Applying 3D Structured Light Scanning to Roman Leather Insoles From Vindolanda: A Novel Approach to Podiatric Data Collection

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Abstract and Keywords

This thesis research introduces a novel 3D structured light scanning and digital, post-processing enhancement methodology influenced by digital approaches used in anthropological archaeology, ichnology, and forensic podiatry to the analysis of Roman leather insoles from Vindolanda. The primary objective was to capture 2D and 3D footprint impression evidence on the surface of 81 insoles for enhanced visualization and analysis in order to refine the quality of podiatric data that can be extracted from Roman footwear. I conducted three case studies (pointed toe, sandal, and children’s insoles) based on a set of distinct, but related research questions concerning the refinement of our understanding of local demographic variables (sex, age, and health) and Roman footwear practices. The successful visualization of footprint impressions in this research represents the most accurate Roman podiatric data to date, providing unprecedented insight into the research questions that have been difficult to answer using traditional analyses.

Keywords: 3D Structured Light Scanning, 3D imaging, Roman archaeology, Vindolanda, Roman footwear, Leather, Footprint impressions, Forensic podiatry
Summary for Lay Audience

This thesis research introduces a new 3D imaging and digital visualization methodology to the podiatric analysis of Roman leather footwear from Vindolanda, a Roman imperial military fort and settlement just south of Hadrian’s wall in Northern England, occupied from the 1st to 6th centuries AD. The methodology was influenced by digital approaches used recently in anthropological archaeology, ichnology, (the study of fossilized tracks made by animals or humans), and forensic podiatry, (the forensic analysis of footwear impression evidence). The methodology employed uses 3D structured light scanning (SLS), a powerful non-contact 3D scanning technology that measures the entire geometry of an object using a series of projected light patterns and cameras. The 3D models were then digitally enhanced using various tools available in the processing software MeshLab. The primary objective was to capture footprint impressions on the surface of 81 leather insoles for enhanced visualization and analysis to refine the quality of podiatric data extracted from the footwear. I conducted three case studies on three different categories of shoes (pointed toe, sandal, and children’s insoles) based on a set of research questions concerning the refinement of our understanding of local demographic variables (sex, age, and health) and Roman footwear practices. The methodology was successful at visualizing footprint impressions on a significant number of insoles in the dataset and represents the most accurate Roman podiatric data to date. The results of the research provide unprecedented insight into key questions surrounding the populations living in the Roman imperial military community of Vindolanda and the trends in their footwear fashions and practices, which have been difficult to answer using traditional analytical techniques.
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Chapter 1: Introduction

1.1 Overview of the Project

The application of 3D Imaging systems in cultural heritage management and archaeological research has grown continuously in the last two decades, providing researchers with powerful tools to visualize and interact with ancient material culture in a multitude of ways. In particular, the development of an array of non-contact 3D Imaging methods for the digitization of the geometrical properties of three-dimensional objects without the risk of irreversible damage, has led to a wide range of applications of 3D imaging by archaeological projects worldwide. However, in the discipline of Roman archaeology, a significant portion of 3D imaging applications, particularly those involving photogrammetry, laser scanning, and structured light scanning, are for documentation, comparison between imaging techniques, and public dissemination purposes. Thus, the greater potential that non-contact 3D imaging methods have for enhanced visualization, precise measurement, and quantitative and qualitative analysis has not been fully realized within the discipline until recently.

This thesis project attempts to fill these gaps present in Roman archaeological research employing non-contact 3D imaging systems by introducing a new 3D structured light scanning and digital enhancement methodology influenced by vertebrate paleoichnology and the forensic analysis of footwear impression evidence to Roman

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1 Croix et al. 2020, 1-2; Hess et al. 2018, 11; Williams et al. 2019, 364; Barone et al. 2018, 1; Garcia-Molina et al. 2021, 1; Corns 2013, 10.
2 Vertebrae ichnology is the study of traces and tracks made by vertebrate organisms. Paleoichnology refers to the description, classification, and interpretation of ancient ‘trace fossils’ or ‘ichnofossils.’ Catuneanu 2022, 44.
podiatric analysis in an unprecedented, interdisciplinary approach. The project applies 3D structured light scanning and several advanced, digital post-processing software tools to Roman leather insoles from the Vindolanda site assemblage in order to capture 2D print and 3D impression evidence indistinguishable with the naked eye for enhanced topographical visualization, surface feature and wear analysis. The primary objective is to enable and enhance the visualization of podiatric data such as size, shape, placement, pressure distribution and irregularities that can be extracted from trace prints and/or wear impressions left on the surface of Roman leather insoles. The enhanced and accurate podiatric data will allow researchers to gain a more accurate picture of the sex, age and health of the individual Roman wearers from the dataset, which has been difficult to achieve using traditional measurement and analytical techniques.

