a major storm hit Rochefort Point and consequently exposed the root cellar of the Ste. Marie property, revealing a multiple burial (Dunham 2017; Parish 2007). The excavation that followed in 2007 uncovered 45 individuals likely interred in the cellar during the first winter following the siege, as the

harsh conditions, spread of disease, and lack of supplies led to widespread causalities (Dunham 2017). Based on isotopic analysis, it is likely that these 45 individuals represent New Englander soldiers and/or civilians that perished during the winter of 1745-1746 (Ellerbrok 2014).

3.3.4 Sample Inclusion Criteria

For this thesis research, each individual had to have at least 70% of their total skeleton present for analysis, based on standards established by Rowbotham and colleagues (2017). Additionally, only individuals over the age of 12 years were included for this study. These preservation and age thresholds were chosen to provide the most accurate information about fracture prevalence by having an adequate number of elements present and to limit the potential confusion between fracture healing and normal patterns of skeletal growth. Only antemortem and perimortem fractures were included in this study as postmortem fractures cannot be used to explore lived experience or physical impact as they occur after death.

The macroscopic assessment of sex for all individuals was made based on morphoscopic traits of the os coxae, including the traits of Phenice and the greater sciatic notch, as well as sexually dimorphic features of the cranium (see Bruzek 2002; Buikstra and Ubelaker 1994; Genovés 1959; Milner 1992; Phenice 1969; St. Hoyme and İşcan 1989; Walker 2005). For all individuals, age-at-death was assessed using changes to the pubic symphysis and auricular surface (see Brooks and Suchey 1990; Lovejoy et al. 1985; Meindl and Lovejoy 1989; Todd 1921a; Todd 1921b). However, for younger adult individuals (i.e., <25 years), age-at-death was additionally assessed based on

epiphyseal closure and patterns of dental eruption and mineralization (see AlQahtani et al., 2010; Schaefer et al. 2009; Ubelaker1989).

3.4 Macroscopic Fracture Assessment

A skeletal inventory was completed for each individual to determine which skeletal elements were present and could be macroscopically assessed for the presence of fractures. Fractures were evaluated based on the visual presence of a discontinuity in the bone, irregular bone shape, evidence of healing (e.g., a bony callus), and by comparing it to other skeletal samples without visible lesions or pathological changes (Brigham-Sadegh and Oryan 2015; Ghiasi et al. 2017; Grauer and Roberts 1996; Marsell and Einhorn 2011; Oryan et al. 2015). When a fracture was identified the following information was recorded: skeletal element, location on the element, fracture type, displacement information, presence of healing, and the timing of the fracture (i.e., antemortem, perimortem, or postmortem) (Grauer and Roberts 1996; Kemp 2016; L'Abbé et al. 2021; Marsell and Einhorn 2011; Oryan et al. 2015; Ribeiro et al. 2020; Scheirs et al. 2018; Wedel and Galloway 2014). All macroscopic fracture data were recorded using a standardized form (see Appendix A).

3.5 Plain Radiograph Image Capture and Rendering

Only individuals with two or more rib fractures were chosen for the subsample that underwent radiographic imaging to better understand fracture events and compare stages of healing. The same subsample of individuals was used for micro-CT imaging to understand if healing assessments were consistent across imaging methods. The GE

Discovery XRH656HD Digital Radiographic System at St. Joseph's Hospital was set up and calibrated before imaging began by Dr. Garvin based on standard operating procedures. The ribs were positioned with the pleural surface superior to achieve optimal visibility of each bony callus and placed on a 35 x 43-inch x-ray plate with a film-focus distance (i.e., the distance between the focal spot anode in the x-ray tube to the plate) set at one meter. One image was captured per individual with rib bones stabilized using x-ray foam to ensure no movement occurred during the image capture process (see Figure 3.1). For each image, the following exposure settings were used: 40kV (i.e., x-ray tube voltage measured in kilovolts [kV]), 4 mAs (i.e., the amount of radiation produced measured in milliampère-seconds [mAs]), and 100-160 mA (i.e., quantity of x-rays produced, measured in milliampères [mA]) with edge enhancement software and no filtration. These specific settings were chosen based on the combination of imaging protocols set by Viero and colleagues (2021) and the expert opinions of Dr. Garvin and Dr. Nelson to best visualize the fracture callus due to the lack of soft tissue present. Once imaging was complete, the Digital Imaging and Communications in Medicine (DICOM) files were transferred to a secure external hard drive and transported to UNB for image rendering and analysis.

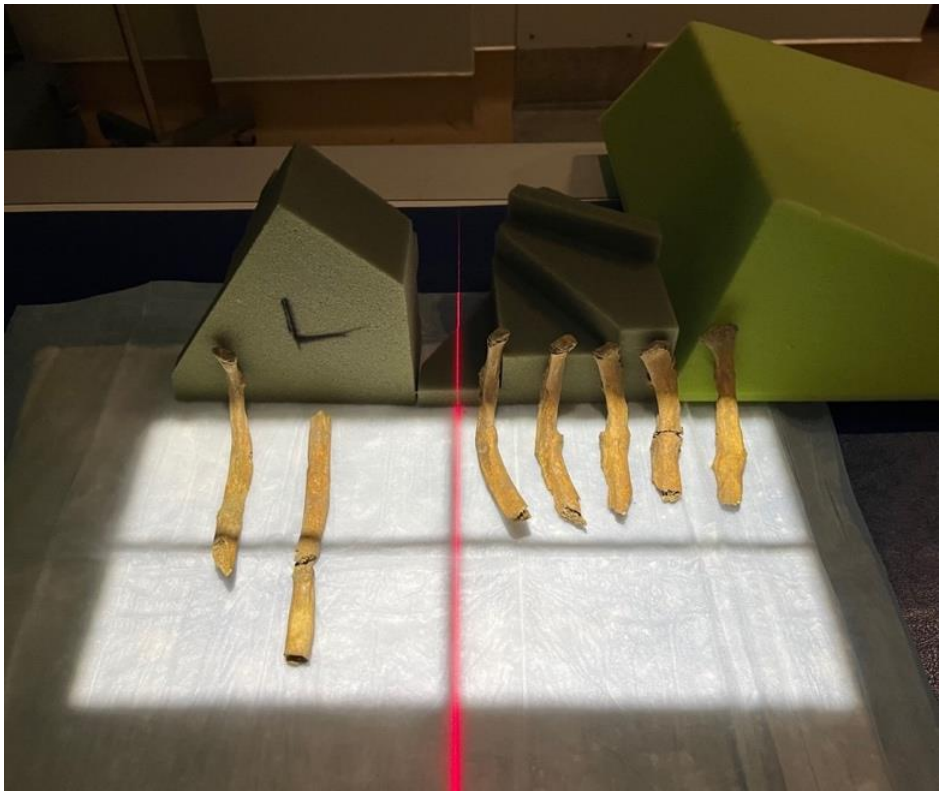


Figure 3.1: Radiograph image capture setup with rib bones placed on x-ray plate with the pleural surface facing superiorly and balanced against x-ray foam to prevent movement

The radiograph files were viewed using the GE Media Viewer DICOM reader. The raw x-ray files were adjusted individually as needed using the windowing tool in the DICOM reader for brightness and contrast to ensure the callus and surrounding bone was clear prior to the assessment of fracture healing. This windowing procedure was chosen to be consistent with established micro-CT standards discussed further in section 3.6.3.

3.6 Microscopic Computed Tomography Imagining

3.6.1 Preliminary Nikon XT 225 ST Setup

The micro-CT image capture took place at the Museum of Ontario Archaeology in London, ON using a Nikon XT 225 ST Micro-CT machine and under the supervision of Dr. Nelson. The Nikon XT underwent an automatic conditioning procedure prior to each scanning session to ensure the stability of the machine and system settings. Once the automatic conditioning was complete, a shading correction setting was created for each session, which adjusted the x-ray tube voltage (kV), the power of x-ray current (measured in watts [W]), and the current exposure time (measured in microampere [μA]). To ensure micro-CT image clarity, the overall micro-CT exposure settings were set between a value of 10,000-65,000, which was achieved by adjusting the x-ray current energy and exposure time. The exposure settings used for this thesis research were as follows; 100kV, 115μA and 11.5W based on the expert opinion of Dr. Nelson and methodology for scanning rib bones presented by Viero and colleagues (2021). Prior to scanning, a molybdenum target was chosen to best capture the micro-CT images. The target is the part of the micro-CT system that emits the x-rays that will pass through the sample to produce an image (Conlogue et al. 2020). A molybdenum target was chosen as it provides better contrast on micro-CT images of bones in comparison to the typical tungsten target.

3.6.2 Spatial Resolution and Projection Settings

To begin image capture, individual ribs were mounted in a clear plastic tube and secured with low density foam (i.e., radiolucent foam) to ensure minimal movement

during the scanning process and best visualization of the fracture callus (see Figure 3.2). The tube was secured to the Nikon XT turntable, and the height and rotation of the turntable were adjusted so the fracture callus was centered in the frame. A 360-degree rotation of the turntable was manually conducted prior to each scan to ensure the fracture callus did not leave the frame at any point during scan.

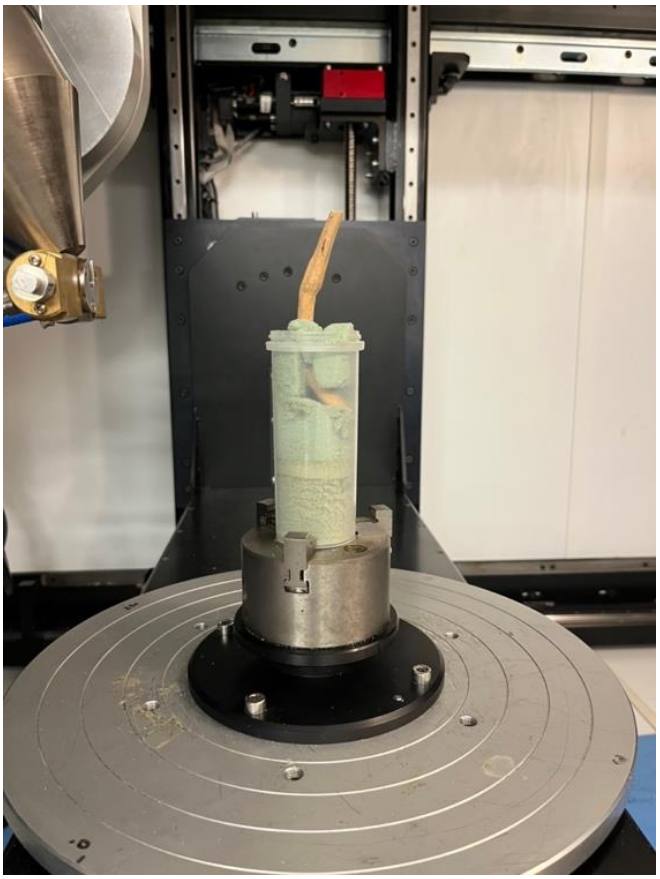


Figure 3.2: Sample mounted in plastic tube and secured using foam

When taking a micro-CT scan, image spatial resolution for both 2D and 3D data must be established. Spatial resolution is the shortest quantifiable distance between the Nikon XT source and the detector, and the ribs where all the essential microstructures

and components of the bone can be visualized clearly (Conlogue et al. 2020). In the 2D radiographs, this is represented in pixel size (measured in micrometres [μm]) that can be quantified to scale, where the chosen pixel size represents a micrometer-by-micrometer section of bone. In the 3D model produced by the micro-CT, spatial resolution requires a 3D value which is represented by volumetric pixels or voxels, which adds a third dimension of measurement (Conlogue et al. 2020). For this thesis research, a voxel size of 22 μm was chosen based on values established in a previous study (see Viero et al. 2021).

Each projection taken during a micro-CT scan represents a singular 2D radiograph captured as the sample rotates 360 degrees. Micro-CT image capture can be conducted using two different methods: a long scan or short scan. The long scan takes 1,571 different projections over 4 hours and 21 minutes. The long scan method helps to minimize image artifacts which aids in overall visualization of bone microstructures. Based on the time and funding available, only a short scan method could be implemented for this research, where each fracture callus (n=31) was scanned for 53 minutes, for a total of 3,141 projections at a rate of approximately one projection per second. While the short scan method can result in more image artifacts, they can be reduced during the image render process. Overall, the short scan method provides adequate data for analysis of fracture healing.

3.6.3 Micro-CT Image Rendering

Once scanning for each image was complete, the image capture data were exported as a TIFF stack, which held the 3,141 projections. The TIFF stack was

uploaded to CT Pro 3.0 computer software to convert the 2D radiographs into 3D data. In CT Pro, each TIFF stack underwent image configuration to help enhance the image and reduce any image artifacts that may have been produced during the scan, including beam hardening and mask radius. Beam hardening produces image artifacts when the low energy photons in an x-ray beam are absorbed more than high energy photons while trying to pass through a dense material. This can result in streaking and a material appearing denser than it is which can impact visibility of the image (Buzug 2008). Additionally, mask radius was adjusted to limit any artifacts (i.e., streaks or tube inclusion) produced by movement during the scan or interference caused by the clear plastic tube (Buzug 2008). When image correction was complete, CT Pro generated a new set of 3D files, a volume group information (vgi) file, and a volumetric (vol) file to allow for adequate image rendering.

Both the vgi and vol files were uploaded to the Dragonfly 2023.2 computer software to complete image rendering of the micro-CT scans. The Dragonfly 2023.2 program creates four different image windows that allow for different visualizations of the fracture callus. The software creates three 2D views, each in a different spatial plane (i.e., XY, XZ, YZ) that stack the various projection slices and allow visualization of different layers of the bone. Additionally, the projections are all combined to create a 3D model of each fracture callus. Each set of 3D files were individually uploaded to Dragonfly 2023.2. The first step after the file had been imported was to adjust the windowing and leveling settings. These settings were essential to highlight the contrast in density between the different areas of the fracture callus, where more dense areas are lighter in colour, and areas of lower density are darker in colour. Windowing and leveling settings were chosen to optimize image clarity and show the contrast in

densities between the callus and surrounding bone (see Appendix B, Table B-1). Lookup tables (LUT) and software preset settings were used to generate pseudocolour in both the 2D and 3D image windows to enhance the appearance of each image. A grayscale LUT was used for all 2D images, while various grayscale LUTs were utilized for the 3D model (see Appendix B, Table B-1). Additionally, a system preset titled “bones 2” was applied to the 3D model, which is designed specifically to enhance visualization of osteological material.

Standardized images and videos were taken of each 2D spatial plane, with the focus crosshairs placed at the center of the callus (see Figure 3.3). Images and videos for the 2D XZ and YZ planes were taken to visualize as much of the fracture callus as possible for analysis by examining each projection slice. Images of the XY plane were taken above, below, and at the center of the fracture callus to demonstrate the difference in bone density and organization across the rib bone. For the 3D model, images were taken of the plural, ventral, superior, and inferior surfaces, as well as the internal structures above, below, and at the center of the fracture callus using the clip function on Dragonfly 2023.2 (see Appendix B, Figure B-1).

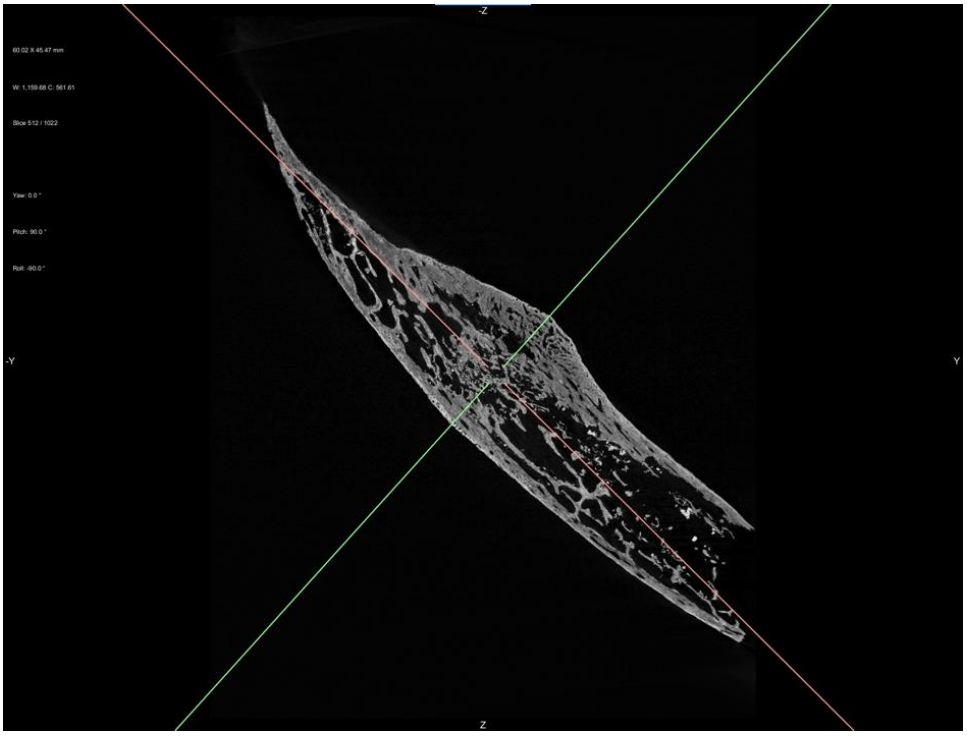


Figure 3.3: Image rendering setup in Dragonfly 2023.2 demonstrating focus crosshair placement through the center of the fracture callus

3.7 Microscopic Fracture Healing Assessment

Assessment of fracture healing was conducted for both radiographs and micro-CT images based on modified descriptions from clinical and forensic studies (see Hufnagl 2005; Oryan et al. 2015; Salih et al. 2015; Tritella et al. 2020; Viero et al. 2021) (see Table 3.1; Figure 3.4). Additionally, a flow chart and annotated reference images were used to classify the radiograph and micro-CT images into each stage (see Figure 3.4, Figure 3.5, Figure 3.6). Stage 1 and 2 reference images were not used, as the original studies based on clinical and forensic contexts where soft tissue was present, did not apply to this bioarchaeological study; therefore, stages 1 and 2 could easily be assessed with the naked eye on dry bone. All subsequent stages however, required reference images to assess. Radiographs for each fracture callus were examined first

using the six-point scoring system, followed by the micro-CT images five days later. Because the images were not anonymized at this stage and the same bone was being represented in each image, assessing the x-ray and micro-CT images five days apart was determined to be sufficient in minimizing any potential intraobserver bias. All fracture healing data were collected and recorded on standardized forms (see Appendix A).

Table 3.1: Modified scoring descriptions for the assessment of fracture healing using radiographs and micro-CT

Score	Description
1	• No fracture callus visible • Sharp edges of fracture margins
2	• Clear fracture line present • Blurring/blunting around fracture margins • Widening of the fracture gap • Increased bone density around fracture margins (i.e., sclerosis) • Start of immature fracture callus (i.e., "cloud-like/puffy" area surround the fracture)
3	• Radiopaque area surrounding the fracture, bulging around fracture gap • Clear fracture line present
4	• Fracture gap is connected in some areas by woven bone • Fracture line begins to blur • Callus is bulged over the fracture gap
5	• Fracture line is faint • Well-developed, smooth callus connected across all areas of the fracture gap
6	• Callus is faint, minimal bulge present • No fracture line present • Evidence of remodelling (i.e., the fractured area is reaching similar radiodensity to the surrounding bone)

(modified from Hufnagl 2005; Oryan et al. 2015; Salih et al. 2015; Tritella et al. 2020; Viero et al. 2021)

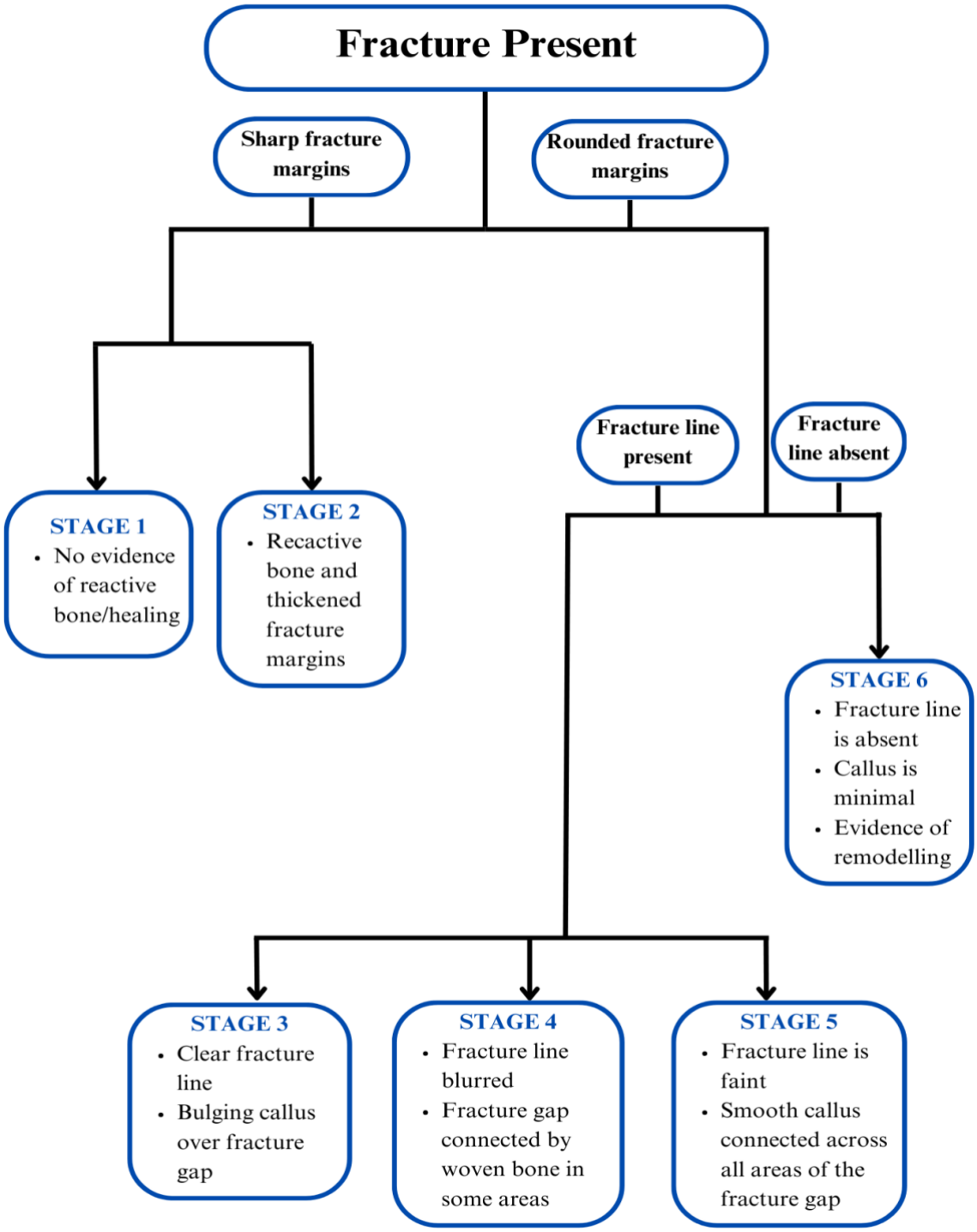


Figure 3.4: Fracture healing flow chart for x-ray and micro-CT assessment of fracture healing (modified from Hufnagl 2005; Oryan et al. 2015; Salih et al. 2015; Tritella et al. 2020; Viero et al. 2021)

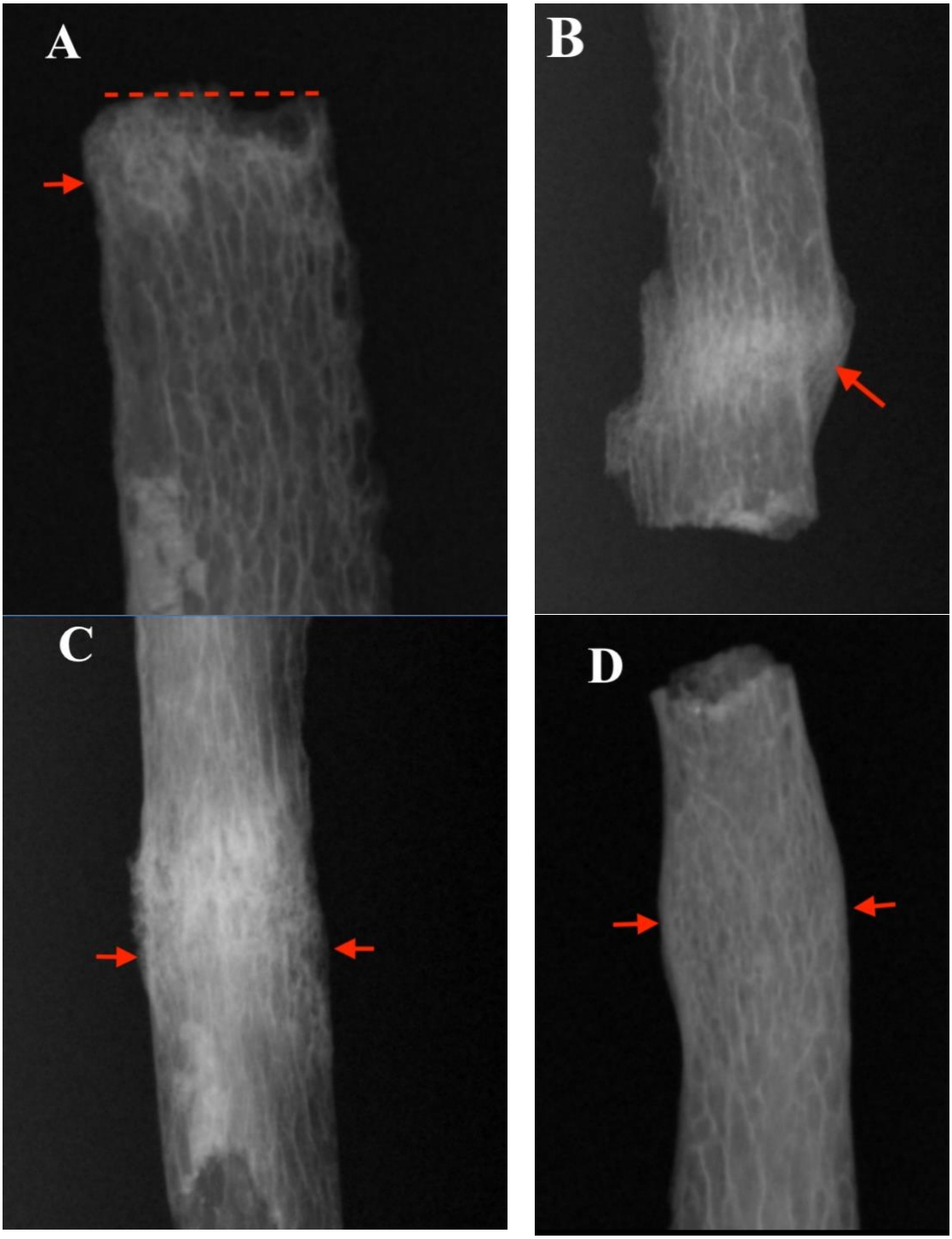


Figure 3.5: Fracture healing references images for radiographs stages 3-6

A: Stage 3, clear fracture line (dashed red line) with prominent callus bulge (red arrows)
B: Stage 4, fracture callus still has a bulge and not connected with woven bone across all areas (red arrows)
C: Stage 5, smooth callus connected across all areas of the fracture gap (red arrows)
D: Stage 6, fracture line is absent with evidence of remodeling (red arrows)

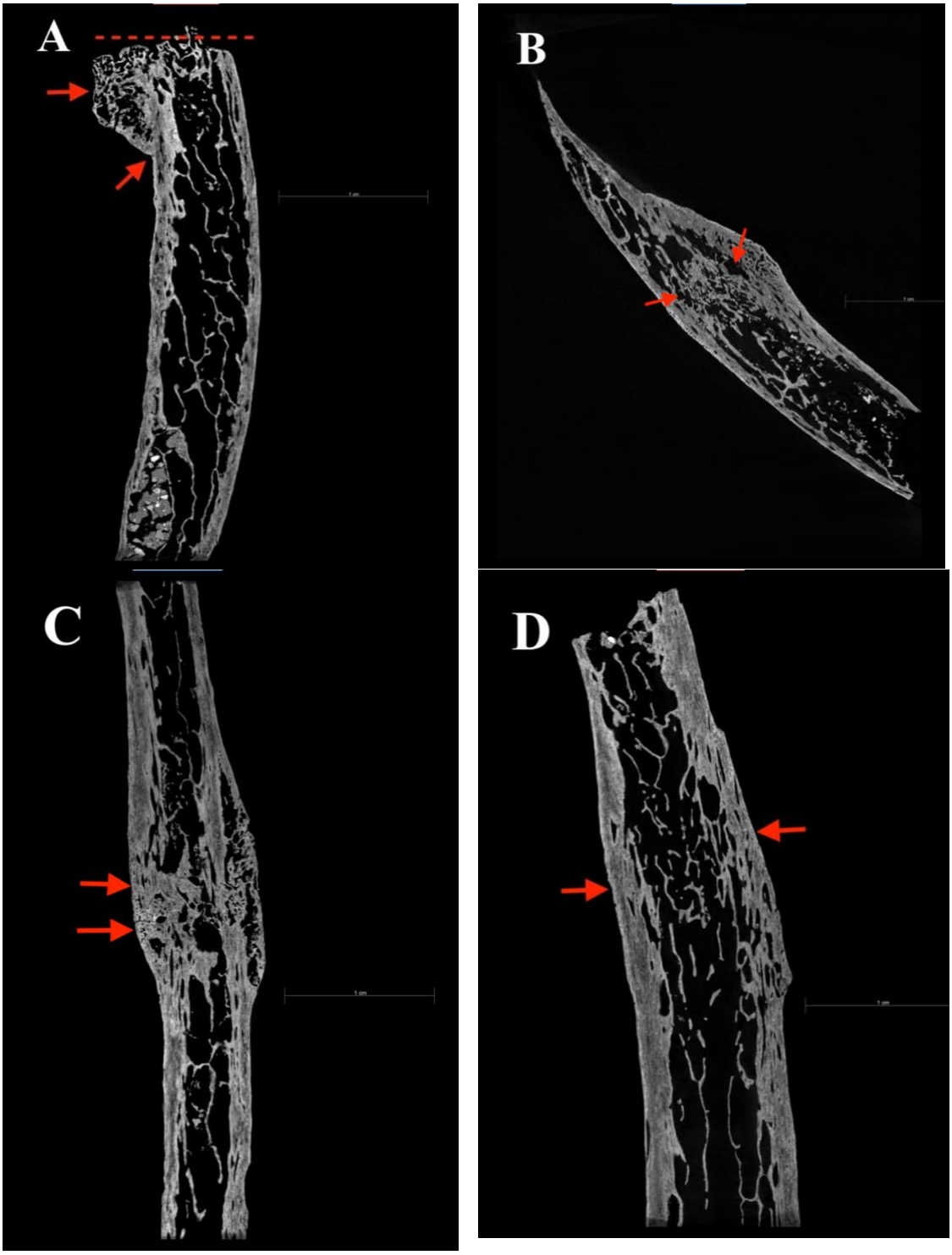


Figure 3.6: Fracture healing references images for micro-CT stages 3-6

A: Stage 3, clear fracture line (dashed red line) with prominent callus bulge (red arrows)
B: Stage 4, fracture callus still has a bulge and not connected with woven bone across all areas (red arrows), with the fracture line present
C: Stage 5, smooth callus connected across all areas of the fracture gap (red arrows)
D: Stage 6, fracture line is absent with evidence of remodeling (red arrows)

3.8 Intraobserver Error

To ensure the macroscopic, radiographic, and micro-CT data were consistently assessed, intraobserver error testing was also completed. All initial macroscopic assessments were completed by September 21st, 2023, and on October 27th, 2023. A subsample of individuals (25%) was randomly selected and anonymized for re-evaluation. Similarly, the assessment of fracture healing in plain radiographs and micro-CT images were completed on November 20th, 2023, and November 25th, respectively. These data were not anonymized; however, the similar nature of these images and time between the first and second rounds of scoring likely diminished any memory bias. Comparison between the first and second rounds of macroscopic, x-ray, and CT assessments were evaluated using Cohen's kappa statistic (κ_w) in the IBM SPSS Statistic 29.0 software program. This statistical test evaluates the level of agreement between multiple rounds of subjective assessment, where a score of <0.000 shows poor agreement and 1.000 represents almost perfect agreement (see Table 3.2).

Table 3.2: Landis and Koch (1997) interpretation of the Kappa Statistic

Kappa Static Value	Strength of Agreement
<0.00	Poor
0.00-0.20	Slight
0.21-0.40	Fair
0.41-0.60	Moderate
0.61-0.80	Substantial
0.81-1.00	Almost Prefect

3.8 Conclusion

This chapter reviewed the access permissions for this study as well as contextual information for the Block 3 and Rochefort Point cemeteries and the Ste. Marie multiple burial. Next, the inclusionary criteria for the skeletal sample were discussed, followed by an overview of the macroscopic methods. Radiographic and micro-CT image capture and rendering procedures, and the scoring system used to assess fracture healing was also reviewed. Finally, the intraobserver error assessment method was outlined to ensure consistency across the three methods of analysis used in this research.

CHAPTER 4 – Results

4.1 Introduction

The chapter will present the findings of this research, beginning with a review of the population sample. Next, the intraobserver error reliability testing of both macroscopic and microscopic assessments will be discussed, followed by the fracture prevalence results within and between three population samples. This chapter will conclude with a review of the microscopic imaging subsample and the results of fracture healing assessment.

4.2 Population Sample

For this research, 32 individuals from the Block 3, Ste. Marie, and Rochefort Point skeletal collections met the preservation (>70% across the entire skeleton) and age criteria (average age 12 year or older). From the Block 3 collection, there were five males between the ages of 17.5 and 37.5 years. From the Ste. Marie mass burial, there were also five males between the ages of 22 and 37 years. From the Rochefort Point cemetery there were 22 individuals assessed, including 16 males, one female, and five individuals of indeterminate sex with an age range between 12 and 60+ years (see Table 4.1).

Table 4.1: Block 3, Rochefort Point, and Ste. Marie sample summary and skeletal completeness percentage

Burial #	Collection	Sex	Average Age (years)	Skeletal Completeness
1	Block 3	Male	37.5	~76%
7	Block 3	Male	32.5	~76
16	Block 3	Male	27	~71%
19	Block 3	Male	17.5	~87%
20	Block 3	Male	27.5	~82%
55L28E7	Ste. Marie	Male	37	~88%
55L28E9	Ste. Marie	Male	22	~83%
55L28E13	Ste. Marie	Male	35	~94%
55L28F18	Ste. Marie	Male	32.5	~90%
55L28F29	Ste. Marie	Male	32.5	~86%
1/2017	Rochefort Point	Male	16.5	~80%
2/2017	Rochefort Point	Indeterminate	18.5	~94%
3/2017	Rochefort Point	Male	32.5	~95%
4/2017	Rochefort Point	Indeterminate	16.5	~81%
5/2017	Rochefort Point	Male	32	~97%
7/2017	Rochefort Point	Indeterminate	18	~75%
20/2017	Rochefort Point	Indeterminate	15.5	~87%
21/2017	Rochefort Point	Male	30	~93%
26/2017	Rochefort Point	Male	32	~71%
28/2018	Rochefort Point	Male	25.5	~79%
72/2019	Rochefort Point	Male	32	~89%
73/2019	Rochefort Point	Male	34.5	~74%
77/2019	Rochefort Point	Male	47	~97%
84/2019	Rochefort Point	Male	22	~87%
85/2019	Rochefort Point	Indeterminate	12	~84%
86/2019	Rochefort Point	Male	22.5	~90%
88/2019	Rochefort Point	Male	27	~84%
89/2019	Rochefort Point	Male	27	~97%
90/2019	Rochefort Point	Male	42	~94%
96/2019	Rochefort Point	Female	60+	~94%
99/2019	Rochefort Point	Male	32.5	~99%
214/2023	Rochefort Point	Male	24.5	~72%
TOTAL	32	M:26, F:1, I:5	AVG: 28.8	AVG: 86%
M= Male; F= Female; I= Indeterminate; AVG= Average				

4.3 Intraobserver Error

To ensure the macroscopic, radiograph, and micro-CT data were consistently assessed, intraobserver error testing was completed using Cohen's kappa statistic (κ_w) in the IBM SPSS Statistic 29.0 software program. As discussed in Chapter 3, section 3.8, this statistical test evaluates the level of agreement between multiple rounds of subjective assessment, where a score of <0.000 shows poor agreement and 1.000 represents almost perfect agreement (see Table 3).

All initial macroscopic assessments were completed by September 21st, 2023, and on October 27th, 2023. Approximately 25% of the individuals (n=8/32) from the total sample were randomly selected and anonymized for re-evaluation. Similarly, the assessment of fracture healing in plain radiographs and micro-CT images were completed on November 20th, 2023, and November 25th, 2023, respectively. On December 14th, 2023, 25% of the rib fractures (n=8 fractures) from the total imaging sample (n=32 rib fractures) were randomly selected and anonymized for re-evaluation. Comparison between the first and second rounds of macroscopic, radiograph, and micro-CT assessments were also evaluated using the kappa statistic (see Table 4.2).

Table 4.2: Kappa statistic values for macroscopic, radiograph, and micro-CT assessments

Assessment	κ_w	Standard Error	Confidence Interval (95%)
Macroscopic	0.862	0.130	<0.001
Radiograph	0.784	0.202	0.003
Micro-CT	1.000	N/A	N/A

4.4 Macroscopic Analysis

4.4.1 Fracture Prevalence and Location on the Body

Table 4.3 is a fracture summary for this population sample, where a total of 12 individuals (37.5% of the total sample) were found to have at least one fracture present, with a total of 52 fractures observed overall. Of these 12 individuals, 58% (n=7/12) had more than one fracture present. Fractures were found in most regions in the body, including the cranium, thorax, upper limbs, and lower limbs (see Figure 4.1 and Table 4.3).

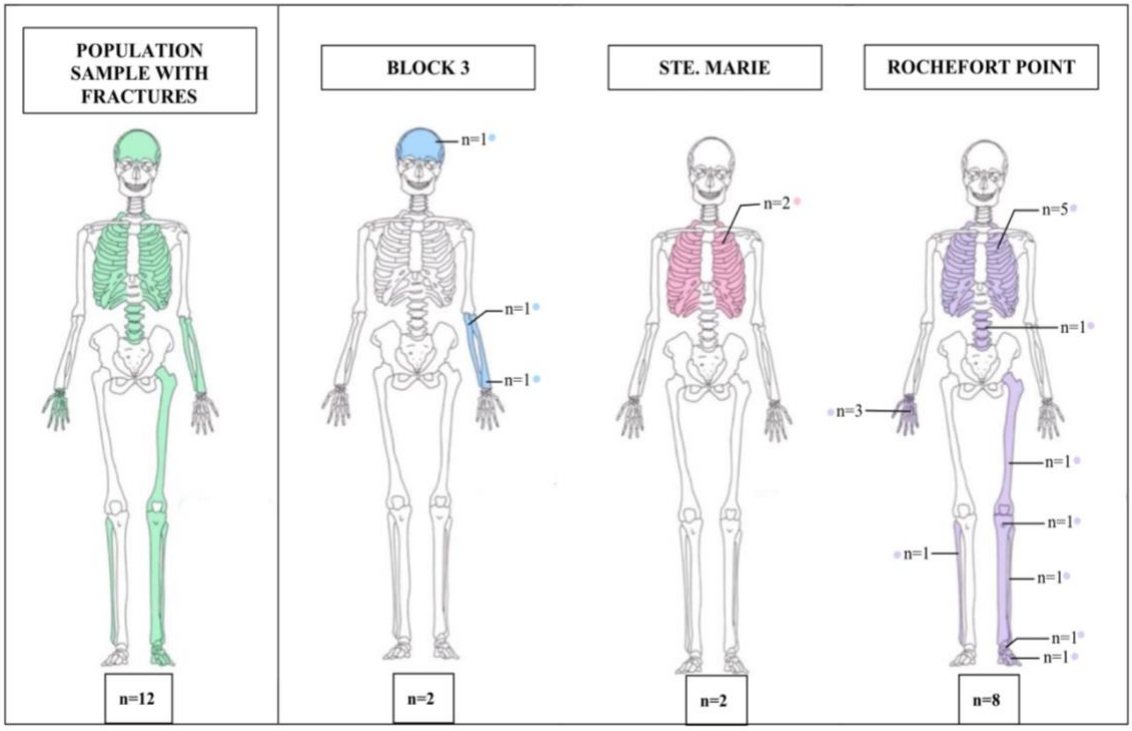


Figure 4.1: Summary of fracture locations and number of individuals affected across all three subsamples

Table 4.3: Detailed summary of fracture presence and location within the sample

Burial #	Collection	Fractured Element(s)	Axial or Appendicular	# of Fractures
1	Block 3	Left ulna	Appendicular	1
19	Block 3	• Left radius • Cranium	Both	4
55L34E7	Ste. Marie	Ribs: • Left Ribs: 2, 3, 4, mid-thoracic, lower mid-thoracic • Right Ribs: 10, mid-thoracic ribs (n=2), lower mid-thoracic rib (n=1)	Axial	9
55L34E13	Ste. Marie	Unsided rib fragment	Axial	1
21/2017	Rochefort Point	Ribs: • Left Ribs: 6-8, 10-11 • Right Ribs: 7, 9 Hand: • Right 1st and 2nd metacarpals Vertebrae: • Lumbar vertebrae 1-3	Both	12
28/2018	Rochefort Point	• Right 5th proximal phalanx • Right fibula	Appendicular	2
73/2019	Rochefort Point	Right lower mid-thoracic ribs (n=2)	Axial	2
77/2019	Rochefort Point	Ribs: • Left ribs: left rib (n=1), mid-thoracic ribs (n=2) • Right ribs: 7-11 • Unsided fragment Hand • Right 1st metacarpal	Both	13
84/2019	Rochefort Point	Ribs: • Left: mid-thoracic ribs (n=2) Lower Leg: • Left tibia • Left fibula • Left calcaneus	Both	5
85/2019	Rochefort Point	Left femur	Appendicular	1
89/2019	Rochefort Point	Left lower thoracic rib	Axial	1
99/2019	Rochefort Point	Left 5th metatarsal	Appendicular	1

Fracture prevalence (presence vs. absence) across subsamples was compared using a chi-squared test to understand differences between the subsamples, which yielded no statistical difference (p= 0.981). Due to the small sample size, a Fisher's exact test was performed to test the association between fracture prevalence in the subsamples, finding no statistical significance (p=0.609). The mean number of fractures between skeletal collections was also tested using an independent samples t-test, with no statistical differences between the number of fractures across each subsample (see Table 4.4).

Table 4.4: Independent sample t-test comparing mean number of fractures between each skeletal subsample

Subsample Comparison	t-value	df	p-value
Rochefort Point to Ste. Marie	-0.224	25	0.824
Rochefort Point to Block 3	0.351	25	0.729
Block 3 to Ste. Marie	0.520	8	0.617

The majority of fractures that could be definitively sided were found on the left side of the body (n=23/50, 46%), followed by the right side (n=21/50, 42%), and the center elements (n=6/50, 12%). Independent samples t-tests were used to understand statistical differences found between left, right, and center fractures. The results of these tests showed a statistical difference between the number of fractures on the left side when compared to the center of the body, but no difference between the left and right side, or between the right side and center of the body (see Table 4.5).

Table 4.5: Independent samples t-test comparing number of fractures to fracture location on the left, right, and center of the body

Side Comparison	t-value	df	p-value
Left to Right	0.416	62	0.679
Left to Center	2.273	62	0.027*
Right to Center	1.825	62	0.073

* Statistically significant at the 95% confidence interval

Comparison of axial versus appendicular fractures was completed using a chi-squared test and yielded no statistical difference (p= 0.263) between fracture location. Most individuals exhibited two or more fractures (n= 7/12 ,58%) with the most common fracture location being the ribs (n= 7/12, 58%). While ribs were the most common to have fractures present, for those who had more than one fracture, multiple skeletal elements were usually affected (n= 5/7, 71%).

4.4.2 Fracture Prevalence and Age

Independent samples t-tests were used to compare average age-at-death and fracture presence within the total sample, with no statistically significant differences in age between those with and without fractures (t-value = -0.438; df = 30; p= 0.664). The average age for those with a fracture was 29.8 years and the average age of those without a fracture was 28.2 years. A linear regression correlation was used to test the relationship between age and number of fractures finding a weak positive relationship between the two (R^2=0.1743) (see Figure 4.2) (see Ratner 2009). Additionally, an independent sample t-test was used to compare average age-at-death within each

subsample, with no statistically significant differences in age between those with and without fractures across the three subsamples (see Figure 8; Table 9).

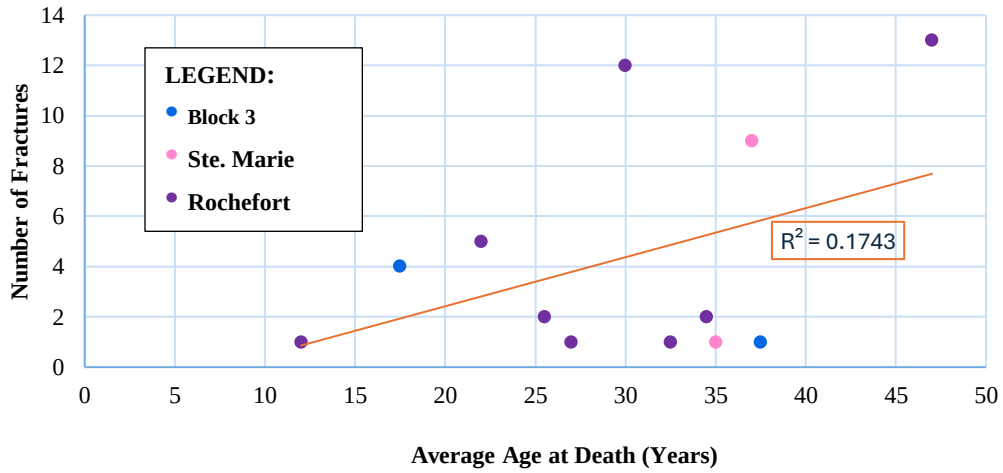


Figure 4.2: Average age at death compared to the number of fractures present within each individual

Table 4.6: Independent samples t-test comparing average age at death to fracture presence in each subsample

Collection	Average Age at Death (years)	t-value	df	p-value
Rochefort Point	FP = 28.8 FA = 27.8	-0.194	20	0.848
Ste. Marie	FP = 36 FA = 29	-1.529	3	0.224
Block 3	FP = 27.5 FA = 29	0.148	1.062	0.906
FP= fractures present, FA= fractures absent				

4.4.3 Fracture Data

The fracture data including fracture healing, type, displacement, and reduction are summarized in Table 4.7. The majority of the fractures present were well-healed (n=32/52, 62%), followed by active healing (n=16/52, 31%), and unhealed fractures

(n=4/52, 8%). All fractures were determined to be antemortem (n=48/52, 92%) or perimortem (n=4/52, 8%) (see Table 4.7). Due to many of the fractures being well-healed, the fracture type and displacement were difficult to determine. However, for the fractures where type (n=16/52, 31%) and displacement (n=6/52, 12%) could be assessed, the most common fracture type observed was oblique (n=6/16, 38%), followed by transverse (n=3/16, 19%), comminuted (n=3/16, 19%), and radiating (n=3/16, 19%), and one compression fracture. Fracture displacement was present in six individuals (see Table 4.7). Nine fractures were determined to be non-reduced, while the majority of fracture reduction was unobservable due to the level of healing present. In bioarchaeology, fracture reduction can be difficult to assess (Grauer and Roberts 1996; Gilmour et al. 2019; Lovell,1997) as it is not always clear whether intervention occurred or if the fracture simply remained in alignment post-injury. Therefore, only fractures that were obviously non-reduced due to bone shortening and/or displacement will be discussed.