The project concentrates on a set of specific, pre-established research questions and overarching project goals concerning the refinement of our knowledge of Roman footwear practices and demographic variables regarding the local populations of Vindolanda provided by the foot impressions (podiatric data) left on their shoes. The primary research questions addressed by the project are twofold: First, how were certain styles of Roman leather footwear worn regarding the exact positioning of the foot on the insole? Secondly, can we assign specific Roman leather shoe styles to certain sex and age groups, such as men, women, adolescents, and young children with more certainty than is currently possible? In order to answer these research questions, I conducted three distinct

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3 Non-contact 3D imaging systems are systems that do not require physical contact with the object, and thus do not cause any surface or structural damage. Corrns 2013, 10; Ruiz et al. 2022, 6.

4 The site of Vindolanda is a Roman Auxiliary fort and museum just to the south of Hadrian’s Wall in Northumberland, UK. Background context for the Roman fort and the site museum’s leather footwear assemblage is given in 3.1.
but interrelated case studies using 3D structured light scanning on three specific datasets from the leather shoe assemblage at the site of Vindolanda: sandals of all sizes with identifiable toe thongs, insoles of all sizes with pointed toe areas, and insoles with relative sizes traditionally assigned to children. The resulting 3D datasets were then digitally visualized, analysed, and compared for the most accurate and complete analysis, satisfying the research questions proposed above and by each case study.

The following sections of this chapter introduce and compare common non-contact 3D imaging systems and methods found in cultural heritage and archaeological research and provide a technical overview of the principles of 3D structured light scanning technology, its technical limitations and optimisations. This is followed by a brief introduction to the broad application of 3D structured light scanning in cultural heritage and archaeology. Finally, the chapter concludes with an explanation of why 3D structured light scanning was chosen as the most suitable 3D imaging system over other outlined methods for the type of artefacts and project goals outlined in the project.

1.2 Overview of 3D Imaging Systems and Methods

In cultural heritage management and archaeology, various non-contact, non-invasive 3D imaging and digitization systems have been utilized in the last two decades for a number of different applications involving valuable, potentially fragile artefacts. Non-contact 3D imaging systems are fundamentally categorized into either light-independent or light-dependent methods. Light-independent methods, such as image based or contact sensing methods, do not directly sense light in order to capture three-dimensional data, but instead use geometrical and topographical principles. In contrast, light-dependent
methods, such as laser triangulation, structured light, and time-of-flight scanning, directly sense light in various ways to capture three-dimensional data.\(^5\) **Light-dependent** methods are the most widely used methods in cultural heritage and archaeology for 3D digitization and the subject of interest for this thesis, and thus, only light-dependent methods will be discussed further.

The category of light-dependent 3D digitization methods can be further subdivided into *active* and *passive* range-sensing methods. In *active* range-sensing methods, light is artificially emitted from the device and detected on the surface of an object by the digitization system. In contrast, *passive* range-sensing methods use the reflection of natural ambient light or thermal energy from the object itself in order to capture spatial information.\(^6\) *Active* range-sensor methods use the triangulation principle to measure and acquire the 3D point cloud data processed for 3D models\(^7\), but *passive* range-sensor methods use image-based modeling techniques, integrating image matching and Structure from Motion (SfM) principles (figure 1.1).\(^8\) In addition, certain *active* and *passive* range-sensing methods can be classified as either short-range or long and mid-range techniques based on the distances they are able to sufficiently capture surface data within their field of view\(^9\) (FoV).

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\(^5\) Pavlidis and Royo 2018, 195; Corns 2013, 10-11; Manikowska 2019, 11.

\(^6\) Pavlidis and Royo 2018, 195; Corns 2013, 10-11; Milosz et al. 2022, 2; Manikowska 2019, 11.

\(^7\) See 1.3 below for a brief explanation and illustration of how the triangulation principle operates in a structured light scanning system.

\(^8\) Manikowska 2019, 11.

\(^9\) The field of view (FoV) of an optical instrument is defined as, “the maximum area of a sample that a camera can image, determined by the focal length of the lens and the sensor size.” Teledyne Princeton Instruments, “Field of View and Angular Field of View: Educational Notes,” *Teledyne Princeton Instruments*, October 16, 2020, https://www.princetoninstruments.com/learn/camera-fundamentals/field-of-view-and-angular-field-of-view#:~:text=Field%20of%20view%20defines%20the,of%20pixels%20on%20the%20sensor.
There are several popular imaging systems within the *active* and *passive* range-sensing methods categories; laser triangulation, time-of-flight (ToF) (e.g. LiDAR or LADAR scanning), and structured light scanning are the most popular within active range-sensing methods,\(^\text{11}\) and stereo-photogrammetry and Structure from Motion (SfM)\(^\text{12}\) are common within passive methods.\(^\text{13}\) Despite sharing some fundamental technical principles, these imaging technologies function differently and come with their own set of technical and functional perks, limitations, and type of data produced. Currently, there is not one specific method that allows a user to effectively digitize all varieties of objects and structures regardless of their physical characteristics. Some 3D imaging technologies