Table 4.7: Summary of fracture type, healing, displacement, and reduction for all individuals

Burial #	Fracture Type	Fracture Timing	Level of Healing	Displacement	Reduction
1	Unobservable	AM	Well-healed	Unobservable	Unobservable
19	· Radius: N/A · Cranium: radiating fractures	AM	Radius: well-healed Cranium: active healing	Displaced	Not reduced
55L34E7	· Left Rib 3: Oblique · Left Rib 4: transverse	AM	Active healing: · Left Ribs: 3, 4, mid-thoracic, lower mid-thoracic · Right Ribs: mid-thoracic ribs (n=2), Well-healed: · Left Rib 2 · Right Ribs: 10, lower mid-thoracic rib (n=1)	Unobservable	Unobservable
55L34E13	Unobservable	AM	Active healing	Unobservable	Unobservable
21/2017	· Ribs: Unobservable · Right 2nd metacarpal: oblique · Right 1st metacarpal: Unobservable · Vertebrae: Unobservable	AM	Well-healed Except for the right ribs which are in active healing	Unobservable Except for right 2nd metacarpal is displaced	Unobservable Except for right 2nd metacarpal with is not reduced
28/2018	· Fibula: Unobservable · Right 5th proximal phalanx: compression	AM	Well-healed	Unobservable	Unobservable
73/2019	Unobservable	AM	· One well-healed · One active healing	Unobservable	Unobservable
77/2019	Unobservable Exceptions: · left rib (n=1): oblique · Right Rib 7: Oblique (fracture #1) and transverse (fracture #2) · Right Rib 8: oblique (fracture #2) · Right Rib 11: Oblique	AM	Well-healed Exceptions: · Right Rib 7 fracture #2 · Right Rib 8 fracture #3 · Right Rib 8 fracture #2 · Right Rib11	Unobservable	Unobservable
84/2019	· Ribs: Unobservable · Tibia: comminuted · Fibula: transverse · Calcaneus: comminuted	Ribs: AM Tibia, Fibula, calcaneus: Peri	· Ribs: well-healed · Tibia: unhealed · Fibula: unhealed · Calcaneus: unhealed	Ribs: Unobservable Tibia: displaced Fibula: displaced Calcaneus: displaced	Ribs: Unobservable Tibia, fibula, calcaneus: not reduced
85/2019	Femur: comminuted (butterfly) fracture	Peri	Unhealed	Displaced	Not reduced
89/2019	Unobservable	AM	Well-healed	Unobservable	Unobservable
99/2019	Unobservable	AM	Well-healed	Unobservable	Unobservable
AM= Antemortem, Peri= Perimortem					

4.5 Radiograph and Micro-CT Analysis

4.5.1 Imaging Subsample

The individuals chosen for microscopic imaging are listed in Table 11, with a total of five burials from the Ste. Marie (n=1) and Rochefort Point (n=4) collections. The 12th rib fracture of Burial 77/2019 was not included in this subsample as it was found during intra-observer error testing once imaging had already concluded. One radiograph per individual was taken, with the exception of individual 55L34E7 which required two images to capture all fractures, for a total of six radiographs (see Table 4.8). Micro-CT scans were taken of each fracture (n=31), for a total of 31 short micro-CT scans (see Table 4.8). Ribs were designated by number and side; however, when side/rib number could not be determined, fractures were given an arbitrary number (i.e. #1, #2, #3, etc.). Additionally, consecutive numbers were assigned when multiple fractures were observed on a single rib from the head end towards the sternal end.

Table 4.8: Summary of rib fractures for radiograph and micro-CT imaging

Burial #	Collection	# of fractures	# of fragments	# of Radiographs	# of Micro-CT scans
55L34E7	Ste. Marie	9	9	2	9
21/2107	Rochefort Point	7	9	1	9
73/2019	Rochefort Point	2	2	1	2
77/2016	Rochefort Point	11	10	1	11
84/2019	Rochefort Point	2	2	1	2

4.5.2 Fracture Healing Assessment

Table 4.9 provides the fracture healing scores for all radiographs and micro-CT images. A chi-square test was used to assess whether there was a difference between the micro-CT and radiograph scores for the same fracture. There was no statistical difference observed ($p= 0.310$) despite the scores not matching across multiple examples (see Table 4.9). Additionally, three individuals that could be scored based on their radiographs could not be accurately scored using micro-CT imaging due soil inclusions obstructing the callus, or due to the location of the healed fracture which impacted how the image was captured (see Table 4.9).

Table 4.9: Fracture healing scores for radiograph and micro-CT images

Burial #	Side and Element/designation	Radiograph Score	Micro-CT Score
55L34E7	Left Rib 3	4	5
55L34E7	Left Rib 4	5	5
55L34E7	Right lower rib	6	6
55L34E7	Right Rib 10	6	6
55L34E7	Left Rib 2	6	6
55L34E7	Right mid-thoracic rib/#6	5	4
55L34E7	Left lower mid thoracic rib	6	6
55L34E7	Right mid-thoracic rib/#8	3	3
55L34E7	Left mid-thoracic rib	3	3
21/2017	Left Rib 6	6	6
21/2017	Left Rib 7	5	6
21/2017	Left Rib 8	5	6
21/2017	Left Rib 10	5	6
21/2017	Left Rib 11	6	6
21/2017	Right Rib 7	5	5
21/2017	Right Rib 9	5	5
73/2019	Right lower thoracic rib	6	6
73/2019	Right lower mid-thoracic rib	6	6
77/2019	Left mid-thoracic rib/#1	5	6
77/2019	Left mid-thoracic rib/#2	5	6
77/2019	Right Rib 7/fracture #1	5	5
77/2019	Right Rib 7/fracture #2	5	5
77/2019	Right Rib 8/fracture #1	6	Could not be assessed
77/2019	Right Rib 8/fracture #2	5	5
77/2019	Right Rib 8/fracture #3	4	Could not be assessed
77/2019	R Rib 11	4	3
77/2019	Left Rib	5	6
77/2019	Right Rib 10	6	Could not be assessed
77/2019	Right Rib 9	6	6
84/2019	Left mid-thoracic rib/#1	5	4
84/2019	Left mid-thoracic rib/#2	5	4

(Fracture healing scores modified from Hufnagl 2005; Oryan et al. 2015; Salih et al. 2015; Tritella et al. 2020; Viero et al. 2022)

4.6 Conclusion

This chapter reviewed the population sample and the results of all macroscopic and microscopic assessments. Intraobserver error results indicated that all methods were reliable, finding substantial to almost perfect agreement between rounds of assessment. Macroscopic assessment found 52 fractures in most major regions of the body across 12 individuals. The majority of individuals (n = 7/12, 58%) had two or more fractures, with fractures being more prevalent on the left side. All fractures were determined to be antemortem or perimortem, and a variety of fracture types showing various degrees of healing and displacement were observed. Radiographic and micro-CT methods were both able to produce an image of the internal callus structure that was used to score fracture healing, with no statistically significance difference found between the two methods of scoring.

CHAPTER 5 – Discussion

5.1 Introduction

This chapter will contextualize the results of the fracture data from this study, comparing these data with populations from New France and England. Fracture causes, types, and location on the body will be discussed to understand why and how fractures occurred. The physical impact of fractures through the examination of clinical and historical data will also be explored to understand the lives of past individuals. A discussion of medical care will be provided to situate fracture healing within this 18th century sample. Finally, an overview of the microscopic imaging results and their interpretation will be provided in addition to the study limitations.

5.2 Fracture Prevalence and Trends

5.2.1 Fracture Prevalence

To begin, it is important to acknowledge that not all fractures examined here may have occurred at the Fortress. Due to the advanced level of healing present in many cases, it is possible that individuals may have sustained injures prior to their time in the colony. With this in mind, the overall crude fracture prevalence within the sample was 37.5% (n=12/32), with a total of 52 fractures. Fracture data from comparative contemporary populations in New France and England suggest that the fracture prevalence found at Louisbourg is higher than average (see Table 5.1).

Table 5.1: Fracture/trauma prevalence across comparative populations

Site	Time Period	Fracture/Trauma Prevalence	Reference(s)
New Biloxi, New France	1717-1723	11% (n= 3/27)	Danforth et al. (2013) Funkhouser (2014)
London, England	17th -19th centuries	36.8% (n=256/721)	Mant (2016)
Block 3 cemetery, Louisbourg, New France	1713-1723	11.5% (n=3/26)	Scott et al. (2020)
Current study	1713-1760s	37.5% (n=12/32)	Corbett (2024)

For example, New Biloxi was a French colony in Louisiana, occupied from 1717-1721 (Danforth et al. 2013; Funkhouser 2014). Much like the Fortress of Louisbourg, the population of New Biloxi was mostly young adult males who were typically soldiers, convicts, or tradespeople (Funkhouser 2014; Scott et al. 2020). Poor health was common across New France, demonstrated by several paleopathological indicators (i.e., dental caries, antemortem tooth loss, metabolic disease, etc.) including the presence of skeletal trauma. Twenty-seven individuals from the Moran cemetery in New Biloxi were evaluated with only 11% of individuals showing evidence of skeletal trauma (n=3/27) (Danforth 2013; Funkhouser 2014; Scott et al. 2020). Similarly, Scott and colleagues (2020) compared the skeletal trauma at New Biloxi to Louisbourg's Block 3 cemetery (1713-1723), finding a similar prevalence of fracture trauma (n= 3/26, 11.5%). In the context of this study however, only five individuals from the Block 3 cemetery could be assessed based on preservation criteria (i.e., >70%); therefore, it is not surprising that the overall fracture prevalence reported here (37.5%) from a much large sample size and from multiple cemeteries at Louisbourg is more on par with prevalence rates found in 18th century London, England. Mant (2016) investigated 5

different hospital cemeteries from 18th century London, which were mainly comprised of lower/working class individuals. Across the hospital cemeteries, there was a crude fracture prevalence of 36.8% (n=256/721).

London, New Biloxi, and Louisbourg were all considered urban centers, with marked differences in population size which may account for some of the differences in these fracture prevalence data. Specifically, the population size of London during the 18th century began with approximately 575,000 people, steadily growing to over one million by the 19th century (Hitchcock 2023; Mant 2016). Comparatively, Louisbourg at the height of its occupation only reached approximately 10,000 inhabitants (Johnston 1984). Therefore, the similarity in fracture prevalence is even more telling in this instance as those at Louisbourg, when considering overall population size, had a slightly higher fracture prevalence (37.5%, n=12/32) than those in London (36.8%, n=256/721) with no statistically significant difference found between the fracture prevalence at these two sites (p=0.154).

When comparing the number of fractures across the three skeletal collections in this study, there were no statistical differences observed (see Chapter 4, section 4.4.1). The 70% preservation threshold used for this study excluded many individuals from the Block 3 and Ste. Marie cemeteries, creating an uneven distribution of individuals from each collection which may be affecting the statistical results. While the lack of statistical difference (p=0.981) may suggest that there was a similar level of fracture risk across burial areas, the findings from the total Block 3 cemetery by Scott and colleagues (2020) suggests underlying differences between fracture prevalence in each burial area at Louisbourg. For example, Block 3 represents the earlier period of occupation during which construction of the town and fortifications began with a small labour force,

compared to the time period of the Rochefort Point cemetery use (Johnston 2001; McLennan 1981). As discussed, the Rochefort Point cemetery was in use for the longest period, spanning multiple administrative changes during which Louisbourg's population flourished with an influx of labourers immigrating to the colony to find work (Johnston 2001). Therefore, it is not surprising that the Block 3 cemetery's fracture prevalence is slightly higher (40%, n=2/5) than the Rochefort Point subsample (36%, n=8/22), as these earliest settlers at Louisbourg faced unique challenges which would have diminished overtime as the population and workforce at Louisbourg grew. Similarly, the Ste. Marie multiple burial represents a brief period after the first siege as reflected in a 40% (n=2/5) fracture prevalence. Not only were these individuals impacted by risk factors associated with the siege but also factors associated with rebuilding the Fortress during the harsh winter months with insufficient supplies (Dunham 2017; Johnston 2013), very similar to what would have been experienced by the Block 3 individuals. Despite these varying challenges during different periods of Louisbourg's history, the overall fracture prevalence within this study is relatively high in comparison to other archaeological populations arguably due to increased risk factors associated with colonial life.

Ribs were the most common element to be fractured in this study; therefore, a consideration of their prevalence in relation to other archaeological populations is warranted. Ribs are one of the most common skeletal elements to be impacted by fractures within archaeological and modern clinical populations (Curate and Cunha 2022; Brickley 2006; Kara et al. 2003; Mant 2016; Sirmali et al. 2003). Rib fractures were found in 22% of the total sample (n=7/32) at Louisbourg, which is similar to other comparative studies. For example, Brickley (2006) conducted a study specifically on rib

fractures, reporting a 15.6% (n=55/352) rib fracture prevalence in an 18th century English population. This population comes from the St. Martin's Churchyard in Birmingham, England interred between 1750 and 1850, with slightly more males than females within the sample (males: n=180, females: n=130); however, of the 55 individuals who had rib fractures the majority were male (n=44/55, 80%). Individuals buried at St. Martin's were mainly part of the working class, as well as a few people of higher status indicated by different burial practices (Brickley 2006). Males from both St. Martin's and Louisbourg likely participated in arduous occupations such as construction and metal working, which may have put them at an increased risk of fractures resulting in a similar prevalence (Brickley 2006; Johnston 2001; Rule 1992). This aligns with the modern clinical data that suggests rib fractures are most common in young adult males (Farr et al. 2017). Given that the sample used for this research was male dominated, finding multiple rib fractures was not a surprising result when compared to clinical data and the findings from Brickley (2006).

5.2.2 Sex and Age Trends

Within this study, the majority of the sample consisted of adult male individuals (n=26/32), with only one individual identified as female. While this sex distribution likely reflects the actual living population in 18th century Louisbourg (i.e., male to female ratio was approximately 10:1) (Johnston 1984), it does not allow for the comparison of fracture data across sexes. Further, there were no significant trends in age-at-death and fracture prevalence between the three subsamples (see Chapter 4, section 4.4.2). The data within this study did not allow for meaningful comparisons

between age cohorts; however, there are some patterns between fracture presence and age-at-death. A linear regression correlation found a very weak positive correlation between age and number of fractures (R^2=0.1743) which suggests that the number of fractures an individual has increases with age. While is it not surprising that injuries accumulate with age, the fact that older individuals show more recent injuries could indicate they were going back to work/doing activities prior to being fully healed from previous injuries which made them more vulnerable to reinjury (Pitcher 2014). At Louisbourg, there was always a shortage of labourers with pay usually reflecting output, two related factors that likely drove instances of reinjury (Johnston 2001; Pitcher 2014). For example, documentation of road building at Louisbourg suggests some labourers were paid by how much they accomplished rather than an hourly or daily wage, urging individuals to work faster, which potentially increased the risk of injury (Pitcher 2014). The wages for construction work at Louisbourg were high in comparison to those in France, which may have incentivised labourers to work despite injuries (Johnston 2001). Most telling is that for soldiers, pension requests were only made once serious injury occurred where an individual was crippled/maimed to the point they could no longer work (Pitcher 2014). Documentation of minor injuries are not abundant within the historical record at Louisbourg, which could also indicate individuals continued to work without reporting their injuries or receiving treatment, further increasing the risk of reinjury (Marasco et al. 2015; Pitcher 2014).

5.3. Fracture Location on the Skeleton

As discussed in Chapter 4, section 4.4.1, fractures were found in most regions of the skeleton, including the cranium, ribs, vertebrae, upper limb, and lower limb. Statistically, there was no difference between fracture presence when comparing the left and right side. However, the left side of the body displayed significantly more fractures than the center of the body. Additionally, the right side of the body showed an almost significant difference ($p=0.073$) when compared to the center, indicating more fractures to the right side. In general, fractures are more commonly found on elements that can be sided (i.e., limbs, ribs, etc.), rather than those in the center of the body (i.e., vertebrae) (Brickley 2006; Mant 2016; Wedel and Galloway 2014) possibly due to the protective function served by the bones of the thorax (Cappello and De Troyer 2002; Holcombe and Derstine 2022). For example, the biomechanical aspects of the spine make it resistant to fracturing, with intervertebral disks designed to absorb and disperse energy from impact, and vertebral bodies that are reinforced by trabecular bone and pedicles (Adams and Dolan 2011; Currey 2003). Therefore, this difference is likely driven more by bone biomechanics rather than fracture risk differences within these specific regions of the skeleton. However, this is not to say that bones such as the ribs are easily fractured. While rib injuries are the most common injury within this sample (22%, $n=7/32$), they require a high level of force to fracture which may speak to the severity of injuries observed (Easter 2001; Wedel and Galloway 2014).

5.4 Fracture Causes, Physical Impact, and Level of Healing

Fractures are most likely the result of direct or indirect blunt force trauma but can also be caused by certain pathological conditions (e.g., osteoporosis, tuberculosis, etc.) and/or excess biomechanical stress (see Brickley 2006; Dirkmaat 2012; Gupta and Zioupos 2008; Judd and Roberts 1998; Lovell 1997; Lundon et al. 1999; Matos 2009; Oryan et al. 2015; Sànchez-Riera et al. 2010; Wedel and Galloway 2014). All fractures reported here were the result of direct or indirect blunt force trauma rather than pathology, as common disease conditions associated with fractures (i.e., metabolic, cancerous, infectious) were absent from the individuals assessed (Scott 2017; Scott 2018; Scott 2019; Scott et al. 2023). While it is possible that some of these conditions were present and had yet to manifest on the skeletal elements of the individuals assessed (Judd and Roberts 1998; Matos 2009; Sànchez-Riera et al. 2010; Scott et al. 2023; Turner 2002), the early stages of any such diseases likely did not negatively impact the structural integrity of the skeleton enough to cause fractures. Further, the fractures in this study are unlikely to be due to excess biomechanical stress based on their appearance and location (Ficek et al. 2020; Wedel and Galloway 2014). Stress fractures mainly occur in weight bearing elements (i.e., lower limb, vertebral bodies) and are typically small fractures that are difficult to identify both macroscopically and through microscopic imaging (Ficek et al. 2020; Kiel and Kaiser 2024). Based on the location and clear appearance of fractures in this sample, they are likely not due to excess biomechanical stress.

The macroscopic assessment of fractures revealed that most fractures were well-healed or in some stage of healing, with only 8% (n=4/52) showing no evidence of

healing. While these data suggests that most individuals were able to survive and heal from their injuries, it is not wholly representative of the effect fractures may have had on quality of life and the ability to participate in everyday society. Historical accounts and surgeon reports indicate that broken bones were some of the most common injuries at Louisbourg, but the impacts of these fractures are rarely discussed (Hoad 1972; Johnston 1981). Therefore, considering fractures within this sample alongside historical accounts and clinical data will better reflect the stories of these 18th century individuals.

5.4.1 Ribs and Vertebrae

Injuries to the ribs and vertebrae were both identified within the sample. Fractures to the transverse processes of the first to third lumbar vertebrae were found in one individual (Burial 21/2017), alongside rib and metacarpal fractures that likely represent trauma from heavy occupational labour (Scott et al. 2019). According to Wedel and Galloway (2014), fractures to the lumbar vertebrae are typically due to falls or motor vehicle accidents in modern contexts, and usually found alongside other injuries. Firsthand historical data from Louisbourg and literature from New England suggest that individuals falling from a great height was not uncommon, especially at the Fortress where individuals worked on the fortification walls surrounding the site (Geake 2023; Johnston 2001; McLennan 1918: Anonymous 1745). Due to the lack of skilled tradespeople, the soldiers at Louisbourg took on most of the fortification maintenance, which was an extremely arduous occupation, made even more precarious due to the instability of the soil at the site that often led to collapse during construction (Greer 1997; Pitcher 2014; Scott at al. 2019). One account mentions how an individual fell “off

the wall which Doubtless Broke Some of his Inwards" which was due to "His Being in Drink" (Anonymous 1745: pp. 37). Tireless labour, unfavourable weather conditions, and overall poor health led to soldiers to consume excessive amounts of alcohol (Johnston 2002; Pitcher 2014). Inebriation coupled with dangerous working conditions, may have led to fractures of the vertebrae due to blunt force injury.

Rib fractures comprise the majority of injuries observed within the Fortress of Louisbourg skeletal sample. Fractures were noted from the 2nd to the 11th ribs across seven individuals, with most fractures on the mid-thoracic and lower ribs (4th to 11th ribs). As the fractures were mainly located on the rib angle or midshaft, blunt force impact to the chest was the likely cause (Brickley 2006; Wedel and Galloway 2014). While most fracture types in the ribs were unobservable due to the presence of healing, both oblique fractures (n=4) and transverse fractures (n=2) were observed. Studies of modern rib fractures compiled by Wedel and Galloway (2014) suggest that transverse fractures (i.e., fractures perpendicular to the bone) typically occur as a result of direct impact to the chest, while oblique fractures (i.e., diagonal fractures) more commonly occur due to falls from a height or motor vehicle accidents. Injuries to the lower ribs (~10th-12th ribs) may also be due to rotational injuries, such as falls during occupational tasks (Brickley 2006; Mant 2016; Wedel and Galloway 2014). While military life and fortification maintenance posed significant threats to the soldier population, civilians were also at significant risk of workplace injury. Occupations were arduous throughout the 18th century world, with little concern for safe working conditions (Greer 1997; Johnson 2017; Johnston 2001; Mant et al. 2020; Miller 2009; Pitcher 2014). Although there are significantly less historical records pertaining to the civilian workforce at Louisbourg, population reports indicate civilians typically had multiple jobs especially

when the colony was in its infancy (Schmeisser 1976). For example, some individuals were carpenters as well as tavern/innkeepers, which may have yielded similar fracture risks to soldiers working in construction (Schmeisser 1976). Additionally, with the lack of skilled tradespeople in the colony, individuals working multiple occupations likely did not have specialized training which could have resulted in an increased risk of injury (Al Mamlook et al. 2020; Pitcher 2014).

Rib fractures can also be sustained due to interpersonal violence (see Brickley and Smith 2006; Łukasik et al. 2019; Mant et al. 2020; Martin and Harrod 2015; Pankowská et al. 2019; Šlaus et al. 2012). While not exclusively the result of violence, injuries to the ribs have been linked to patterns of abuse and conflict (de la Cova 2012; Murphy et al. 2010; Shepherd et al. 1990; Tung 2007). Between cramped barracks and excessive alcohol consumption, brawls were common among the soldiers, which may have contributed to the high prevalence rib fractures, especially when coupled with metacarpal fractures (Pitcher 2014; Scott et al. 2019). For example, in 1744, a mutiny broke out during which the soldiers turned on the officers and threatened violence if their demands (i.e., an increase in firewood, rations, and a stop on wage deductions) were not met (Greer 1977). While the officers gave into the demands quickly to prevent violence in the town, the records from the day of the mutiny are far from complete (Greer 1977). This is one example of hostility and unrest within the garrison and the very real threat of violence which no doubt contributed to at least some of the fractures observed in this study.

While all the rib fractures within this sample show active to advanced stages of healing, many researchers have commented on the dangerous complications associated with rib fractures due to their close proximity to the vital organs, as well as prolonged

pain due to the inability to completely stabilize these types of fractures (Brickley 2006; Fabricant et al. 2013; Kara et al. 2003; Marasco et al. 2015; Sirmali et al. 2003; Ziegler and Agarwal 1994). Brickley (2006) summarized some of the main soft tissue complications including flail chest, pneumonia, pneumothorax, and hemothorax that can cause bleeding or fluid build-up on the pleural surface as well as damage to the lung tissue resulting in difficulty breathing. Rib fractures located near the top of the ribcage (ribs 1-3) are typically associated with risk of severe bleeding due to their proximity to primary vessels (Sirmali et al. 2003). Additionally, fractures to the mid/lower ribs (ribs 9-12), can result in lacerations to the spleen, kidneys, and/or liver (Sirmali et al 2003). The mortality rate of rib fractures in modern clinical settings ranges between 4-20%, where the chance of soft tissue complications increases with the number of fractured ribs (Sirmali et al 2003; Ziegler and Agarwal 1994). Within this skeletal sample, five individuals presented with two or more rib fractures highlighting the increased risk for soft tissue complications, especially Burials 77/2019 and 55L28E7 who had 13 and 9 rib fractures, respectively.

Despite the extensive healing observed, many clinical studies suggest the pain from broken ribs can last up to 24 months, hindering mobility and the ability to participate in everyday tasks (Fabricant et al. 2013; Kara et al. 2003; Kerr-Valentic et al. 2003; Marasco et al. 2015). Multiple studies have examined the quality of life in individuals with rib fractures at different intervals in their healing process where even a singular rib fracture caused patients significant pain up to 24 months post injury, affecting their ability to complete both occupational and everyday tasks (Fabricant et al. 2013; Marasco et al. 2015). Kerr-Valentic and colleagues (2003) also highlight the lengthy healing process associated with fractured ribs, stating individuals may have been

unable to work for upwards of 70 days. These examples demonstrate the immense physical impact rib fractures could have had on those living at Louisbourg. Prolonged pain from rib fractures may have prevented individuals from working, limiting their income, and/or increasing the risk of reinjury and further complications if they returned to work before healing was complete (Fabricant et al. 2013; Marasco et al. 2015; Pitcher 2014). In addition to pain caused from rib fractures, individuals are also at risk of lung-related illnesses (Kerr-Valentic et al. 2003; Sirmali et al. 2003). Partial immobility of the chest due to fracture pain limits an individual's ability to take a deep breath, which can result in a build-up of bacteria in the lung tissue and increases vulnerability to lung-related illnesses (Easter 2001; Marco et al. 2020; Wu et al. 2015). As Louisbourg was already a breeding ground for various pathogens due to unhygienic living conditions (Donovan 1982; Johnston 1981; McLennan 1918), it is likely that at least some of the individuals suffering from rib fractures were consequently affected by lung issues that further diminished their quality of life.

5.4.2 Lower Limb

Lower limb fractures within this sample represent key perimortem injuries that were likely life-threatening to the individuals who sustained them. Burial 85/2019 was a non-adult individual (approximately 12 years old) from the Rochefort Point cemetery who presented with a butterfly fracture to the left femur (see Figure 5.1), which is a subtype of a comminuted fracture typically seen in modern day pedestrian-motor vehicle accidents (Wedel and Galloway 2014). This specific type of fracture results from bending forces creating tension on one side of the bone and compression on the other,

leading the separation of the ends of the bone and displacement of a distinctive triangular piece of bone (Wedel and Galloway 2014). Fractures to the femur require high amounts of force and velocity due to the increased strength and density of the femur required to support obligate bipedalism (Arun and Jadhav 2016; van der Meulen et al. 2001). Additionally, non-adult bones are more resistant to fracturing due to their increased elasticity during development, allowing for more deformation before fracturing occurs (Forestier- Zhang and Bishop 2016; Lindman 2001; Öhman et al. 2011). Therefore, butterfly fractures in younger individuals are relatively rare and require a high energy mechanism acting on the bone (Tsai et al. 2022; Wedel and Galloway 2014). For example, Mant (2016) discusses historical accounts from 18th century England of pedestrians involved in accidents with horse drawn wagons/carts. In one account a cart ran over an individual's leg and caused the limb to break (see Mant 2016). Another mentions a large woolen sack flying off a wagon, which broke the femur of a pedestrian and severed the surrounding blood vessels leading to their death (see Mant 2016). While horse drawn vehicles generally travelled at a slow speed of about 3.5 miles per hour (5.6 kilometers per hour), if a horse became spooked or anxious speed could increase (Fox 1990; Morris 2007; Tarr and Mcshane 2008). Coupled with potentially heavy loads and a lack of pedestrian safety measures (i.e., crosswalks, stops signs, etc.) in the 18th century, cart/wagon-pedestrian collisions could have caused significant harm and injuries such as the femoral fracture observed in Burial85/2019 (see Ishaque and Noland 2006; Mant 2016; Morris 2007; Tarr and Mcshane 2008).

Figure 5.1: Butterfly fracture to the femur (red arrows) of Burial 85/2019 alongside the uninjured right limb for comparison. Note the proximal, lateral, and distal epiphyses are not shown

The butterfly fracture of Burial 85/2019, represents a key perimortem injury within this sample. The absence of healing in this fracture indicates it occurred at or around the time of death (Ribeiro et al. 2020; Scheirs et al. 2018). Comminuted injuries to the lower limb present many dangers including damage to surrounding vessels and nerves (Lovell 2016; McKay et al. 2001; Wedel and Galloway 2014). Comminuted fractures were often viewed as a death sentence in the 18th century due to their increased risk of blood loss (Kakria 2005). The butterfly fracture to the left femur of this individual is located on the proximal midshaft region, which is close to the femoral

artery and its associated branches (see Figure 5.2) (Cary 2005; Krishna et al. 2022; Moore et al. 2015). A complete rupture of the femoral artery can result in exsanguination in seconds to minutes if not treated (Blaivas et al. 2006). Additionally, when excavated, the left femur of Burial 85/2019 was not in alignment, further suggesting that the fracture was not reduced at the time of death.

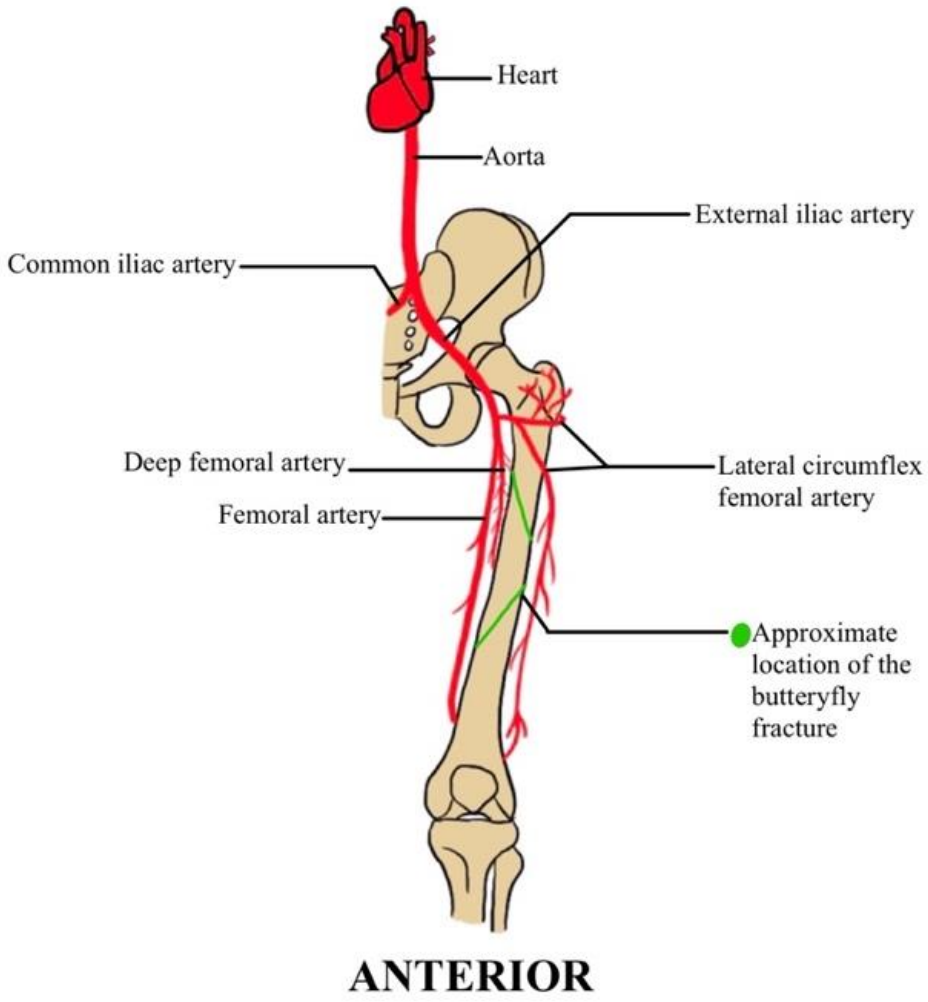


Figure 5.2: Location of femoral artery in relation to butterfly fracture on the left femur of Burial 85/2019

Similarly, Burial 84/2019 also had a major perimortem comminuted fracture to the left tibia and calcaneus, coupled with a transverse fracture of fibula, that likely occurred at the same time due to the similar lack of healing (see Figure 5.3). The absence of healing in each of these injuries indicates they occurred at or around the time of death for these individuals (Ribeiro et al. 2020; Scheirs et al. 2018). Like the butterfly fracture, a large amount of force would have been required to cause this type of injury, such as a high energy impact from a moving object or a fall from a great height (Tampe et al. 2018; Wennergren et al. 2018; Wedel and Galloway 2014). Another potential explanation may be falling from a horse. A firsthand historical account from Louisbourg mentions a man who "had fallen thro the Bridge with his horse" and "had Broke his leg" (Williams 1745, pp. 130). While the circumstances surrounding this injury are unclear, it is possible that both examples represent injuries related to large animals. A widescale study of modern equine-related injuries indicates that lower limb fractures are the second most common injury when being thrown from horseback (Young et al. 2015). An additional study by Carmichael and colleagues (2014) states that surgical intervention was most frequently required in cases of horseback riding injuries in the lower limb, which may indicate increased severity. According to a census conducted in 1752 near the height of Louisbourg's occupation, there was one horse for every 80 inhabitants, which may have presented at least some risks for equine-related injuries similar to those seen in Burial 84/2019 (Donovan 2006).

Figure 5.3: Comminuted fracture to the left tibia, fibula, and calcaneus (red arrows) of Burial 84/2019 alongside the uninjured right side for comparison

Similar to the femoral fracture and its risk to surrounding soft tissues, there is also a risk for severe hemorrhaging around the tibia due to its proximity to the popliteal artery, which can rupture during tibial plateau fractures like those observed in Burial 84/2019 (Liu et al. 2020). Branches of the popliteal artery travel down the lower limb between the tibia and fibula which may have also been at risk of rupture with this comminuted fracture (see Figure 5.4). Overall, both comminuted lower limb fractures in

Burial 85/2019 and Burial 84/2019 could have significantly contributed to cause of death based on their perimortem timing and potential artery rupture.

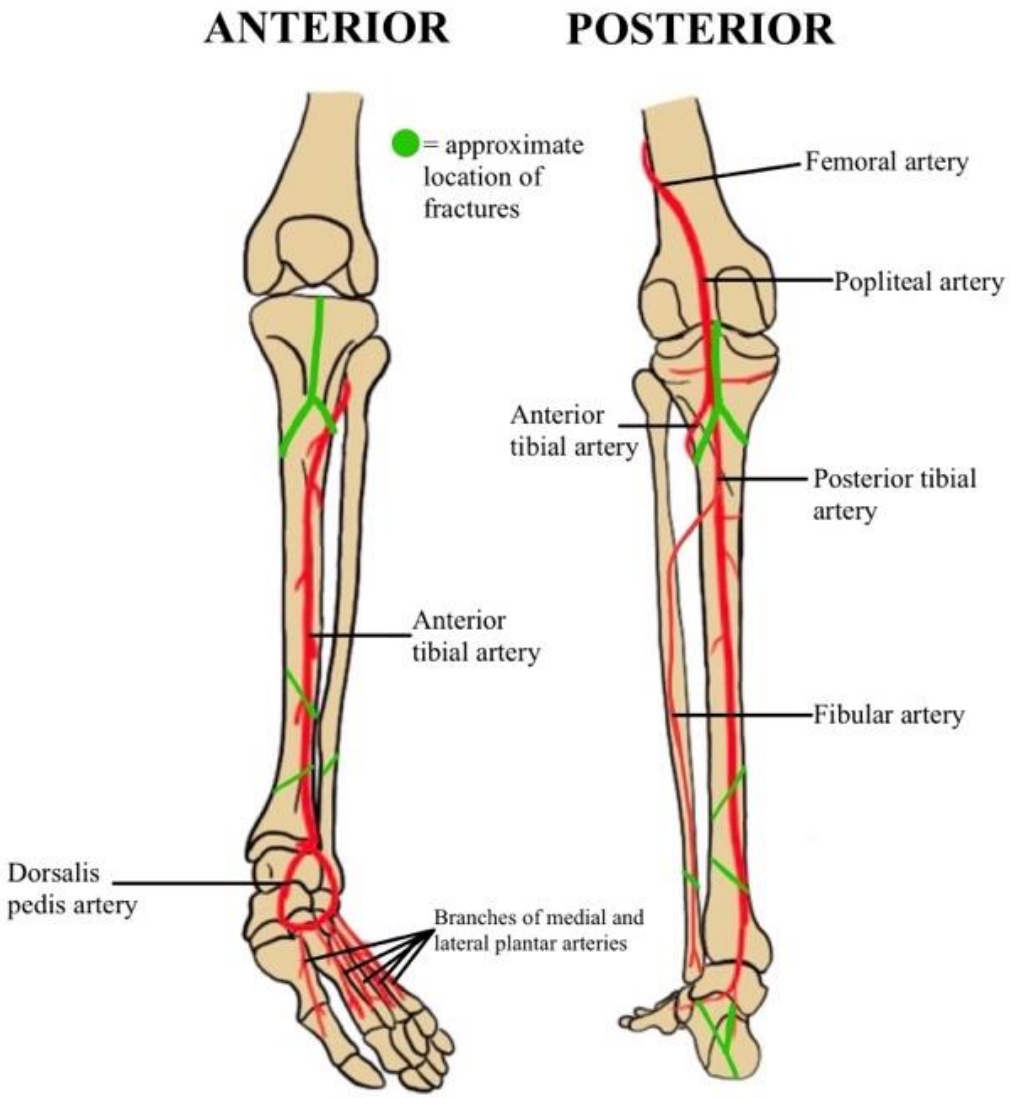


Figure 5.4: Location of the popliteal artery and its associated branches in relation to the comminuted fracture to the left lower limb of Burial 84/2019

5.4.3 Upper Limb

Fractures to the forearm (i.e., radius and ulna) can most often result from accidental injury (i.e., falling onto outstretched arm(s)), but can also indicate defensive injuries (see Judd 2008; Hermans et al. 2021; Hughston 1957; Lovell 1997; Pankowská

et al. 2019; Wedel and Galloway 2014). One isolated fracture to the midshaft of the left radius of Burial 19 from the Block 3 cemetery was identified (see Figure 5.5). Based on the level of displacement observed and the midshaft location of the fracture, it is more likely that this fracture is from a high energy direct impact rather than a fall (Putnam and Fisher 1993; Wedel and Galloway 2014). This type of injury is typically seen in motor vehicle collisions in modern populations, or industrial incidents, which may suggest that this fracture was work-related (Putnam and Fisher 1993; Wedel and Galloway 2014). In addition to the fracture risks associated with being a soldier at Louisbourg, many civilians were involved in the fishing industry, which places a lot of strain on the upper extremities (see Balcom 1995; Case et al. 2015; Grimsmo-Powney et al. 2010). According to Balcom (1995), fishing at the Fortress was done offshore on small and larger fishing vessels, as well as inshore through handlining (i.e., a line held in the hands with hooks on the end instead of a rod). Fractures to the upper extremity are common in modern day commercial fishing, typically from impacts attained through hauling and/or handling gear (i.e., fishing nets/cages) on the deck during poor weather (see Case et al. 2015). Poor weather proved dangerous for the fishermen at Louisbourg as well, with high winds and rain that likely made the conditions on deck slippery (Balcom 1995). Fishermen were urged to work through inclement weather to maximize their catch as the long winter season negatively impacted productivity of the fishing industry (Balcom 1995). Hazardous weather conditions and excess strain on the upper limb may have led to increased risk of upper limb fractures, such as those seen in Burial 19, through impacts from objects on board or falls (Balcom 1995; Case et al. 2015; Grimsmo-Powney et al. 2010). Similar to the soldiers, the fishermen were known to consume

excess amounts of alcohol, which may have also increased the risk of injury due to inebriation (see Pitcher 2014).

Figure 5.5: Isolated fracture to the left radius (red arrow) of Burial 19 from Block 3, with the uninjured right radius for comparison (photo by Kelsey E. Kane)

This historical record at Louisbourg highlights the physical impact of fractures to the upper limb, specifically the arm (Johnston 1981; Pitcher 2014). One account mentions a young soldier admitted to hospital for a broken arm, but he did not receive care for over 17 hours stating that his arm "had swollen to a size larger than his thigh" (Johnston 1981, pp. 7) which likely caused immense pain. Additionally, a lack of reduction of a fracture within the upper limb can result in limb shortening. For example, the radial shaft fracture observed in Burial 19 is approximately 20 mm shorter than the uninjured right radius suggesting initial fracture displacement and malalignment during healing (Boyd 2018; Ehlinger et al. 2020; Marsell and Einhorn 2011; Lovell 2016) (see Figure 5.5). This radial displacement may have impacted the extensor and flexor muscle of the forearm, as well as the median and/or radial nerve based on its anterior malalignment (Moore et al. 2015). Damage to these muscles and/or nerves could have

had direct impacts on this individual's ability to pronate/extend the forearm and flex the wrist and fingers (Moore et al. 2015). This limited mobility in the forearm may have affected this individual's ability to participate in everyday and/or occupational tasks, decreasing their overall quality of life.

Fractures to the metacarpals and phalanges have been linked to interpersonal violence and occupational and accidental injury (Brickley and Smith 2006; Butt 1962; Mant 2016; Wedel and Galloway 2014). Burials 21/2017 and 77/2019 from the Rochefort Point cemetery had fractures to the right first metacarpal which may indicate a life of heavy labour, as opposed to injuries of the 2nd, 3rd, and 5th metacarpals which are more diagnostic of interpersonal violence (Scott et al. 2019). The first metacarpal can be injured through striking an object with a closed fist or due to an object striking the metacarpal (Wedel and Galloway 2014). These types of injuries may have happened through occupation as construction and maintenance were constant during the 18th century due to the western push towards the industrial revolution and ongoing urbanization (see Fonzo et al. 2020; Johnston 1984; Mant 2020). Additionally, one compression fracture was observed on the right 5th proximal phalanx of Burial 28/2018, which is the most common location of phalangeal fractures in modern populations (Moura et al. 2022). Compression fractures typically occur due to a crushing force acting on the bone such as closing a door on the finger (Moura et al. 2022; Wedel and Galloway 2014). All fractures to the hand occurred on the right side, which may suggest handedness was a factor in these injuries. Occupations are typically performed using the dominant hand, which was the right side for approximately 90% of people in the 18th century (McManus et al. 2010). Left hand prejudice was widespread in the 18th century due to Catholic beliefs of its connection to the devil (Milenković et al. 2015). Therefore,

the location of injury and handedness suggest that these hand injuries are more likely due to occupational injury rather than interpersonal violence.

5.4.4 Cranium

Burial 19 from the Block 3 cemetery was the only individual to have a cranial fracture, with two instances of blunt force trauma to the left and right posterior parietal bones that resulted in radiating fractures from both impact points (see Figure 5.6). Cranial trauma is most often associated with interpersonal violence or accidental injury (Khudaveryan et al. 2021; Łukasik et al. 2019; Martin and Harrod 2015; Wedel and Galloway 2014). Due to the cylindrical shape of the cranial vault, radiating fractures stem from the point(s) of impact to disperse excess force across the bone, following the path of least resistance (Dirkmaat 2012; Kroman et al. 2011; Wedel and Galloway 2014). Fractures of the cranial vault require significant force and are usually due to a blow from an object, motor vehicle collisions, or a fall from a great height (Kranioti 2015; Mant 2016; Wedel and Galloway 2014).

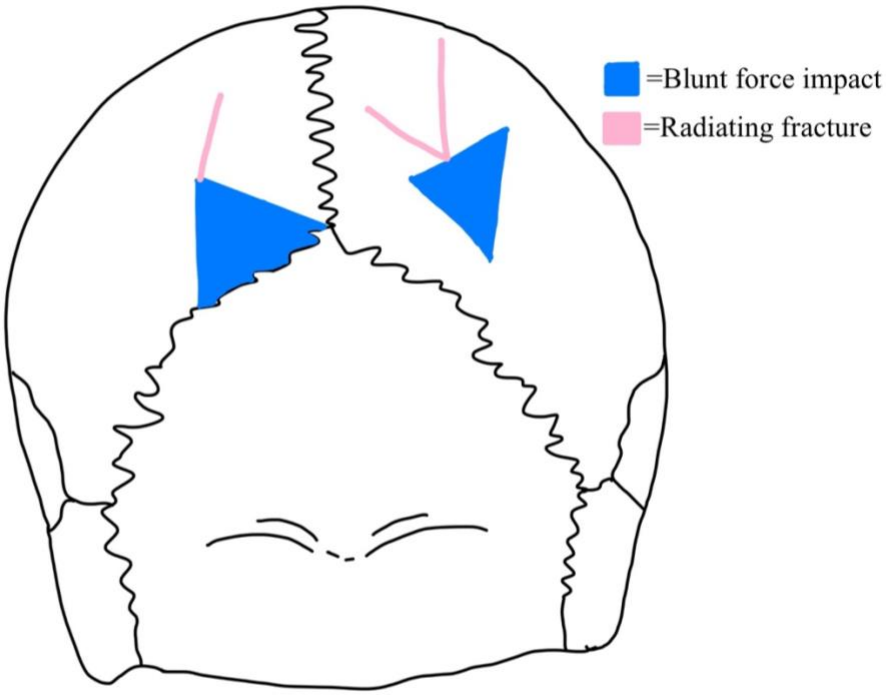


Figure 5.6: Blunt force trauma impact points and radiating fractures on the posterior parietals of Burial 19 from the Block 3 cemetery.

Unfortunately, due to taphonomic processes, the cranium of Burial 19 was not intact, which limits the interpretations of how these fractures occurred. There are two clear impact points, which may indicate blows to the back of the head with a blunt object, rather than a fall (Wedel and Galloway 2014). During the Block 3 period, construction of the town and fortifications began to flourish; however, there was a distinct lack of capable labourers to take on the job (McLennan 1918; Pitcher 2014). While the majority of the labour pool at Louisbourg came from the garrisoned soldiers, the main architect at the Fortress during this period expressed complaints about the recruits being too weak and young to complete the buildings as planned (see Pitcher 2014). In modern contexts, construction workers are at a high risk of head injury, with up to 39% of all fatal head injuries coming from the construction industry (Colantonio et

al. 2009; Tricco et al. 2009). Without modern day safety measures and personal protective equipment (i.e., hard hats), as well the lack of strong and capable labours, it is somewhat unsurprising to observe an injury as extreme as that seen in Burial 19 (Pitcher 2014; Tricco et al. 2009).

Fractures to the cranium often have a high mortality rate in both archaeological and clinical populations (Fujiwara et al. 2021; Łukasik et al. 2019). If individuals survive cranial injuries, there is also a significant risk of impaired cognitive function, an increased likelihood of concussion, and the development of other traumatic brain injuries (TBI), including hemorrhages (Fujiwara et al. 2021; Gurdjian 1993). In the case of Burial 19, there is some evidence of bony reaction along the margins of the fracture indicating this individual survived for some time after the initial injury, at least several days to weeks (see Figure 5.7) (Bigham-Sadegh and Oryan 2015; Marsell and Einhorn 2011). A TBI to the posterior portion of the cranium may cause significant impact to the parietal and potentially occipital lobes (Armstrong 2018; Rauchman et al. 2022; Sen 2017). Traumatic brain injury to the parietal lobe can have serious impacts on motor functions and vision, potentially affecting coordinated limb movements and diminishing spatial awareness (Moore et al. 2015; Rauchman et al. 2022). The occipital lobe holds the visual cortex, which regulates vision and visual processing (see Armstrong 2018; Moore et al. 2015; Sen 2017). When damaged, this area can cause an inability to recognize words and/or faces, or visually detect movement. It can also result in blindness (Rauchman et al. 2022; Sen 2017). Therefore, blunt force injuries to these areas, like those in Burial 19, may have had lasting effects that could have drastically decreased their quality of life and ability to perform everyday and/or occupational tasks related to coordination (Moore et al. 2015; Rauchman et al. 2022; Sen 2017).

Figure 5.7: Early signs of healing (red arrows) along the injury margins of the right side of the lambdoidal suture in Burial 19 from the Block 3 cemetery (photo by Kelsey E. Kane)

5.5 Medical Care in the 18th Century

While there is ample documentation of medical care and practices within this period, hospitals and surgeons were not always seen in a positive light (Johnston 1981; Mant 2020). In France, the Royal Academy of Surgery was not established until 1731 and as such, formal standardized training was sparse (Hoad 1972). Historical accounts in England also suggest that hospitals were sometimes seen as places where individuals go to die, rather than a place to be healed (Mant 2020). The state of medical practice at

Louisbourg was similar to those in England and France, but while establishing itself as a colony there was a frequent lack of supplies (e.g., medical instruments and tools) and personnel (Johnston 1981; Thomson 1996). The Brothers of Charity were the main medical practitioners during the early years at Louisbourg and were stated to frequently neglect overall patient well-being (Johnston 1981). While the arrival of surgeons during both French and New Englander occupation improved the overall medical care at the Fortress, the lack of supplies, unsanitary conditions, and lack of medical personnel in the colony may have led to higher mortality and morbidity rates (Hoad 1972; Johnson 1981; Thomson 1996).