\(^{10}\) Retrieved from: Corns 2013, 16.
\(^{11}\) For an overview of these active range-sensing methods see Pieraccini et al. 2001, Kelley and Wood 2018, 5-34, Manikowska 2019, 11-29, Corns 2013,10-17.
\(^{12}\) For more technical information on SfM, particularly in cultural heritage contexts, see Corns 2013, 15-16, Kelly and Wood 2018,15, Manikowska 2019, and van der Merwe 2021, 2.
\(^{13}\) Pavlidis and Royo 2018, 196; Corns 2013, 10-16; Milosz et al. 2022, 2; Manikowska 2019, 11, 12-27.
are more suitable for capturing certain types and sizes of objects, and function most effectively in certain environments or for certain research applications over other techniques.\textsuperscript{14} Thus, the choice of a 3D digitization method often depends on the specific type, size, shape, texture, and level of detail needed of the object(s) being digitized.\textsuperscript{15} Active range-sensors, particularly laser triangulation and structured light scanning, have become a very common choice for the 3D digitization of cultural heritage in recent years, in particular for non-expert users, as they capture 3D information (x, y, and z coordinates, not just x and y) automatically in high resolution and accuracy at very fast speeds, and are suitable for different types of objects.\textsuperscript{16} 3D Structured light scanners in particular have seen an increase in popularity in 3D imaging projects of all types of scientific and humanistic disciplines within the last decade for these reasons, and are discussed in greater detail below.

1.3 3D Structured Light Scanning (SLS): Technical Overview

Structured light scanning (SLS) is an optical, light-dependent, \textit{active}-range sensor and triangulation-based imaging technique.\textsuperscript{17} Structured light scanner setups traditionally consist of a projector, at least one stereo camera\textsuperscript{18} and surface point detectors.\textsuperscript{19} Unlike its

\textsuperscript{14} For a more comprehensive discussion of factors determining the best 3D imaging system for cultural heritage applications see Pavlidis and Royo 2018 & Manikowska 2019.
\textsuperscript{15} Manikowska 2019, 11; Croix et al. 2020, 2; Ruiz et al. 2021, 18.
\textsuperscript{16} Akca 2012, 140; Polig et al. 2021, 2.
\textsuperscript{17} For a concise overview of SLS technology for lay audiences see Rieke-Zapp and Royo 2017, and for a more exhaustive and specialized overview of SLS technology see Geng 2011.
\textsuperscript{18} Some SLS kits have a two-camera system in order to mitigate errors and capture more information to produce higher-precision scans. Polyga, “3D Scanning 101: The Basics of the Structured-Light 3D Scanning Process,” https://www.polyga.com/3d-scanning-101/#:~:text=Structured%2DLight%203D%20scanners%20can,using%20only%20one%20camera%20system.
\textsuperscript{19} Hess et al. 2018, 8; Milosz et al. 2022, 2; Barszcz et al. 2021, 4; McPherron et al. 2009, 20; Wang et al. 2021, 847-8; Rieke-Zapp and Royo 2017, 247.
closest counterpart, laser triangulation scanning, which operates by projecting laser lines or dots, structured light scanners operate by projecting patterns of a structured light sequence (usually a series of black and white fringes with different widths, a dot matrix or other pattern) in order to acquire three-dimensional topometric data of an object down to sub-millimetre accuracy. The result is a three-dimensional model (known as 3D point cloud data) of the object with high resolution, detailed surface geometry and feature depths (figure 1.2). Structured light scanners utilize either one or multiple wavelengths of light, the most common being white light, but blue and green light have become increasingly popular in recent years due to their increased precision, accuracy, and higher quality data outputs. The acquisition and calculation of the object’s 3D point cloud data is completed by the scanner’s surface point detectors in real time using trigonometric triangulation. As the pre-measured light pattern projected onto the object’s surface becomes deformed due to variations in its surface feature depths, the sensors precisely calculate the positions and levels of deformations using a triangle between the pre-calibrated positions and angles of the scanner’s cameras (typically 30°) in relation to the projector and the point of interest on the object, known as the triangulation principle (See figure 1.2-A).