Based on the historical record from Louisbourg and comparative 18th century studies, fractures were a relatively common occurrence (see Johnston 1981; Mant 2016; Mant 2020; Pitcher 2014). However, until the late 18th century the treatment of fractures was limited to external (i.e., non-operative) fixations, excluding amputation (Kakria 2005; Sachs et al. 1999). Without the aid of modern imaging technology such as x-ray, fractures were diagnosed based on criteria such as patient pain, macroscopic observations of the limb, swelling, loss of function, and visible broken bone fragments in cases of compound fractures (Mant 2020). Treatment mainly revolved around reduction of the limb in cases of displacement and splinting/immobilisation of the fracture so it could heal (Mant 2020; Porter 1993; Wagner and Slivko 1989). A historical account at Louisbourg of a male with a broken leg indicated that the limb was "Soon Reduced again, which Gives Reason to Hope He'll Soon get well" (Anonymous 1745), suggesting that fracture reduction, at least in some cases, was practiced at the Fortress. It is also important to note that amputation was a common practice in the 18th century, especially in the case of comminuted fractures (Hughes et al. 2024; Mant 2020; Porter

1993). Hughes and colleagues (2024) discuss one example of amputation from the Ste. Marie skeletal collection which may have been due to trauma such as a comminuted fracture. The widespread fracture healing observed within this study, indicates that individuals were able to survive their injuries. While it cannot be said for certain whether medical intervention occurred, it is clear treatment was available and/or individuals had a basic understanding of the importance of immobilizing a fracture when possible. As fractures were a relatively common injury, historical records indicate surgeons were trained on how to treat them which may also account for the high number of healed injuries within this sample (Mant 2020; Thomson 1996). The two perimortem fractures (Burials 84/2019 and 85/2019) observed were comminuted, which was not typically treatable outside of amputation in the 18th century and therefore, carried a high risk of mortality due to vascular complications (Blaivas et al. 2006; Liu et al. 2020; Porter 1993).

5.6 Microscopic Assessment of Rib Fracture Healing and Fracture Events

When assessing the level of fracture healing using microscopic methods, most rib fractures scored between 5 and 6 (n=22/31, 71%), which suggests that individuals were able to survive and heal from their injuries for a prolonged period (approximately several months to years). This advanced level of rib healing may be attributed to the location of these fractures and lack of specialized medical supplies required to treat rib fractures (Bemelman et al. 2015; Brickley 2006; Hoepelman et al. 2023; Marasco et al. 2015; Sirmali et al. 2003; Wagner and Slivko 1989). As discussed in section 5.4, there are considerable secondary risks associated with rib fractures (i.e., development of

pneumothorax, hemothorax, etc.); however, injuries to the ribs do typically heal provided there is no reinjury during the healing process (Brickley 2006; Marasco et al. 2015; Sirmali et al. 2003). The mortality rate of rib fractures, in the past and present is approximately 4-20% across studies, which indicated most individuals survive injuries to the ribs (Brickley 2006; Marasco et al. 2015; Sirmali et al. 2003; Ziegler and Agarwal 1994). Additionally, rib fractures without added soft tissue complications do not typically require specialized medical supplies for treatment and rehabilitation (Bemelman et al. 2015; Hoepelman et al. 2023; Wijffels et al. 2020). In the 18th century, treatment of rib fractures was mainly done through binding the chest using bandages and prescribing rest for the patient, which may explain why the majority of rib injuries were healed in this sample (Bemelman et al. 2015; Wagner and Slivko 1989).

Microscopic assessment of fracture healing also allowed for the analysis of multiple fracture events. It can be difficult to confidently identify fracture events macroscopically as the callus microstructure is not visible to the unaided eye. Due to this, integrating both microscopic and macroscopic observations can provide a more holistic understanding of fracture events. Within this study, two individuals had multiple fractures events (Burials 21/2017 and 77/2019). Burial 21/2017 had a total of five left rib fractures and two right rib fractures, with additional fractures to the right hand and lumbar vertebrae. A previous case study on this individual by Scott and colleagues (2019), macroscopically identified at least two separate fracture events in the ribs, with the left side demonstrating more advanced healing than the right. The micro-CT imaging from this study supported this finding. Burial 77/2019 also had at least two fracture events identified through micro-CT assessment. Specifically, the right 7th rib presented with two fractures (see Figure 5.8), that appeared macroscopically to have differing

levels of healing based on the reactive bone present; however, microscopic analysis confirmed the same stage of healing for both fractures (see Figure 5.9; Figure 5.10). Through reviewing these two examples, it is clear that micro-CT has the potential to be a useful tool for assessment of fracture events than macroscopic observation alone.

Figure 5.8: Fractures to the right 7th rib (red arrows) of Burial 77/2019 (photo by Kelsey E. Kane)

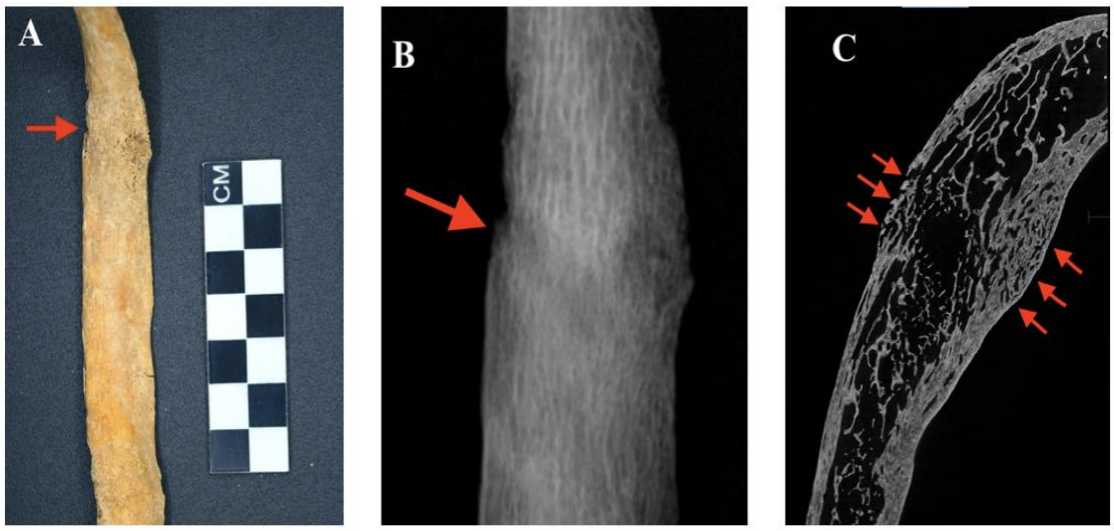


Figure 5.9: Right 7th rib fracture 1 (red arrows) of Burial 77/2019, A) macroscopic (photo by Kelsey E. Kane), B) radiograph, C) micro-CT

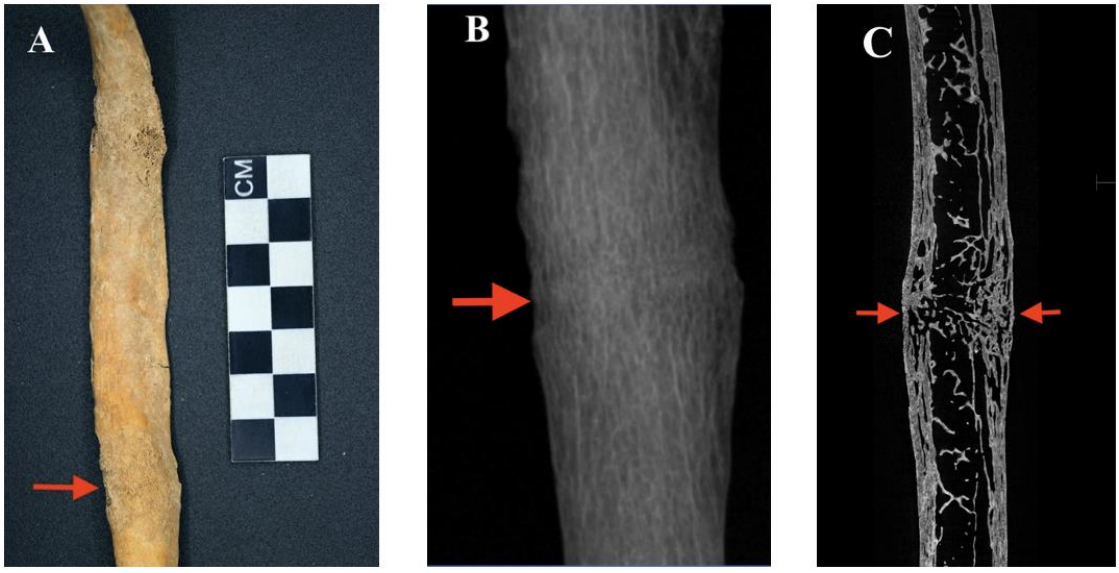


Figure 5.10: Right 7th rib fracture 2 (red arrows) of Burial 77/2019, A) macroscopic (photo by Kelsey E. Kane), B) radiograph, C) micro-CT

5.7 Study Limitations

Sample Size, Preservation, and Demography

The first limitation of this study was the relatively small sample size (n=32). While small sample sizes are not uncommon in bioarchaeological studies (see Henderson and Nikita 2016; Ramsier et al. 2021; Wissler et al. 2022), they can limit population-level interpretations as the data collected likely is not representative of the entire population. Additionally, a small sample size can potentially skew the results of statistical tests (Button et al. 2013; Hackshaw 2008; Wissler et al. 2022). While there was only one statistically significant result within this study, a larger sample size would increase statistical power and be able to detect if true significant differences were present within the sample, which could lead to alternative interpretations of the data. Statistical significance is not a requirement to draw meaningful connections from a data set; however, it is an important support for any interpretations being made. While the 70% preservation threshold used for this study was employed to maximize the accuracy of fracture prevalence, it did exclude those who had fractures but poor skeletal preservation which likely created further sample bias.

Another limitation of this study relates to the osteological paradox, which may limit interpretations of fractures at the Fortress. This concept acknowledges that the study of skeletal stress markers in the past, such as fractures, is challenging as only some lesions may manifest and be visible on the skeleton (DeWitte and Stojanowski 2015; Ortner 2003; Waldron 1994; Wood et al. 1992). Ortner (2003) states that about 15% of individuals in a population will show some type of skeletal pathology, which may not accurately represent the prevalence in the living population at the time. In the case of

fractures, the process of remodelling may cause past injuries to be undetectable through macroscopic or microscopic assessment, and as such the results of this study may not be representative of the actual prevalence of injury at the Fortress during its occupation.

Additionally, the demographics of this sample population limited any interpretations related to sex and age trends. Most individuals at Louisbourg were young adult males garrisoned at the Fortress (Johnson 1984) which are arguably represented, at least in part, within this sample (n=26 males, n=1 female, n=5 indeterminate sex). Moreover, the average age at death for this skeletal sample was 28.8 years. Therefore, any interpretations made largely reflect the young adult male experience at Louisbourg rather than the entire population.

Methodological Limitations of Microscopic Imaging

As discussed in Chapter 2, section 2.4.2 there are advantages and disadvantages to both x-ray and micro-CT imaging. The image capture for radiographs was easy and efficient as it took less than one hour to complete. Image rendering also took approximately two hours to complete the entire sample. While the images produced allowed for visualization of the internal structure of the fracture callus, the clarity and level of detail was lower than micro-CT which limited the interpretation that could be made based on radiographs alone. Specifically, the differences in density were relatively clear, but the callus microstructure could not be clearly visualized. In contrast, micro-CT images demonstrated a high level of clarity and detail that allowed for the visualization of differing densities and the callus microstructure to clearly differentiate between woven and lamellar bone. The ability to visualize these differences allowed for a more accurate interpretation of the stage of fracture healing (Viero et al. 2021; Viero et al.

2022). The 3D model is also beneficial in studies where the skeletal collection is not always available for long-term analysis. Despite the obvious benefits to using micro-CT in fracture research, the image capture and render is longer and more costly than x-ray. Image capture took approximately 32 hours between setup, image capture, and initial rendering, followed by approximately 20 hours of image rendering for the entire sample. Image rendering of micro-CT images also use software programs that have specific technology requirements that not all researchers may have access to. Mounting the rib bones for each scan also posed a challenge. While radiolucent foam was used to secure each sample, movement during the samples caused some image artifacts that interfered with the clarity. Additionally, when the fracture callus was located on the rib angle, image capture was difficult based on its relatively visibility to the sensor and the target. This resulted in the inability to score certain fracture calluses on micro-CT scans. In sum, the increased amount of detail on the micro-CT scans allowed for better differentiation between fracture healing stages; however, either visualization method can be used alongside traditional macroscopic assessment.

5.8 Conclusion

Overall, this chapter provided a discussion of the fracture data from the Fortress of Louisbourg skeletal collection. The prevalence of fractures at Louisbourg was considerably higher than comparative data from New France and England. Blunt force injury was the likely mechanism behind all the fractures observed in this sample, resulting from occupational and/or accidental injury, as well as interpersonal violence. The rich historical record at Louisbourg helps to contextualize the skeletal fractures

observed, highlighting the physical impact of these injuries and how they may have affected the ability to work and participate in everyday tasks. Fractures to the ribs were the most common fracture observed, likely due to dangerous working conditions and/or interpersonal violence. Perimortem fractures to the lower limb highlighted some of the dangers associated with skeletal trauma, especially in relation to surrounding soft tissues. Finally, microscopic analysis of healing can aid in the understanding of fracture events, beyond just macroscopic assessment. The culmination of these macroscopic and microscopic findings, as well as historical and clinical contexts have provided a robust understanding of fractures at the 18th century Fortress of Louisbourg.

CHAPTER 6 - Conclusion

6.1 Introduction

The study of fractures in bioarchaeology has contributed to the understanding of past populations, allowing for the exploration of many facets of the lived experience from medical care to occupation (Dittmar et al. 2021; Grauer and Roberts 1996; Judd and Roberts 1999; Lovell and Grauer 2019; Martin and Harrod 2015; Matos 2009; Milner et al. 2015; Šlaus et al. 2012; Wakely 1996). This thesis produced robust macroscopic data about the prevalence of fractures at the 18th century Fortress of Louisbourg, which provides another avenue to understand the potential physical impacts of this type of trauma on the individuals who sustained them. Using microscopic imaging, this thesis also presented a new avenue of research into fracture healing in past populations. Overall, the combination of macroscopic and microscopic methods provides an opportunity for in-depth analysis of fractures at an important National Historical Site of Canada.

6.2 Revisiting the Research Questions and Expected Results

1. What is the prevalence of skeletal fractures at the Fortress of Louisbourg, and does this differ across subsamples?

The overall fracture prevalence in this sample was 37.5% (n=12/32), which was slightly higher than comparative populations from 18th century New France and London, England (Danforth et al. 2013; Funkhouser 2014; Scott et al. 2020; Mant 2016). Of the 12 individuals with fractures, 58% (n=7/12) had more than one fracture present. Due to

the advanced stage of healing in many fractures, it cannot be determined if all fractures in this sample occurred at the Fortress; however, the slightly higher prevalence may speak to the increased fracture risks at Louisbourg due to factors such as occupational hazards especially in combination with alcohol consumption (Johnston 1981; Johnston 1984; Pitcher 2014). Between the three subsamples there are slight differences in the overall fracture prevalence, with Block 3 (40%, n=2/5) and Ste. Marie (40%, n=2/5) being higher than Rochefort Point (36%, n=8/22), but was not statistically supported. The earliest settlers at Louisbourg from the Block 3 subsample faced unique challenges which would have diminished overtime as the population and workforce at Louisbourg grew, which may explain this observed pattern. Similarly, the individuals from the Ste. Marie subsample faced many risk factors associated with the siege as well as factors associated with rebuilding the Fortress during the harsh winter months with insufficient supplies (Dunham 2017; Johnston 2013), very similar to what would have been experienced by the Block 3 individuals.

2. Does the type and severity of fractures differ within and between subsamples?

Due to the advanced level of healing present in most fractures, fracture type could only be determined for 31% of the total fractures (n=16/52). Antemortem fractures were most common, with only two individuals from the Rochefort Point subsample showing evidence of perimortem fractures. In terms of fracture severity, the two perimortem injuries likely contributed to the overall cause of death due to possible soft tissue involvement, whereas the antemortem fractures were more difficult to assess in terms of severity due to their advanced stage of healing. This contradicts the expected

the results, as the majority of severe perimortem injuries were observed in the Rochefort Point subsample. This may relate to differences in fracture risk that came with the growing population such as the increase in taverns and alcohol consumption, as well as the potential for equine-related injuries. Additionally, while medical care was more established towards the end of Louisbourg's occupation, comminuted fractures such as those in Burials 84/2019 and 85/2019 were often untreatable outside of amputation (Blaivas et al. 2006; Liu et al. 2020; Porter 1993), which may explain why these injuries were unable to heal.

3. Can micro-CT technology be used to assess fracture healing in bioarchaeological contexts?

Micro-CT imaging was able to capture the internal callus structure of fractured ribs, which allowed for an assessment of fracture healing and multiple fracture events. The high fracture healing scores assigned to many ribs suggests that individuals were able to survive from their injures for a prolonged period which may be attributed to the location of injury and lack of specialized medical supplies required to treat rib fractures. Multiple fracture events were also assessed using micro-CT images, which is useful in corroborating or providing alternative interpretations of macroscopic observations. The advanced degree of detail present on the micro-CT images has the potential to be beneficial to future studies of fractures in bioarchaeology. There were several challenges related to micro-CT imaging including image artifacts, visualization of fractures on the rib angle, and time required for each micro-CT image. Despite these challenges, the

increased level of detail in micro-CT images in comparison to radiographs, contributed valuable information to this study.

4. What is the physical impact of these fractures on the lived experience (e.g., mobility, reinjury, occupation, etc.)?

The physical impact of fractures within this sample was explored using a combination of historical, clinical, and bioarchaeological data. Fractures were assessed to understand their impact on an individual's ability to participate in society and everyday tasks. For example, instances of perimortem comminuted fractures to the lower limb in two individuals from the Rochefort Point subsample may have contributed to their mortality as the immense forces required to cause these injuries likely damaged surrounding arteries possibly leading to exsanguination (Blaivas et al. 2006; Cary 2005; Krishna et al. 2022; Liu et al. 2020; Moore et al. 2015). Additionally, fractures to the ribs observed in all subsamples may have caused significant prolonged pain that could have limited mobility and the ability to participate in occupational tasks (Brickley 2006; Fabricant et al. 2013; Kara et al. 2003; Kerr-Valentic et al. 2003; Marasco et al. 2015). Based on the historical record from the 18th century, fractures were common injuries that were mainly treated by casting, or in some cases amputation (Johnston 1981; Mant 2016; Mant 2020; Pitcher 2014). The fracture to the radius of Burial 19 from the Block 3 subsample shows marked displacement and a lack of reduction which may speak to the limited medical care available during this occupation period, aligning with the expected results. Historical documentation from Louisbourg specifically, highlights the many fracture risks for soldiers and the multiple pension requests due to fractures sustained

while working on the fortifications. These few examples highlight the various physical impact fractures had on those living in 18th century Louisbourg (Pitcher 2014).

6.3 Future Research

There are several potential avenues for future research pertaining to fractures and the use of micro-CT to assess fracture healing. First, the integration of isotopic data to explore the geographic origins of the individuals in this sample could assist with fracture interpretation. Louisbourg went through many administrative changes during its occupation and had many seasonal visitors which may be represented in the skeletal population at this site. While historical documentation can provide an idea of who was buried in these distinct burial areas, isotopic data may help clarify this. The benefit is that understanding where individuals grew up and spent the majority of their lives would help inform their specific fracture risks and/or causes.

Second, the investigation of burial practices and grave goods could aid in the study of disability at Louisbourg. While many of the burials display similar mortuary treatments and burial locations, deviations in these patterns, coupled with the presence of physical trauma may be used to bridge the gap between physical impairment and social disability. Through the on-going excavations at Rochefort Point, new burial patterns and grave goods may emerge that could speak to disability and how physical impairments or social stigmas around physical impairments may have impacted the lived experience. Continued exploration of historical documentation pertaining to disability should also be explored at Louisbourg, as well as in other contemporary populations in New France, England, and France to fully explore the relationship between fractures and

disability and how that can be assessed and studied in bioarchaeological research. In addition to disability, the study of fractures could be used to incorporate anthropology of care paradigms to understand fracture treatment and kinship bonds at the Fortress.

Future research into microscopic method standardization for fracture healing stages and image capture is warranted. Microscopic assessment was primarily used to differentiate fracture events within this study, which if used on a wider range of injuries and individuals may allow for a better understanding of the lived experience and the physical impact of fractures in bioarchaeology. Additionally, growing research into micro-CT suggests determining time since injury may be possible, which provide a more specific timeline of fracture healing that can aid in interpretations of past injuries (Viero et al. 2022). There are currently no standardized microscopic stages of fracture healing within the literature, which makes assessment and comparisons across populations challenging. While studies in forensic anthropology are working to refine the use of micro-CT to assess fracture healing/time since injury, specific standards related to bioarchaeological samples should be developed to account for preservation differences in forensic versus bioarchaeological samples. Additionally, image capture standards for both micro-CT and x-rays should be established to allow for proper comparisons across studies. While there are many studies that use microscopic imaging (e.g., Dittmar et al. 2021; Djurić et al. 2006; Grauer and Roberts 1996; Judd and Roberts 1998; Judd and Roberts 1999; Matos 2009; Šlaus et al. 2012), there are currently no best practices when imaging a fracture callus outside of clinical studies which may not be applicable due to the lack of soft tissue in bioarchaeological samples.

6.4 Research Contributions

This research contributes broadly to the study of skeletal trauma, specifically fractures in bioarchaeology. The fracture data generated by this project can be used comparatively to explore fracture prevalence and causes across other 18th century populations and specifically provides further details about life at Louisbourg. Additionally, this research is the first of its kind to use micro-CT to evaluate fracture healing within a bioarchaeological context, adding to the growing literature in related fields surrounding microscopic techniques to examine fractures. The use of micro-CT to examine fracture healing is still a relatively novel technique within the field of anthropology (e.g., Viero et al. 2021; Viero et al. 2022), but with continued research, it presents a valuable tool to examine fracture healing and traumatic events. Overall, this research highlights the fracture trauma present in 18th century Louisbourg and its potential impact on those who endured these injuries.

BIBLIOGRAPHY

Abrahamyan, M. (2017). On the Physics of the Bone Fracture. International Journal of Ortopeady and Traumotology, 2, 1–4. https://doi.org/10.11648/j.ijot.20170201.11.

Adams, M. A., & Dolan, P. (2011). Biomechanics of vertebral compression fractures and clinical application. Archives of Orthopaedic and Trauma Surgery, 131(12), 1703–1710. https://doi.org/10.1007/s00402-011-1355-9.

Agarwal, S. C. (2016). Bone morphologies and histories: Life course approaches in bioarchaeology. American Journal of Biological Anthropology, 159(S61), 130–149. https://doi.org/10.1002/ajpa.22905.

Agnew, A. M., & Justus, H. M. (2014). Preliminary Investigations of The Bioarchaeology of Medieval Giecz (XI-XII C.): Examples of Trauma and Stress. Anthropological Review, 77(2), 189–203. https://doi.org/10.2478/anre-2014-0015.

Agnew, A. M., Betsinger, T. K., & Justus, H. M. (2015). Post-Cranial Traumatic Injury Patterns in Two Medieval Polish Populations: The Effects of Lifestyle Differences. PLOS ONE, 10(6), e0129458. https://doi.org/10.1371/journal.pone.0129458.

Al-Ayyoub, M., & Al-Zghool, D. (2013). Determining the Type of Long Bone Fractures in X-Ray Images. WSEAS Transactions on Information Science and Applications, 8 (10), 261–270.

Al Mamlook, R., Bzizi, M., Alkasasbeh, M., Ali, T., & Elmagre, E. (2020). Factors Affecting Labor Productivity in the Construction Industry. 2, 24–30. https://doi.org/10.11648/j.1jese.20200402.13

Allen, M. R., & Burr, D. B. (2014). Chapter 4 - Bone Modeling and Remodeling. Basic and Applied Bone Biology. D. B. Burr & M. R. Allen, editors. Academic Press: San Diego. Pp. 75–90.

AlQahtani SJ, Hector MP, Liversidge HM. (2010). Brief communication: The London atlas of human tooth development and eruption. American Journal of Biological Anthropology, 142 (3):481-490.

Anonymous. (1745). First journal. In: Louisbourg journals 1745, De Forest, L.E., editor. The Society of Colonial Wars in the State of New York: New York. Pp. 1 –54.

Armstrong, R. A. (2018). Visual problems associated with traumatic brain injury. Clinical and Experimental Optometry, 101(6), 716–726. https://doi.org/10.1111/cxo.12670.

Arun, K. V., & Jadhav, K. V. (2016). Behaviour of Human Femur Bone Under Bending and Impact Loads. European Journal of Clinical and Biomedical Sciences, 2 (2): 6–13. http://doi.org/10.11648/j.ejcbs.20160202.1.

Balcom, B. A. (1995). The Cod Fishery of Isle Royale, 1713-58. In: Aspects of Louisbourg: Essays on the history of an eighteenth-century French community in North America. University College of Cape Breton Press/Louisbourg Institute, Sydney, NS.

Beaupied, H., Lespessailles, E., & Benhamou, C.-L. (2007). Evaluation of macrostructural bone biomechanics. Joint Bone Spine, 74(3), 233–239. https://doi.org/10.1016/j.jbspin.2007.01.019.

Bemelman, M., Poeze, M., Blokhuis, T. J., & Leenen, L. P. H. (2010). Historic overview of treatment techniques for rib fractures and flail chest. European Journal of Trauma and Emergency Surgery, 36(5), 407–415. https://doi.org/10.1007/s00068-010-0046-5.

Bigham-Sadegh, A., & Oryan, A. (2015). Basic concepts regarding fracture healing and the current options and future directions in managing bone fractures. International Wound Journal, 12(3), 238–247. https://doi.org/10.1111/iwj.12231.

Blaivas, M., Shiver, S., Lyon, M., & Adhikari, S. (2006). Control of hemorrhage in critical femoral or inguinal penetrating wounds—An ultrasound evaluation. Prehospital and Disaster Medicine, 21(6), 379–382. https://doi.org/10.1017/s1049023x00004076.

Blau, S. (2017). How traumatic: A review of the role of the forensic anthropologist in the examination and interpretation of skeletal trauma. Australian Journal of Forensic Sciences, 49(3), 261–280. https://doi.org/10.1080/00450618.2016.1153715.

Berthon, W., Tihanyi, B., Pálfi, G., Dutour, O., & Coqueugniot, H. (2016). Can Micro-CT and 3D Imaging Allow Differentiating the Main Aetiologies of Entheseal Changes? In: The Talking Dead: New Results from Central – and Eastern European Osteoarchaeology, Gál, S.S., editor. Mega Publishing House: Cluj-Napoca. Pp. 29-41.

Boerckel, J. D., Mason, D. E., McDermott, A. M., & Alsberg, E. (2014). Microcomputed tomography: Approaches and applications in bioengineering. Stem Cell Research & Therapy, 5(6), 144. https://doi.org/10.1186/scrt534.

Booth, T. J., Redfern, R. C., & Gowland, R. L. (2016). Immaculate conceptions: Micro-CT analysis of diagenesis in Romano-British infant skeletons. Journal of Archaeological Science, 74, 124–134. https://doi.org/10.1016/j.jas.2016.08.007.

Bouxsein, M. L., Boyd, S. K., Christiansen, B. A., Guldberg, R. E., Jepsen, K. J., & Müller, R. (2010). Guidelines for assessment of bone microstructure in rodents using micro–computed tomography. Journal of Bone and Mineral Research, 25(7), 1468–1486. https://doi.org/10.1002/jbmr.141.

Boyd, D. C. (2018). The anatomical basis for fracture repair: Recognition of the healing continuum and its forensic applications to investigate pediatric and elderly abuse. Forensic Anthropology Theoretical Framework and Scientific Basis. C.C. Boyd & D.C. Boyd, editors. John Wiley and Sons Ltd. Pp. 151-200.

Brickley, M. (2006). Rib fractures in the archaeological record: A useful source of sociocultural information? International Journal of Osteoarchaeology, 16(1), 61–75. https://doi.org/10.1002/oa.809.

Brickley, M., & Smith, M. (2006). Culturally Determined Patterns of Violence: Biological Anthropological Investigations at a Historic Urban Cemetery. American Anthropologist, 108(1), 163–177. https://doi.org/10.1525/aa.2006.108.1.163.

Brooks S. T. & Suchey J. M. (1990). Skeletal Age Determination Based on the Os Pubis: A Comparison of the Acsadi–Nemeskeri and Suchey–Brooks Methods. Human Evolution 5, 227–238.

Bruzek, J. (2002). A Method for Visual Determination of Sex, using the Human Hip Bone. American Journal of Physical Anthropology 117, 157–168.

Buikstra J, Ubelaker D. (1994). Standards for Data Collection from Human Skeletal Remains. Arkansas: Arkansas Archeological Survey Research Series.

Butt, W. (1962). Fractures of the hand. Canadian Medical Association Journal, 86, 731–735.

Button, K. S., Ioannidis, J. P. A., Mokrysz, C., Nosek, B. A., Flint, J., Robinson, E. S. J., & Munafò, M. R. (2013). Power failure: Why small sample size undermines the reliability of neuroscience. Nature Reviews Neuroscience, 14(5), 365–376. https://doi.org/10.1038/nrn3475.

Buzug, T. (2008). Fundamentals of X-ray Physics. Computed Tomography: From Photon Statistics to Modern Cone-Beam CT. Buzug, T., Ed. Springer: Berlin, Heidelberg. Pp. 15–73. https://doi.org/10.1007/978-3-540-39408-2_2.

Cagigao, E. T. (2009). Chapter 9 -Talking Bones: Bioarchaeological Analysis of Individuals from Palpa. New Technologies for Archaeology: Multidisciplinary Investigations in Palpa and Nasca, Peru. M. Reindel & G. A. Wagner, Eds. Springer: Berlin, Heidelberg. Pp. 141–158. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-540-87438-6_9.

Cappella, A., & Cattaneo, C. (2019). Exiting the limbo of perimortem trauma: A brief review of microscopic markers of hemorrhaging and early healing signs in bone. Forensic Science International, 302, 109856. https://doi.org/10.1016/j.forsciint.2019.06.014.

Cappello, M., & De Troyer, A. (2002). On the respiratory function of the ribs. Journal of Applied Physiology, 92(4), 1642–1646. https://doi.org/10.1152/japplphysiol.01053.2001.

Carmichael, S. P., Davenport, D. L., Kearney, P. A., & Bernard, A. C. (2014). On and Off the Horse: Mechanisms and Patterns of Injury in Mounted and Unmounted Equestrians. Injury, 45(9), 1479–1483. https://doi.org/10.1016/j.injury.2014.03.016.

Cary, D. V. (2005). Management of traumatic femoral shaft fractures. JAAPA: Official Journal of the American Academy of Physician Assistants, 18(2), 50–51. https://doi.org/10.1097/01720610-200502000-00008.

Case, S., Bovbjerg, V., Lucas, D., Syron, L., & Kincl, L. (2015). Reported traumatic injuries among West Coast Dungeness crab fishermen, 2002–2014. International Maritime Health, 66(4), 207–210. https://doi.org/10.5603/IMH.2015.0041.

Cattaneo, C., Andreola, S., Marinelli, E., Poppa, P., Porta, D., & Grandi, M. (2010). The Detection of Microscopic Markers of Hemorrhaging and Wound Age on Dry Bone: A Pilot Study. The American Journal of Forensic Medicine and Pathology, 31(1), 22. https://doi.org/10.1097/PAF.0b013e3181c15d74.

Chen, J.-H., Liu, C., You, L., & Simmons, C. A. (2010). Boning up on Wolff's Law: Mechanical regulation of the cells that make and maintain bone. Journal of Biomechanics, 43(1), 108–118. https://doi.org/10.1016/j.jbiomech.2009.09.016.

Claes, L., Recknagel, S., & Ignatius, A. (2012). Fracture healing under healthy and inflammatory conditions. Nature Reviews Rheumatology, 8(3), 133–143. https://doi.org/10.1038/nrrheum.2012.1.

Cohen Jr., M. M. (2006). The new bone biology: Pathologic, molecular, and clinical correlates. American Journal of Medical Genetics Part A, 140(23), 2646–2706. https://doi.org/10.1002/ajmg.a.31368.

Colantonio, A., McVittie, D., Lewko, J., & Yin, J. (2009). Traumatic brain injuries in the construction industry. Brain Injury, 23(11), 873–878. https://doi.org/10.1080/02699050903036033.

Conlogue, G. J., Nelson, A. J., & Lurie, A. G. (2020). Computed Tomography (CT), multi-detector computed Tomography (MDCT), micro-CT, and cone beam computed Tomography (CBCT). Advances in Paleoimaging: Applications for Paleoanthropology, Bioarchaeology, Forensics, and Cultural Artifacts. Conlogue, G. J., Nelson, A. J., & Lurie, A. G., editors. CRC Press: Abingdon. Pp. 111-178.

Curate, F., & Cunha, E. (2022). Rib fractures in the Coimbra Identified Skeletal Collection: Potential associations with biological sex, age-at-death and bone mineral density. Antropologia Portuguesa, (39), 7–26. https://doi.org/10.14195/2182-7982_39_1.

Currey, J. D. (2003). How Well Are Bones Designed to Resist Fracture? Journal of Bone and Mineral Research, 18(4), 591–598. https://doi.org/10.1359/jbmr.2003.18.4.591

Danforth, M. E., Cook, D. N., Funkhouser, J. L., Greer, M., Guzik, H., Harvey, A. R., Hester, B.T, Webster Jr., H. W., & Wise Jr. R. (2013). Bioarchaeological investigations of the French colonial cemetery at the Moran Site (22HR511), Harrison County, Mississippi. Biloxi: Mississippi Department of Marine Resources.

de la Cova, C. (2012). Patterns of trauma and violence in 19th-century-born African American and Euro-American females. International Journal of Paleopathology, 2(2), 61–68. https://doi.org/10.1016/j.ijpp.2012.09.009.

DeWitte, S. N., & Stojanowski, C. M. (2015). The Osteological Paradox 20 Years Later: Past Perspectives, Future Directions. Journal of Archaeological Research, 23(4), 397–450.

Dijkstra, S., Oudkerk, M., & Wiggers, T. (1997). Prediction of pathological subtrochanteric fractures due to metastatic lesions. Archives of Orthopaedic and Trauma Surgery, 116, 221–224. https://doi.org/10.1007/BF00393714.

Dirkmaat, D. (2012). A companion to forensic anthropology, Vol. 10. John Wiley & Sons.

Dittmar, J. M., Mitchell, P. D., Cessford, C., Inskip, S. A., & Robb, J. E. (2021). Medieval injuries: Skeletal trauma as an indicator of past living conditions and hazard risk in Cambridge, England. American Journal of Physical Anthropology, 175(3), 626–645. https://doi.org/10.1002/ajpa.24225.

Djurić, M. P., Roberts, C. A., Rakočević, Z. B., Djonić, D. D., & Lešić, A. R. (2006). Fractures in late medieval skeletal populations from Serbia. American Journal of Physical Anthropology, 130(2), 167–178. https://doi.org/10.1002/ajpa.20270.

Donovan, K. (1982). Communities and families: Family life and living conditions in eighteenth century Louisbourg. Material Culture Review/Revue de la Culture Matérielle, 15.

Donovan, K. (2006). Imposing discipline upon nature: Gardens, agriculture and animal husbandry in cape Breton, 1713–1758. Material Culture Review/Revue de la Culture Matérielle, 64.

Dunham, R. (2017). A Cultural Legacy under Threat: Managing Eroding Coastal Heritage at the Fortress of Louisbourg National Historic Site. Ocean Yearbook Online, 31(1), 27–54. https://doi.org/10.1163/22116001-03101003.

Easter, A. (2001). Management of patients with multiple rib fractures. American Journal of Critical Care, 10(5), 320–327.

Ehlinger, M., Favreau, H., Eichler, D., Adam, P., & Bonnomet, F. (2020). Early mechanical complications following fixation of proximal femur fractures: From prevention to treatment. Orthopaedics & Traumatology: Surgery & Research, 106(1, Supplement), S79–S87. https://doi.org/10.1016/j.otsr.2019.02.027.

Einhorn, T. A., & Gerstenfeld, L. C. (2015). Fracture healing: Mechanisms and interventions. Nature Reviews Rheumatology, 11(1), 45–54. https://doi.org/10.1038/nrrheum.2014.164.

Ellerbrok, B.A. (2014). An isotopic reconstruction of diet and origins in an 18th-century mass burial site at the Fortress of Louisbourg, Nova Scotia. Master's Thesis, Memorial University of Newfoundland, Newfoundland.

Fabricant, L., Ham, B., Mullins, R., & Mayberry, J. (2013). Prolonged pain and disability are common after rib fractures. The American Journal of Surgery, 205(5), 511–516. https://doi.org/10.1016/j.amjsurg.2012.12.007

Farr, J. N., Melton III, L. J., Achenbach, S. J., Atkinson, E. J., Khosla, S., & Amin, S. (2017). Fracture Incidence and Characteristics in Young Adults Aged 18 to 49 Years: A Population-Based Study. Journal of Bone and Mineral Research, 32(12), 2347–2354. https://doi.org/10.1002/jbmr.3228.

Ficek, K., Cyganik, P., Rajca, J., Racut, A., Kiełtyka, A., Grzywocz, J., & Hajduk, G. (2020). Stress fractures in uncommon location: Six case reports and review of the literature. World Journal of Clinical Cases, 8(18), 4135–4150. https://doi.org/10.12998/wjcc.v8.i18.4135.

Flohr, S., Brinker, U., Schramm, A., Kierdorf, U., Staude, A., Piek, J., Jantzen, D., Hauenstein, K., & Orschiedt, J. (2015). Flint arrowhead embedded in a human humerus from the Bronze Age site in the Tollense valley, Germany – A high-resolution micro-CT study to distinguish antemortem from perimortem projectile trauma to bone. International Journal of Paleopathology, 9, 76–81. https://doi.org/10.1016/j.ijpp.2015.02.004.

Florencio-Silva, R., Sasso, G. R. da S., Sasso-Cerri, E., Simões, M. J., & Cerri, P. S. (2015). Biology of Bone Tissue: Structure, Function, and Factors That Influence Bone Cells. BioMed Research International, 2015, e421746. https://doi.org/10.1155/2015/421746.

Fonzo, M., Scott, A. B., & Duffy, M. (2020). Eighteenth Century Urban Growth and Parasite Spread at the Fortress of Louisbourg, Nova Scotia, Canada. In: The Bioarchaeology of Urbanization: The Biological, Demographic, and Social Consequences of Living in Cities, T. K. Betsinger & S. N. DeWitte, editors. Cham: Springer International Publishing. Pp. 295–316.

Forestier-Zhang, L., & Bishop, N. (2016). Bone strength in children: Understanding basic bone biomechanics. Archives of Disease in Childhood. Education and Practice Edition, 101(1), 2–7. https://doi.org/10.1136/archdischild-2015-308597.

Fox, C. P. (1990). Working Horses: Looking Back 100 Years to America's Horse-drawn Days: with 300 Historic Photographs. Mischka Press/Heart Prairie.

Frankel, V. H., Kaplan, D. J., & Egol, K. A. (2016). Biomechanics of Fractures. Journal of Orthopaedic Trauma, 30, S1-S6. https://doi.org/10.1097/BOT.0000000000000579.

Fritz, J. M., & McDonald, J. R. (2008). Osteomyelitis: Approach to Diagnosis and Treatment. The Physician and Sportsmedicine. https://doi.org/10.3810/psm.2008.12.11.

Frost, H. M. (1990). Skeletal structural adaptations to mechanical usage (SATMU): 2. Redefining Wolff's Law: The remodeling problem. The Anatomical Record, *226*(4), 414–422. https://doi.org/10.1002/ar.1092260403.

Frost, H. M. (1994). Wolff's Law and bone's structural adaptations to mechanical usage: An overview for clinicians. *The Angle Orthodontist*, *64*(3), 175–188. https://doi.org/10.1043/0003-3219(1994)064<0175:WLABSA>2.0.CO;2.

Fujiwara, G., Okada, Y., Ishii, W., Iizuka, R., Murakami, M., Sakakibara, T., Yamaki, T, & Hashimoto, N. (2021). Association of skull fracture with in-hospital mortality in severe traumatic brain injury patients. The American Journal of Emergency Medicine, 46, 78–83. https://doi.org/10.1016/j.ajem.2021.03.020.

Funkhouser, J. L. (2014) "A Paleopathological Analysis of the Moran French Colonial. Master's thesis, University of Southern Mississippi: Hattiesburg, MS. https://aquila.usm.edu/masters_theses/8.

Geake, R. A. (2023). Death in Early New England: Rites, Rituals and Remembrance. Charleston, SC: The History Press.

Genovés, S. (1959). L'estimation des différences sexuelles dans l'os coxal: Différences m'triques et différences morphologiques (Estimating sexual differences in the os coxa: Metric differences and morphological differences). Bulletins et Mémoires de la Société d'Anthropologie de Paris, 10, 3–95.

Ghiasi, M. S., Chen, J., Vaziri, A., Rodriguez, E. K., & Nazarian, A. (2017). Bone fracture healing in mechanobiological modeling: A review of principles and methods. Bone Reports, 6, 87–100. https://doi.org/10.1016/j.bonr.2017.03.002.

Gilbert, S. F. (2000). Osteogenesis: The Development of Bones. Developmental Biology, 6th edition. Sinauer Associates: Sutherland.

Gilmour, R. J., Brickley, M. B., Jurriaans, E., & Prowse, T. L. (2019). Maintaining mobility after fracture: A biomechanical analysis of fracture consequences at the Roman Sites of Ancaster (UK) and Vagnari (Italy). International Journal of Paleopathology, 24, 119–129. https://doi.org/10.1016/j.ijpp.2018.09.002.

Gupta, H. S., & Zioupos, P. (2008). Fracture of bone tissue: The 'hows' and the 'whys.' Medical Engineering & Physics, 30(10), 1209–1226. https://doi.org/10.1016/j.medengphy.2008.09.007.

Gurdjian, E. S. (1933). STUDIES ON ACUTE CRANIAL AND INTRACRANIAL INJURIES. Annals of Surgery, 97(3), 327.

Grauer, A. L., & Roberts, C. A. (1996). Paleoepidemiology, healing, and possible treatment of trauma in the medieval cemetery population of St. Helen-on-the-Walls, York, England. American Journal of Biological Anthropology, 100(4), 531–544. https://doi.org/10.1002/(SICI)1096-8644(199608)100:4<531::AID-AJPA7>3.0.CO;2-T.

Greer, A. (1977). Mutiny at Louisbourg, December 1744. Social History, 10(20), 305–336.

Grimsmo-Powney, H., Harris, E. C., Reading, I., & Coggon, D. (2010). OCCUPATIONAL HEALTH NEEDS OF COMMERCIAL FISHERMEN IN SOUTH-WEST ENGLAND. Occupational Medicine (Oxford, England), 60(1), 49–53. https://doi.org/10.1093/occmed/kqp137.

Hackshaw, A. (2008). Small studies: Strengths and limitations. European Respiratory Journal, 32(5), 1141–1143. https://doi.org/10.1183/09031936.00136408.

Hadjidakis, D. J., & Androulakis, I. I. (2006). Bone Remodeling. Annals of the New York Academy of Sciences, 1092(1), 385–396. https://doi.org/10.1196/annals.1365.035.

Hart, N. H., Nimphius, S., Rantalainen, T., Ireland, A., Siafarikas, A., & Newton, R. U. (2017). Mechanical basis of bone strength: Influence of bone material, bone structure and muscle action. Journal of Musculoskeletal & Neuronal Interactions, 17(3), 114–139.

Hassett, B. R. (2018). Which Bone to Pick: Creation, Curation, and Dissemination of Online 3D Digital Bioarchaeological Data. Archaeologies, 14(2), 231–249. https://doi.org/10.1007/s11759-018-9344-z.

Henderson, C. Y., & Nikita, E. (2016). Accounting for multiple effects and the problem of small sample sizes in osteology: A case study focussing on entheseal changes. Archaeological and Anthropological Sciences, 8(4), 805–817. https://doi.org/10.1007/s12520-015-0256-1.

Hendrix, R.W. (2002). Fracture healing. Radiology of Skeletal Trauma, 3rd edition. Rogers L. F., editor Churchill Livingstone: Philadelphia, pp 203–230.

Hermans, K., Fransz, D., Walbeehm-Hol, L., Hustinx, P., & Staal, H. (2021). Is a Parry Fracture—An Isolated Fracture of the Ulnar Shaft—Associated with the Probability of Abuse in Children between 2 and 16 Years Old? Children, 8(8), 650. https://doi.org/10.3390/children8080650.

Hitchcock, T. (2023). A Population History of London. The Proceedings of the Old Bailey. https://www.oldbaileyonline.org/about/population-history-of-london. May 26, 2024

Hoad, L. (1972). Surgeons and surgery in the 18th century. Fortress of Louisbourg, National Historic Site, Parks Canada Report.

Hoepelman, R. J., Beeres, Frank. J. P., Beks, R. B., Sweet, A. A. R., Ijpma, F. F., Lansink, K. W. W., van Wageningen, B., Tromp, T. N., Link, B., van Veelen, N. M., Hoogendoorn, J.M., de Jong, M. B., van Baal, M. C. P., Leenen, L. P. H., Groenwold, R. H. H., & Houwert, R. M. (2023). Non-operative vs. operative treatment for multiple rib fractures after blunt thoracic trauma: A multicenter prospective cohort study. European Journal of Trauma and Emergency Surgery, 49(1), 461–471. https://doi.org/10.1007/s00068-022-02093-9.

Holcombe, S. A., & Derstine, B. A. (2022). Rib cortical bone thickness variation in adults by age and sex. Journal of Anatomy, 241(6), 1344–1356. https://doi.org/10.1111/joa.13751

Hufnagl, K. B. D. P. (2005). An Investigation of Time Since Injury: A Radiographic Study of Fracture Healing. Master's thesis, Louisiana State University and Agricultural & Mechanical College: Baton Rouge, Louisiana.

Hughes, N., Scott, A. B., & Pitcher, D. (2024). Surgery under siege: A case study of leg amputation in 18th century Louisbourg, Nova Scotia, Canada. International Journal of Paleopathology, 44, 112–118. https://doi.org/10.1016/j.ijpp.2024.01.002.

Hughston, J. C. (1957). Fractures of the forearm. Journal of Bone and Joint Surgery (American), 44, 1664-1667.

Ishaque M. M., & Noland, R. B. (2006). Making roads safe for pedestrians or keeping them out of the way? An historical perspective on pedestrian policies in Britain. The Journal of Transport History, 27(1), 115–137.

Jiang, Y., Zhao, J., Liao, E.-Y., Dai, R.-C., Wu, X.-P., & Genant, H. K. (2005). Application of micro-CT assessment of 3-D bone microstructure in preclinical and clinical studies. Journal of Bone and Mineral Metabolism, 23, 122–131.

Johnson, C. D. (2017). Daily Life in Colonial New England. Bloomsbury Publishing.

Johnston, A. J. B. (1981). The Frères de la Charité and the Louisbourg Hôpital du Roi. CCHA Study Session, 48. Pp. 5-25.

Johnston, A. J. B. (1984). Life and Religion at Louisbourg, 1713-1758. Montreal: McGill-Queen's University Press.

Johnston, A. J. B. (2001). Control and Order in French Colonial Louisbourg, 1713-1758. East Lansing: Michigan State University Press.

Johnston, A. J. B. (2002). Alcohol Consumption in Eighteenth-Century Louisbourg and the Vain Attempts to Control It. French Colonial History, 2(1), 61–76. https://doi.org/10.1353/fch.2011.0022.

Johnston, A.J.B., 2013. Louisbourg: past, present, future. Nimbus Publishing Limited, Halifax.

Jorge, L. S., Chueire, A. G., & Baptista Rossit, A. R. (2010). Osteomyelitis: A current challenge. The Brazilian Journal of Infectious Diseases, *14*(3), 310–315. https://doi.org/10.1016/S1413-8670(10)70063-5.

Joshi, D., & Singh, T. P. (2020). A survey of fracture detection techniques in bone X-ray images. Artificial Intelligence Review, 53(6), 4475–4517. https://doi.org/10.1007/s10462-019-09799-0.

Judd, M. A. (2008). The parry problem. Journal of Archaeological Science, 35(6), 1658–1666. https://doi.org/10.1016/j.jas.2007.11.005.

Judd, M. A., & Roberts, C. A. (1998). Fracture patterns at the Medieval Leper Hospital in Chichester. American Journal of Physical Anthropology, *105*(1), 43–55. https://doi.org/10.1002/(SICI)1096-8644(199801)105:1<43::AID-AJPA5>3.0.CO;2-E.

Judd, M. A., & Roberts, C. A. (1999). Fracture trauma in a medieval British farming village. American Journal of Biological Anthropology, 109(2), 229–243. https://doi.org/10.1002/(SICI)1096-8644(199906)109:2<229::AID-AJPA7>3.0.CO;2-Y.

Kakria, H. (2005). Evolution in Fracture Management. Medical Journal, Armed Forces India, 61(4), 311–312. https://doi.org/10.1016/S0377-1237(05)80051-6.

Kara, M., Dikmen, E., Erdal, H. H., Simsir, I., & Kara, S. A. (2003). Disclosure of unnoticed rib fractures with the use of ultrasonography in minor blunt chest trauma. *European Journal of Cardio-Thoracic Surgery*, 24(4), 608–613. https://doi.org/10.1016/S1010-7940(03)00383-X.

Kemp, W. L. (2016). Postmortem Change and its Effect on Evaluation of Fractures. Academic Forensic Pathology, 6(1), 28–44. https://doi.org/10.23907/2016.004.

Kerr-Valentic, M. A., Arthur, M., Mullins, R. J., Pearson, T. E., & Mayberry, J. C. (2003). Rib fracture pain and disability: can we do better? Journal of Trauma: Injury, Infection and Critical Care 54: 1058–1064.

Khudaverdyan, A. Yu., Hobosyan, S. G., & Saratikyan, A. A. (2021). Bioarchaeological Evidence for the Health Status of a Late Bronze and Early Iron Ages Bover Population (armenia). Anthropologie (1962), 59(1), 55–78.

Kiel, J., & Kaiser, K. (2024). Stress Reaction and Fractures. In: StatPearls. StatPearls Publishing: Treasure Island, FL.

Kranioti, E. F. (2015). Forensic investigation of cranial injuries due to blunt force trauma: Current best practice. Research and Reports in Forensic Medical Science, 5, 25–37. https://doi.org/10.2147/RRFMS.S70423.

Krishna, S. V., B., S., T.R, S., & Sumanahalli, C. H. (2022). Femoral Artery Injuries in Closed Femur Shaft Fractures: Case Report. *The Surgery Journal*, *8*(3), e219–e223. https://doi.org/10.1055/s-0042-1756206.

Kroman, A., Kress, T., & Porta, D. (2011). Fracture propagation in the human cranium: A re-testing of popular theories. Clinical Anatomy, 24(3), 309–318. https://doi.org/10.1002/ca.21129.

L'Abbé, E. N., Symes, S. A., Stull, K. E., Lacroix, M., & Pokines, J. T. (2021). Taphononmy and the Timing of Bone Fractures in Trauma Analysis. In: Pokines, J. T., L'Abbé, E. N., Symes, S. A., editors. Manual of Forensic Taphonomy, 2nd edition. CRC Press. p. 473-479.

Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. Biometrics, 33(1), 159–174.

Licata, M., Iorio, S., Benaglia, P., Tosi, A., Borgo, M., Armocida, G., Ronga, M., Ruspi, A., Verzeletti, A., & Rossetti, C. (2019). Biomechanical analysis of a femur fracture in osteoarchaeology: Reconstruction of pathomechanics, treatment and gait. Journal of Forensic and Legal Medicine, 61, 115–121. https://doi.org/10.1016/j.jflm.2018.11.009.

Lindaman, L. M. (2001). Bone Healing in Children. Clinics in Podiatric Medicine and Surgery, 18(1), 97–108. https://doi.org/10.1016/S0891-8422(23)01169-2.

Little, D. G., Ramachandran, M., & Schindeler, A. (2007). The anabolic and catabolic responses in bone repair. The Journal of Bone and Joint Surgery, 89(4), 425–433. https://doi.org/10.1302/0301-620X.89B4.18301.

Liu, Y.-W., Li, Y.-H., Yu, T., Yang, T., Li, Y., & Tan, L. (2020). Popliteal artery transection associated with a minimally displaced tibial plateau fracture: A case report and review of the literature. BMC Musculoskeletal Disorders, 21(1), 59. https://doi.org/10.1186/s12891-020-3089-8.

Love, J. C., & Wiersema, J. M. (2016). Skeletal Trauma: An Anthropological Review. Academic Forensic Pathology, 6(3), 463–477. https://doi.org/10.23907/2016.047.

Lovell, N. C. (1997). Trauma analysis in paleopathology. American Journal of Biological Anthropology, 104(S25), 139–170. https://doi.org/10.1002/(SICI)1096-8644(1997)25+<139::AID-AJPA6>3.0.CO;2-#.

Lovell, N. C. (2016). Tiptoeing through the rest of his life: A functional adaptation to a leg shortened by femoral neck fracture. International Journal of Paleopathology, 13, 91–95. https://doi.org/10.1016/j.ijpp.2016.03.001.

Lovell, N. C., & Grauer, A. L. (2019). Analysis and interpretation of trauma in skeletal remains. In M. A. Katzenberg & A. L. Grauer (Eds.), Biological anthropology of the human skeleton. John Wiley & Sons. pp. 335–383.

Lovejoy, C.O., Meindl R.S., Pryzbeck, T.R., Mensforth, R.P. (1985). Chronological Metamorphosis of the Auricular Surface of the Ilium: A New Method for the Determination of Age at Death. American Journal of Biological Anthropology. 68, 15–28.

Łukasik, S., Krenz-Niedbała, M., Zdanowicz, M., Różański, A., & Olszacki, T. (2019). Victims of a 17th century massacre in Central Europe: Perimortem trauma of castle defenders. International Journal of Osteoarchaeology, *29*(2), 281–293. https://doi.org/10.1002/oa.2737.

Lundon, K., Melcher, L., & Bray, K. (1999). Stress Fractures in Ballet: A Twenty-Five Year Review. Journal of Dance Medicine & Science, 3(3), 101–107.

Mandl, K., Carlson, K. S. D., Brönnimann, D., McCall, A., Grassberger, M., Teschler-Nicola, M., Weiss-Krejci, E., & Metscher, B. (2022). Substantiating microCT for diagnosing bioerosion in archaeological bone using a new Virtual Histological Index (VHI). Archaeological and Anthropological Sciences, 14(6), 104. https://doi.org/10.1007/s12520-022-01563-w.

Mant, M. (2016). Slips, trips, falls, and brawls: Fractures of the working poor in London during the long eighteenth century. Doctoral thesis, McMaster University: Hamilton, ON.

Mant, M. (2019). Time after time: Individuals with multiple fractures and injury recidivists in long eighteenth-century (c. 1666–1837) London. International Journal of Paleopathology, 24, 7–18. https://doi.org/10.1016/j.ijpp.2018.08.003.

Mant, M. (2020). 'A Little Time Woud Compleat the Cure': Broken Bones and Fracture Experiences of the Working Poor in London's General Hospitals During the Long Eighteenth Century. Social History of Medicine, 33(2), 438–462. https://doi.org/10.1093/shm/hky023.

Mant, M., de la Cova, C., & Brickley, M. B. (2020). Intersectionality and trauma analysis in bioarchaeology. American Journal of Physical Anthropology, 174(4), 583–594. https://doi.org/10.1002/ajpa.24226.

Marsell, R., & Einhorn, T. A. (2011). The biology of fracture healing. Injury, 42(6), 551–555. https://doi.org/10.1016/j.injury.2011.03.031.

Martin, D. L., & Harrod, R. P. (2015). Bioarchaeological contributions to the study of violence. American Journal of Biological Anthropology, 156(S59), 116–145. https://doi.org/10.1002/ajpa.22662.

Martz, H. E., Logan, C. M., Schneberk, D. J., & Shull, P. J. (2016). X-Ray Imaging: Fundamentals, Industrial Techniques and Applications. CRC Press: Boca Raton.

Marasco, S., Lee, G., Summerhayes, R., Fitzgerald, M., & Bailey, M. (2015). Quality of life after major trauma with multiple rib fractures. Injury, 46(1), 61–65. https://doi.org/10.1016/j.injury.2014.06.014

Marco, C. A., Sorensen, D., Hardman, C., Bowers, B., Holmes, J., & McCarthy, M. C. (2020). Risk factors for pneumonia following rib fractures. The American Journal of Emergency Medicine, 38(3), 610–612. https://doi.org/10.1016/j.ajem.2019.10.021.

Matos, V. (2009). Broken ribs: Paleopathological analysis of costal fractures in the human identified skeletal collection from the Museu Bocage, Lisbon, Portugal (late 19th to middle 20th centuries). American Journal of Physical Anthropology, 140(1), 25–38. https://doi.org/10.1002/ajpa.21032.

Matos, M. A., Lima, L. G., & de Oliveira, L. A. A. (2015). Predisposing factors for early infection in patients with open fractures and proposal for a risk score. Journal of Orthopaedics and Traumatology, 16(3), 195–201. https://doi.org/10.1007/s10195-015-0345-z.

McKay, S. D., MacDermid, J. C., Roth, J. H., & Richards, R. S. (2001). Assessment of complications of distal radius fractures and development of a complication checklist. The Journal of Hand Surgery, 26(5), 916–922. https://doi.org/10.1053/jhsu.2001.26662.

McLennan, J. S. (1918). Louisbourg, from its foundation to its fall, 1713-1758. London: Macmillan.

McManus, I. C., Moore, J., Freegard, M., & Rawles, R. (2010). Science in the Making: Right Hand, Left Hand. III: Estimating historical rates of left-handedness. Laterality, 15(1–2), 186–208. https://doi.org/10.1080/13576500802565313.

Meindl, R. S., & Lovejoy, C. O. (1989). Age Changes in the Pelvis: Implications for Paleodemography. In: Age Markers in the Human Skeleton, Mehmet Y. İşcan, Eds. Charles C. Thomas, Springfield, IL. Pp. 137–168.

Milenković, S., Belojević, G., Paunović, K., & Davidović, D. (2015). Historical aspects of left-handedness. History of Medicine, 782–785.

Miller, S. J. (2009). The Economy of France in the Eighteenth and Nineteenth Centuries: Market Opportunity and Labour Productivity in Languedoc. Rural History, 20(1), 1–30. https://doi.org/10.1017/S0956793308002562.

Milner, G.R. (1992). Determination of Skeletal Age and Sex: A Manual Prepared for the Dickson Mounds Reburial Team. Ms. On file, Dickson Munds Museum, Lewiston, Illinois.

Milner, G. R., Boldsen, J. L., Weise, S., Lauritsen, J. M., & Freund, U. H. (2015). Sex-related risks of trauma in medieval to early modern Denmark, and its relationship to change in interpersonal violence over time. International Journal of Paleopathology, 9, 59–68. https://doi.org/10.1016/j.ijpp.2015.02.002.

Mohamed, A. M. (2008). An Overview of Bone Cells and their Regulating Factors of Differentiation. The Malaysian Journal of Medical Sciences, 15(1), 4–12.

Molino, G., Montalbano, G., Pontremoli, C., Fiorilli, S., & Vitale-Brovarone, C. (2020). Imaging Techniques for the Assessment of the Bone Osteoporosis-Induced Variations with Particular Focus on Micro-CT Potential. Applied Sciences, 10(24), 8939. https://doi.org/10.3390/app10248939.

Moore, C. (1974). Report on cemetery sites. Fortress of Louisbourg, National Historic Site, Parks Canada Report.

Moore, K. L., Agur, A. M. R, & Dalley, A. F. (2015). Moore's Essential Clincal Anatomy, 6th edition. Wolters Kluwer.

Morris, E. (2007). From Horse Power to Horsepower. Access, 30, 2–9.

Moura, S. P., Meulendijks, M. Z., Veeramani, A., Szapary, H., Gomez-Eslava, B., Hoftiezer, Y. A. J., Chen, N. C., & Eberlin, K. R. (2022). Epidemiology and Fracture Patterns of Traumatic Phalangeal Fractures. *Plastic and Reconstructive Surgery – Global Open*, *10*(8), e4455. https://doi.org/10.1097/GOX.0000000000004455.

Murphy, M. S., Gaither, C., Goycochea, E., Verano, J. W., & Cock, G. (2010). Violence and weapon-related trauma at Puruchuco-Huaquerones, Peru. American Journal of Physical Anthropology, 142(4), 636–649. https://doi.org/10.1002/ajpa.21291

Murray, I. R., Foster, C. J., Eros, A., & Robinson, C. M. (2013). Risk Factors for Nonunion After Nonoperative Treatment of Displaced Midshaft Fractures of the Clavicle. Journal of Bone and Joint Surgery, 95(13), 1153. https://doi.org/10.2106/JBJS.K.01275.

Öhman, C., Baleani, M., Pani, C., Taddei, F., Alberghini, M., Viceconti, M., & Manfrini, M. (2011). Compressive behaviour of child and adult cortical bone. Bone, 49(4), 769–776. https://doi.org/10.1016/j.bone.2011.06.035.

Olsen, B. R., Reginato, A. M., & Wang, W. (2000). Bone Development. Annual Review of Cell and Developmental Biology, 16(1), 191–220. https://doi.org/10.1146/annurev.cellbio.16.1.191.

Ortner, D. (2003). Identification of Pathological Conditions in Human Skeletal Remains, 2nd edition. Academic Press.

Oryan, A., Monazzah, S., & Bigham-Sadegh, A. (2015). Bone Injury and Fracture Healing Biology. Biomedical and Environmental Sciences, 28(1), 57–71. https://doi.org/10.3967/bes2015.006.

Pankowská, A., Galeta, P., Uhlík Spěváčková, P., & Nováček, K. (2019). Violence in European medieval monasteries: Skeletal trauma in Teplá monastery (Czech Republic). International Journal of Osteoarchaeology, 29(6), 908–921. https://doi.org/10.1002/oa.2804.

Parish, J. (2007). Physical Anthropology report on the Rochefort Point rescue excavation 2007 – Phase 2. Fortress of Louisbourg, National Historic Site, Parks Canada Report.

Perry, M. A. (2007). Is bioarchaeology a handmaiden to history? Developing a historical bioarchaeology. *Journal of Anthropological Archaeology*, *26*(3), 486–515. https://doi.org/10.1016/j.jaa.2007.02.002.

Phenice, T. (1969). A Newly Developed Visual Method of Sexing in the Os Pubis. American Journal of Physical Anthropology, 30, 297–301.

Pitcher, D. (2014). Louisbourg's Labourer-Soldiers, 1720-1743 Labour and Empire Building in an Era of Peace. Master's thesis, Dalhousie University: Halifax, Nova Scotia.

Porter, R. (1993). Disease, medicine and society in England, 1550-1860, 2nd edition. MacMillan Press Limited: Cambridge, EN.

Provot, S., & Schipani, E. (2005). Molecular mechanisms of endochondral bone development. Biochemical and Biophysical Research Communications, 328(3), 658–665. https://doi.org/10.1016/j.bbrc.2004.11.068.

Putnam, M. D. and M. Fischer (1993). Forearm fractures. In: Fractures and Dislocations, R. B. Gustilo, R. F. Kyle, and D. C. Templeman, editors. Mosby Inc: St. Louis, MO. Pp. 499–552.

Raggatt, L. J., & Partridge, N. C. (2010). Cellular and Molecular Mechanisms of Bone Remodeling. Journal of Biological Chemistry, 285(33), 25103–25108. https://doi.org/10.1074/jbc.R109.041087.

Ramsier, M., Gruenthal-Rankin, A., Gaddis, K., & Koperkiewicz, A. (2021). Sample size and representational bias in bioarchaeology: A case study of stature estimation from medieval Prussia. International Journal of Osteoarchaeology, 31(4), 523–533. https://doi.org/10.1002/oa.2969.

Ratner, B. (2009). The correlation coefficient: Its values range between +1/−1, or do they? Journal of Targeting, Measurement and Analysis for Marketing, 17(2), 139–142. https://doi.org/10.1057/jt.2009.5.

Rauchman, S. H., Albert, J., Pinkhasov, A., & Reiss, A. B. (2022). Mild-to-Moderate Traumatic Brain Injury: A Review with Focus on the Visual System. Neurology International, 14(2), 453–470. https://doi.org/10.3390/neurolint14020038.

Ribeiro, P., Jordana, X., Scheirs, S., Ortega-Sánchez, M., Rodriguez-Baeza, A., McGlynn, H., & Galtés, I. (2020). Distinction between perimortem and postmortem fractures in human cranial bone. International Journal of Legal Medicine, *134*(5), 1765–1774. https://doi.org/10.1007/s00414-020-02356-3.

Roberts, C. A., & Manchester, K. (2007). The Archaeology of Disease, 3rd edition. Cornell University Press: New York.

Ross, A. H., & Juarez, C. A. (2016). Skeletal and radiological manifestations of child abuse: Implications for study in past populations. Clinical Anatomy, 29(7), 844–853. https://doi.org/10.1002/ca.22683.

Rowbotham, S. K., Blau, S., & Hislop-Jambrich, J. (2017). Recording skeletal completeness: A standardised approach. Forensic Science International, 275, 117–123. https://doi.org/10.1016/j.forsciint.2017.02.036

Ruff, C., Holt, B., & Trinkaus, E. (2006). Who's afraid of the big bad Wolff?: "Wolff's law" and bone functional adaptation. American Journal of Physical Anthropology, 129(4), 484–498. https://doi.org/10.1002/ajpa.20371.

Rühli, F. j., Kuhn, G., Evison, R., Müller, R., & Schultz, M. (2007). Diagnostic value of micro-CT in comparison with histology in the qualitative assessment of historical human skull bone pathologies. American Journal of Biological Anthropology, 133(4), 1099–1111. https://doi.org/10.1002/ajpa.20611.

Rule, J. (1992). Labour in a Changing Economy, 1700–1850. In: New Directions in Economic and Social History, Digby, A., Feinstein, C., & D. Jenkins. editors. Red Globe Press: London, EN. Pp. 83–96.

Sachs, M., Bojunga, J., Encke, A. (1999). Historical evolution of a limb amputation. World Journal of Surgery, 23, 1088 –1093.

Salih, S., Dennison, M., Blakey, C., Chan, D., McGregor-Riley, J. C., Royston, S. L., Gowlett, S., & Moore, D. (2015). The callus fracture sign: A radiological predictor of progression to hypertrophic non-union in diaphyseal tibial fractures. Strategies in Trauma and Limb Reconstruction, 10(3), 149–153. https://doi.org/10.1007/s11751-015-0238-y.

Sànchez-Riera, L., Wilson, N., Kamalaraj, N., Nolla, J. M., Kok, C., Li, Y., Maraca, M., Norman, R., Chen, J. S., Smith, E., Sambrook, P. N., Hernàndez, C. S., Woolf, A., March, L. (2010). Osteoporosis and fragility fractures. Best Practice & Research Clinical Rheumatology, 24(6), 793–810. https://doi.org/10.1016/j.berh.2010.10.003.

Schaefer M, Black S, Scheuer L. 2009. Juvenile Osteology: A laboratory and field manual. Burlington: Elsevier.

Schaffler, M. B., & Kennedy, O. D. (2012). Osteocyte Signaling in Bone. Current Osteoporosis Reports, 10(2), 118–125. https://doi.org/10.1007/s11914-012-0105-4.

Scheirs, S., Langenhorst, W., Malgosa, A., Ortega-Sánchez, M., McGlynn, H., Santos, C., Jordana, X., Rodriguez-Baeza, A., & Galtés, I. (2018). Perimortem fracture pattern in ribs by blunt force trauma. International Journal of Legal Medicine, 132(4), 1205–1213. https://doi.org/10.1007/s00414-018-1806-8.

Schindeler, A., McDonald, M. M., Bokko, P., & Little, D. G. (2008). Bone remodeling during fracture repair: The cellular picture. Seminars in Cell & Developmental Biology, 19(5), 459–466. https://doi.org/10.1016/j.semcdb.2008.07.004

Schmeisser, B. (1976). The Population of Louisbourg 1713-1758. Fortress of Louisbourg, National Historic Site, Parks Canada Report.

Scott A. B. (2017). Rochefort Point Cemetery (55L34) 2017 Excavation Report. Submitted to Parks Canada, Fortress of Louisbourg, NS.

Scott A. B. (2018). Rochefort Point Cemetery (55L34) 2017 Excavation Report. Submitted to Parks Canada, Fortress of Louisbourg, NS.

Scott A. B. (2019). Rochefort Point Cemetery (55L34) 2017 Excavation Report. Submitted to Parks Canada, Fortress of Louisbourg, NS.

Scott, A. B., Betsinger, T. K., MacInnes, S., Hughes, N., Fonzo, M., & Forbes, M. N. S. (2023). A Colony without a Cough? A Bioarchaeological Exploration of Tuberculosis at the Eighteenth-Century Fortress of Louisbourg, Canada. Historical Archaeology, 57(1), 315–335. https://doi.org/10.1007/s41636-023-00397-0.

Scott, A. B., Danforth, M., MacInnes, S., Hughes, N., & Fonzo, M. (2020). Colonial Urbanism: A Comparative Exploration of Skeletal Stress in Two Eighteenth Century North American French Colonies. In: The Bioarchaeology of Urbanization T. K. Betsinger & S. N. DeWitte, editors. Cham: Springer International Publishing. Pp. 275–294.

Scott, A. B., Morgan, J. A., MacInnes, S., Fonzo, M., & Hinton, J. (2019). “Whare ye ennemy used to bury there dead”: A New Englander burial at the 18th century Fortress of Louisbourg in Atlantic Canada. *International Journal of Osteoarchaeology*, *29*(1), 91–100. https://doi.org/10.1002/oa.2719.

Sen, N. (2017). An insight into the vision impairment following traumatic brain injury. Neurochemistry International, 111, 103–107. https://doi.org/10.1016/j.neuint.2017.01.019.

Shepherd, J. P., Shapland, M., Pearce, N. X., & Scully, C. (1990). Pattern, Severity and Aetiology of Injuries in Victims of Assault. Journal of the Royal Society of Medicine, 83(2), 75–78. https://doi.org/10.1177/014107689008300206

Sirmali, M., Türüt, H., Topçu, S., Gülhan, E., Yazici, Ü., Kaya, S., & Taştepe, I. (2003). A comprehensive analysis of traumatic rib fractures: Morbidity, mortality and management. *European Journal of Cardio-Thoracic Surgery*, *24*(1), 133–138. https://doi.org/10.1016/S1010-7940(03)00256-2.

Šlaus, M., Novak, M., Bedić, Ž., & Strinović, D. (2012). Bone fractures as indicators of intentional violence in the eastern adriatic from the antique to the late medieval period (2nd–16th century AD). American Journal of Biological Anthropology, 149(1), 26–38. https://doi.org/10.1002/ajpa.22083.

St. Hoyme, L. E., & İşcan, M. Y. (1989). Determination of Sex and Race: Accuracy and Assumptions. In: Reconstruction of Life from the Skeleton, Mehmet Y. İşcan and Kenneth A. R. Kennedy, editors. Alan R. Liss,: New York, NY. Pp. 53–93.

Tampe, U., Widmer, L. W., Weiss, R. J., & Jansson, K.-Å. (2018). Mortality, risk factors and causes of death in Swedish patients with open tibial fractures—A nationwide study of 3, 777 patients. Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine, 26(1), 62. https://doi.org/10.1186/s13049-018-0531-0.

Tanaka, M., Setoguchi, T., Ishidou, Y., Arishima, Y., Hirotsu, M., Saitoh, Y. et al. (2012). Pathological femoral fractures due to osteomalacia associated with adefovir dipivoxil treatment for hepatitis B: A case report. Diagnostic Pathology, 7(1), 108. https://doi.org/10.1186/1746-1596-7-108.

Tarr, J. A., & Mcshane, C. (2008). The Horse as an Urban Technology. Journal of Urban Technology, 15(1), 5–17. https://doi.org/10.1080/10630730802097765.

Teti, A. (2011). Bone Development: Overview of Bone Cells and Signaling. Current Osteoporosis Reports, 9(4), 264–273. https://doi.org/10.1007/s11914-011-0078-8

Thompson, Z., Miclau, T., Hu, D., & Helms, J. A. (2002). A model for intramembranous ossification during fracture healing. Journal of Orthopaedic Research, 20(5), 1091–1098. https://doi.org/10.1016/S0736-0266(02)00017-7

Thomson, G. (1996). Healing all the king's men: Medical treatment at Fortress Louisbourg, 1744. CMAJ: Canadian Medical Association Journal, 155(3), 323–325. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1487996/.

Todd, T.W. (1921a). Age Changes in the Pubic Bone. I: The Male White Pubis. American Journal of Physical Anthropology, 3, 285–334.

Todd, T.W. (1921b). Age Changes in the Pubic Bone. III: The Pubis of the White Female.IV: The Pubic of the Female White–Negro Hybrid. American Journal of Physical Anthropology, 4, 1–70.

Tricco, A. C., Colantonio, A., Chipman, M., Liss, G., & McLellan, B. (2006). Work-related deaths and traumatic brain injury. Brain Injury, 20(7), 719–724. https://doi.org/10.1080/02699050600664640

Tritella, S., Obertová, Z., Sconfienza, L. M., Collini, F., Cristini, E., Amadasi, A., Ciprandi, B., Spairani, R., Albano, D., Viero, A., Cappella, A., Cammilli, P., Sardanelli, F., & Cattaneo, C. (2020). Multi-Rater Agreement Using the Adapted Fracture Healing Scale (AFHS) for the Assessment of Tubular Bones on Conventional Radiographs: Preliminary Study*. Journal of Forensic Sciences, 65(6), 2112–2116. https://doi.org/10.1111/1556-4029.14541.

Tsai, Y., Wang, T., Lee, P., & Chen, C. (2022). The Butterfly Fragment in Wedge-Shaped Femoral Shaft Fracture: Comparison of Two Different Surgical Methods. Orthopaedic Surgery, 14(8), 1663–1672. https://doi.org/10.1111/os.13372.

Tsang, K. Y., Tsang, S. W., Chan, D., & Cheah, K. S. E. (2014). The chondrocytic journey in endochondral bone growth and skeletal dysplasia. Birth Defects Research Part C: Embryo Today: Reviews, 102(1), 52–73. https://doi.org/10.1002/bdrc.21060.

Tung, T. A. (2007). Trauma and violence in the Wari empire of the Peruvian Andes: Warfare, raids, and ritual fights. American Journal of Biological Anthropology, 133(3). https://doi.org/10.1002/ajpa.20565.

Turner, C. H. (2002). Biomechanics of Bone: Determinants of Skeletal Fragility and Bone Quality. Osteoporosis International, 13(2), 97–104. https://doi.org/10.1007/s001980200000.

Ubelaker, DH. (1989). Human Skeletal Remains. 2nd Ed. Taraxacum Press, Washington, DC.

van der Meulen, M. C. H., Jepsen, K. J., & Mikić, B. (2001). Understanding bone strength: Size isn't everything. Bone, 29(2), 101–104. https://doi.org/10.1016/S8756-3282(01)00491-4.

Viero, A., Biehler-Gomez, L., Cappella, A., Messina, C., Montisci, M., & Cattaneo, C. (2021). The potential of micro-CT for dating post-cranial bone fractures: A macroscopic, radiographic, and microtomography study of fractures of known post-traumatic ages. International Journal of Legal Medicine, 135(5), 1913–1921. https://doi.org/10.1007/s00414-021-02582-3.

Viero, A., Biehler-Gomez, L., Messina, C., Cappella, A., Giannoukos, K., Viel, G., Tagliaro, F., & Cattaneo, C. (2022). Utility of micro-CT for dating post-cranial fractures of known post-traumatic ages through 3D measurements of the trabecular inner morphology. Scientific Reports, 12(1), 10543. https://doi.org/10.1038/s41598-022-14530-1.

Wade, A. D., Holdsworth, D. W., & Garvin, G. J. (2011). CT and micro-CT analysis of a case of Paget's disease (osteitis deformans) in the Grant skeletal collection. International Journal of Osteoarchaeology, 21(2), 127–135. https://doi.org/10.1002/oa.1111.

Wagner, R. B., & Slivko, B. (1989). Highlights of the history of nonpenetrating chest trauma. The Surgical Clinics of North America, 69(1), 1–14. https://doi.org/10.1016/s0039-6109(16)44729-8.

Wakely, J. (1996). Limits to interpretation of skeletal trauma—Two case studies from Medieval Abingdon, England. International Journal of Osteoarchaeology, 6(1), 76–83. https://doi.org/10.1002/(SICI)1099-1212(199601)6:1<76:AID-OA233>3.0.CO;2-H.

Waldron T. (1994). Counting the Dead: The Epidemiology of Skeletal Populations. West Sussex, England: John Wiley & Sons.

Walker, P. L. (2005). Greater Sciatic Notch Morphology: Sex, Age, and Population Differences. American Journal of Physical Anthropology 127, 385–391.

Wang, J., Chen, W., Hou, Z.-Y., Lyu, H.-Z., Zhu, Y.-B., & Zhang, Y.-Z. (2019). Law of dynamic deformation of bone. Chinese Medical Journal, 132(21), 2636–2637. https://doi.org/10.1097/CM9.0000000000000483.

Warriner, A. H., Patkar, N. M., Curtis, J. R., Delzell, E., Gary, L., Kilgore, M., & Saag, K. (2011). Which fractures are most attributable to osteoporosis? Journal of Clinical Epidemiology, 64(1), 46–53. https://doi.org/10.1016/j.jclinepi.2010.07.007.

Wedel, V. L. & Galloway, A. (2014). Broken Bones: Anthropological Analysis of Blunt Force Trauma, 2nd edition. Charles C Thomas Publisher.

Welsh, H., Nelson, A. J., Van Der Merwe, A. E., De Boer, H. H., & Brickley, M. B. (2020). An Investigation of Micro-CT Analysis of Bone as a New Diagnostic Method for Paleopathological Cases of Osteomalacia. International Journal of Paleopathology, 31, 23–33. https://doi.org/10.1016/j.ijpp.2020.08.004.

Wennergren, D., Bergdahl, C., Ekelund, J., Juto, H., Sundfeldt, M., & Möller, M. (2018). Epidemiology and incidence of tibia fractures in the Swedish Fracture Register. Injury, 49(11), 2068–2074. https://doi.org/10.1016/j.injury.2018.09.008.

White, T. D., Black, M. T., & Folkens P. A. (2011). Human Osteology. Academic Press.

Wieberg, D. A. M., & Wescott, D. J. (2008). Estimating the Timing of Long Bone Fractures: Correlation Between the Postmortem Interval, Bone Moisture Content, and Blunt Force Trauma Fracture Characteristics*. Journal of Forensic Sciences, 53(5), 1028–1034. https://doi.org/10.1111/j.1556-4029.2008.00801.x.

Wijffels, M. M. E., Prins, J. T. H., Perpetua Alvino, E. J., & Van Lieshout, E. M. M. (2020). Operative versus nonoperative treatment of multiple simple rib fractures: A systematic review and meta-analysis. Injury, 51(11), 2368–2378. https://doi.org/10.1016/j.injury.2020.07.009.

Williams, C. S. (1745). Ninth journal, In: Louisbourg journals 1745, De Forest, L.E. editor. The Society of Colonial Wars in the State of New York: NY. Pp. 120 – 169.

Wissler, A., Blevins, K. E., & Buikstra, J. E. (2022). Missing data in bioarchaeology I: A review of the literature. American Journal of Biological Anthropology, 179(3), 339–348. https://doi.org/10.1002/ajpa.24609.

Wood, J. W., Milner, G. R., Harpending, H. C., and Weiss, K. M. (1992). The Osteological Paradox: Problems of inferring prehistoric health from skeletal samples. Current Anthropology, 33, 343–370.

Wu, W.-M., Yang, Y., Gao, Z.-L., Zhao, T.-C., & He, W.-W. (2015). Which is better to multiple rib fractures, surgical treatment or conservative treatment? International Journal of Clinical and Experimental Medicine, 8(5), 7930–7936.

Young, J. D., Gelbs, J. C., Zhu, D. S., Gallacher, S. E., Sutton, K. M., & Blaine, T. A. (2015). Orthopaedic Injuries in Equestrian Sports. Orthopaedic Journal of Sports Medicine, 3(9), 2325967115603924. https://doi.org/10.1177/2325967115603924.

Yuasa, Y., Miyakoshi, N., Hongo, M., Ebata, K., Tomioka, T., & Shimada, Y. (2017). Sacral Stress Fracture in an Amateur Badminton Player. Case Reports in Orthopedics, 2017, e4268981. https://doi.org/10.1155/2017/426898.

Zalavras, C. G., Patzakis, M. J., Holtom, P. D., & Sherman, R. (2005). Management of Open Fractures. Infectious Disease Clinics, 19(4), 915–929. https://doi.org/10.1016/j.idc.2005.08.001.

Ziegler, D. W., & Agarwal, N. N. (1994). The morbidity and mortality of rib fractures. The Journal of Trauma, 37(6), 975–979. https://doi.org/10.1097/00005373-199412000-00018.

Zimmermann, E. A., & Ritchie, R. O. (2015). Bone as a Structural Material. Advanced Healthcare Materials, 4(9), 1287–1304. https://doi.org/10.1002/adhm.201500070.

Zuckerman, M. K., Kamnikar, K. R., & Mathena, S. A. (2014). Recovering the 'Body Politic': A Relational Ethics of Meaning for Bioarchaeology. *Cambridge Archaeological Journal, 24*(3), 513–522. https://doi.org/10.1017/S0959774314000766.

APPENDIX A

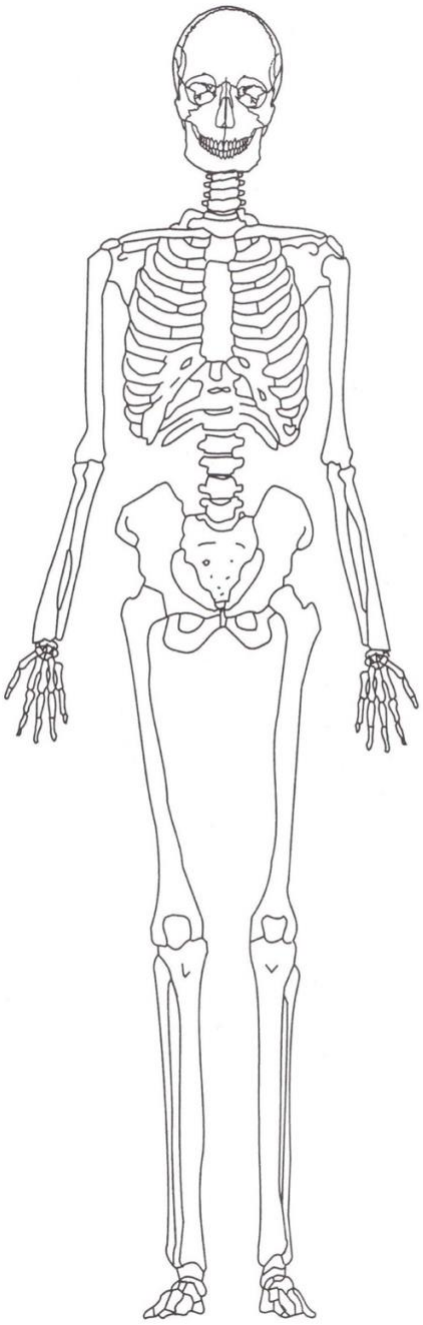
Skeletal Trauma Macroscopic Data Recording Form

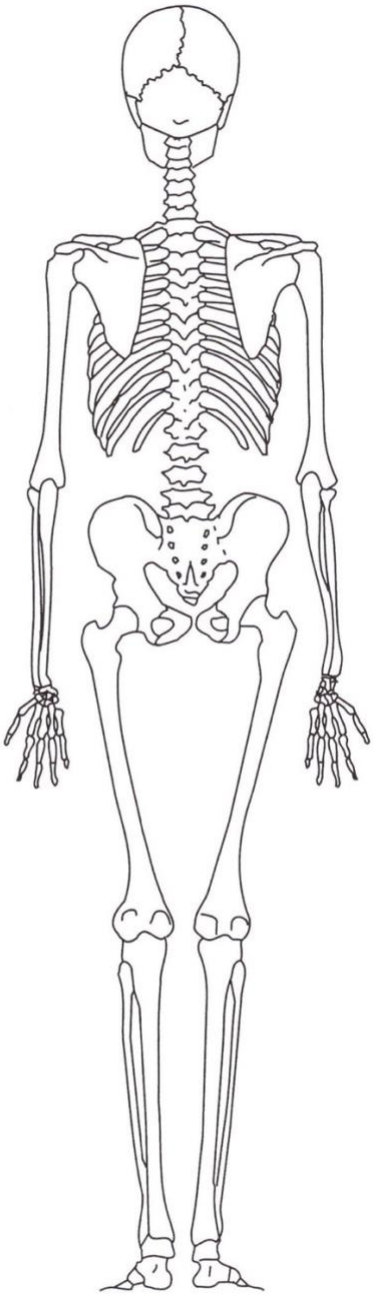
Cemetery: **Date:**
Burial Number: **Observer(s):**
Sex:
Age:

Location on body **Circle:** **Axial** **Appendicular**	
Fracture Type	
Displacement (Complete, partial, or non-displaced)	

Healing or Unhealed	
Fracture timing (Circle)	**Antemortem Perimortem Post-mortem** **Notes:**

NOTES:





Microscopic Fracture Healing Recording Form

Burial #: **Date:**
Cemetery: **Observer: T. Corbett**

Bone and side (designation)	X-Ray/micro-CT score	Comments

APPENDIX B

Table B-1: Windowing and leveling settings for micro-CT images

Burial #/Cemetery	Date dd/mm/yy	Designated #/ Bone and side	2D Selected Range	2D Look-Up Table	3D Selected Range	3D Presets/ Look-Up Table
55L28E7/SM	16/10/2023	#1/ L Rib 3	-61.53 to 1134.22	Grayscale	71.26 to 868.44	Bones 2 /grayscale solid 2
55L28E7/SM	16/10/2023	#2/ L Rib 4	-27.89 to 1470.37	Grayscale	244.54 to 1306.91	Bones 2/ grayscale solid 2
55L28E7/SM	16/10/2023	#3/R lower rib	78.47 to 3469.09	Grayscale	187.86 to 1786.85	Bones 2/ grayscale solid 2
55L28E7/SM	16/10/2023	#4/ R Rib 10	-71.53 to 3738.52	Grayscale	267.17 to 3230.46	Bones 2/ Grayscale solid 2
55L28E7/SM	16/10/2023	#5/ L Rib 2	80.56 to 1209.35	Grayscale	54.31 to 631.77	Bones 2/ grayscale solid 2
55L28E7/SM	16/10/2023	#6/ R mid rib	41.88 to 1352.89	Grayscale	41.88 to 933.33	Bones 2/ grayscale solid 2
55L28E7/SM	16/10/2023	#7/ L lower mid rib	171.17 to 3408.34	Grayscale	107.69 to 1313.53	Bones 2/ grayscale solid 2
55L28E7/SM	16/10/2023	#8/ R mid rib	176.14 to 3375.71	Grayscale	353.92 to 797.97	Bones 2/ grayscale solid 2
55L28E7/SM	16/10/2023	#9/ L mid rib	108.42 to 2971.77	Grayscale	259.14 to 1690.65	Bones 2/ grayscale solid 2
B73(2019)/ RP	17/10/2023	#1/R lower rib	10.09 to 1418.77	Grayscale	135.32 to 1230.93	Bones 2/ grayscale solid 2
B73(2019)/ RP	17/10/2023	#2/ R mid lower rib	50.72 to 1335.78	Grayscale	122.12 to 800.27	Bones 2/ grayscale solid 2
B84(2019)/ RP	17/10/2023	#1/L mid rib	-18.23 to 1141.45	Grayscale	84.87 to 290.94	Bones 2/ grayscale solid 2

B84(2019)/ RP	17/10/2023	#2/L mid rib	-77.97 to 2814.18	Grayscale	323.76 to 1287.58	Bones 2/ grayscale solid 2
B21(2017)/ RP	17/10/2023	R Rib 7	194.14 to 3459.90	Grayscale	108.19 to 795.43	Bones 2/ Grayscale solid 2
B21(2017)/ RP	17/10/2023	L Rib 11	-219.35 to 3616.21	Grayscale	272.44 to 2632.63	Bones 2/ grayscale solid 2
B21(2017)/ RP	17/10/2023	L Rib 8	-60.34 to 1382.73	Grayscale	84.00 to 1166.23	Bones 2/ grayscale solid 2
B21(2017)/ RP	17/10/2023	L Rib 7	28.49 to 1417.56	Grayscale	178.68 to 704.16	Bones 2/ grayscale solid 2
B21(2017)/ RP	17/10/2023	L Rib 6	-1.32 to 1458.49	Grayscale	203.56 to 536.44	Bones 2/ grayscale solid
B77(2019)/ RP	17/10/2023	#1/L mid rib	-18.76 to 1314.28	Grayscale	58.15 to 724.62	Bones 2/ grayscale solid
B77(2019)/ RP	17/10/2023	#6/ L rib	-50.82 to 1277.87	Grayscale	22.96 to 686.84	Bones 2/ grayscale solid 2
B77(2019)/ RP	17/10/2023	#8/R Rib 10	-18.81 to 1162.62	Grayscale	45.06 to 428.15	Bones 2/ grayscale solid 2
B77(2019)/ RP	17/10/2023	#9/R Rib 9	-55.65 to 2799.64	Grayscale	185.66 to 1311.59	Bones 2/ grayscale solid 2
B77(2019)/ RP	18/10/2023	#4 fx1/R Rib 8	-67.22 to 1366.60	Grayscale	82.15 to 291.14	Bones 2/ grayscale solid
B77(2019)/ RP	18/10/2023	#4 fx 2/R Rib 8	-86.57 to 1475.83	Grayscale	96.72 to 329.99	Bones 2/ grayscale solid 2
B77(2019)/ RP	18/10/2023	#4 fx 3/ R Rib 8	61.62 to 3249.73	Grayscale	134.08 to 1872.91	Bones 2/ grayscale solid 2
B77(2019)/ RP	18/10/2023	#3 fx 1/ R Rib 7	-2.77 to 1340.13	Grayscale	112.56 to 727.47	Bones 2/ grayscale solid 2
B77(2019)/ RP	18/10/2023	#3 fx 2/ R Rib 7	-51.27 to 2961.88	Grayscale	250.08 to 1153.80	Bones 2/ grayscale solid 2
B77(2019)/ RP	18/10/2023	#2 frag 1/ L mid rib	51.76 to 1286.29	Grayscale	190.20 to 704.85	Bones 2/ grayscale solid 2

B77(2019)/ RP	18/10/2023	#2 frag 2/ L mid rib	71.86 to 3546.56	Grayscale	286.23 to 1329.55	Bones 2/ grayscale solid 2
B77(2019)/ RP	19/10/2023	#5 frag 1/ R Rib 11	82.03 to 2701.16	Grayscale	390.20 to 2007.77	Bones 2/ grayscale solid 2
B77(2019)/ RP	19/10/2023	#5 frag 2/ R Rib 11	38.62 to 1238.35	Grayscale	247.29 to 612.35	Bones 2/ default 3D
B21(2019)/ RP	19/10/2023	L Rib 10 frag 1	46.91 to 1346.13	Grayscale	138.82 to 598.23	Bones 2/ grayscale solid 2
B21(2019)/ RP	19/10/2023	L Rib 10 frag 2	51.56 to 1283.02	Grayscale	374.12 to 827.49	Bones 2/ grayscale solid 2
B21(2019)/ RP	19/10/2023	R Rib 9 frag 1	2.26 to 1583. 85	Grayscale	150. 98 to 522.65	Bones 2/ grayscale solid 2
B21(2019)/ RP	19/10/2023	R Rib 9 frag 2	3.48 to 1428.70	Grayscale	101.78 to 666.89	Bones 2/ grayscale solid 2

SM= Ste. Marie, RP= Rochefort Point, fx= fracture

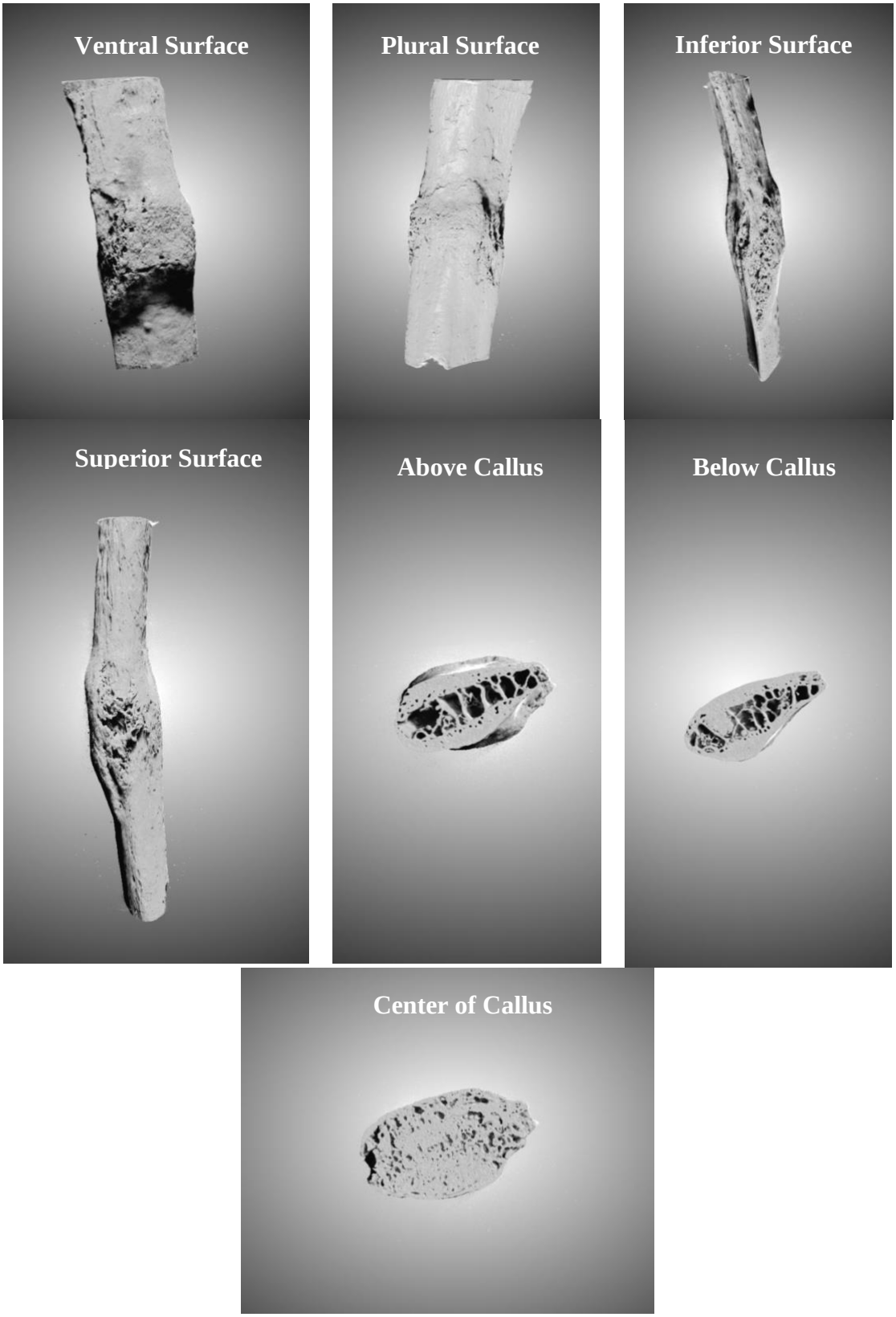


Figure B-1: Micro-CT 3D model views

CURRICULUM VITAE

Taylor Grace Corbett

EDUCATION

2022 HBSc University of Toronto Mississauga, Forensic Anthropology

2024 M.A. University of New Brunswick, Department of Anthropology

AWARDS AND HOURS

2023 Canadian Graduate Scholarship – Master's, Social Sciences and Humanities Research Council of Canada ($17,500)

2023 New Brunswick Innovation Fund Graduate Merit Award, University of New Brunswick ($5000)

2022 Faculty of Arts Graduate Assistantship, University of New Brunswick ($16,053)

2022 New Brunswick Innovation Fund STEM and Social Innovation Award, University of New Brunswick ($4000)

2022 Magee-Third Century Postgraduate Merit Award, University of New Brunswick ($3000)

2018-2022 Dean's List Scholar for Academic Achievement, University of Toronto

PUBLICATIONS/PRESENTATIONS

2023 A Case of Craniosynostosis: Exploring Unique Cranial Morphology at the 18th century Fortress of Louisbourg, University of New Brunswick Graduate Research Conference, poster presentation.

2024 Fractures at the Fortress: A study of fractures at the 18th century Fortress of Louisbourg, Skeletal Stories: Bioarchaeological research from the 18th century Fortress of Louisbourg, University of New Brunswick and Parks Canada.