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20 Hess et al. 2018, 8; Milosz et al. 2022, 2; Barszcz et al. 2021, 4; McPherron et al. 2009, 20; Wang et al. 2021, 847-8; Rieke-Zapp and Royo 2017, 247.
21 van der Merwe 2021, 2; Barszcz et al. 2021, 4; Corns 2013, 12.
22 Kelley and Wood 2018, 24; Hess et al. 2018, 8; Corns 2013, 12; Wang et al. 2021, 847-8; Rieke-Zapp and Royo 2017, 247-250.
Structured light scanners are characterized by their extremely high-speed data acquisition (e.g. a single, several second scan can capture the entire object) and accuracy typically within the sub-millimeter range, but capable up to resolutions in the order of 20 micrometers (μm) for X and Y coordinates, and 3 micrometers (μm) for Z coordinates. Due to hardware limitations, however, most structured light scanners have a specified FoV that limits its use to a short-range sensor, working at distances within tens of centimeters, usually around 15-40 cm. Objects scanned by these types of scanners cannot have features smaller than its Ground Sampling Distance (GSD), the distance to capture the finest detail on the object. For example, if the scanner can capture up to a resolution of 50 micrometers (μm), then the smallest identifiable feature on the object cannot be smaller than 100 micrometers (μm). Thus, structured light scanning is optimized for use

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23 Retrieved from Yravedra et al. 2018, 5, figure 2.
24 Hess et al. 2018, 8; Barszcz et al. 2021, 4; Wang et al. 2021, 848.
on small to medium sized objects (e.g., pottery, figurines, statues), whereas other techniques such as LiDAR or laser triangulation are optimized for long-distance scanning and on larger objects and architectural structures (e.g., large statues, architectural features, the façade of buildings, the interior of rooms).  

1.4 3D Structured Light Scanning in Archaeology and Cultural Heritage

Due to their short-range, high speed data acquisition, high resolution, and realistic, full colour texture capture, structured light scanners have been adopted in cultural heritage management and archaeology for topometric data acquisition of small finds, medium sized artefacts or the small, intricate details of larger artefacts.  

Structured light scanners have the benefit of being highly portable, sometimes even hand-held systems that can be easily transported to site for in-situ scanning or to various kinds of museum collections for efficient workflow. They also use specialist hardware and associated processing software, so errors in scans can be spotted and fixed immediately, and the workflow from scanning to developing complete 3D models in post-processing is typically much quicker than other similar techniques such as photogrammetry. This high-speed data acquisition allows researchers to scan entire collections consisting of tens to hundreds of artefacts in a relatively quick timeframe, usually without the need to hire external operators. Additionally, structured light scanners are relatively user-friendly for non-experts, more so than other imaging methods such as photogrammetry and SfM, which often require more specialized knowledge on processing workflows for suitable results. In recent years,

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26 Hess et al. 2018, 7-8; Barszcz et al. 2021, 4.
structured light scanners have also become more accessible to smaller sized projects at relatively low costs. Overall, structured light scanning has proven itself as a valuable 3D digitization tool in cultural heritage and archaeology for the non-destructive, efficient, cost-effective, and high-quality documentation of various artefacts and structures within the last decade.

Structured light scanning was chosen as the 3D imaging method of choice for this thesis project for many of the same advantages and optimizations stated above (1.2-1.4), but also its suitability for digitizing the physical characteristics of the artefacts in question and providing the quality of 3D data necessary to accomplish the research goals outlined in 1.1. First, because the Roman leather shoes chosen for the case studies of this project were located in the Vindolanda site museum in Northern England, UK and could not be moved outside of the site, the imaging system had to be portable and able to be easily setup at the site museum for all the 3D data acquisition conducted in the project. The system of choice also had to be readily accessible and affordable to me, which was possible thanks to Dr. Rhys Williams, a lecturer in Forensic Science at Teesside University, UK, who has conducted 3D structured light scanning for the Vindolanda site museum and readily agreed to providing and operating the SLS equipment during all the 3D data acquisition conducted in this project. Additionally, due to several logistical factors, all of the data acquisition for the three case studies presented, consisting of a total of eighty-one shoes, had to be completed within a limited time frame of four working days. Thus, the extremely high-data acquisition speeds (efficiency) of structured light scanners made scanning a large dataset in a limited time frame a feasible task. These

29 See Williams et al. 2019 and Hackenbroich and Williams 2022.
three technical aspects regarding structured light scanning were significant factors in the decision to use the technology, but more significantly, structured light scanning was determined to be the most suitable imaging method for scanning the geometric and material characteristics of the Roman leather insoles in the project. I concluded that the size, shape, material and surface conditions of the Roman leather insoles (approx. 120-265 mm in length, relatively flat, easily rotatable and movable, matte in colour) was suitable for capturing the fine surface features and subtle topographic changes in high detail using SLS. The last and most imperative factor confirming that structured light scanning was the most suitable 3D imaging method for this project was the nature of the faint or indistinguishable impression evidence on the insoles and the extremely high 3D data quality necessary to fulfill the analytical goals of the project outlined in 1.1. Structured light scanning is currently the only 3D imaging method with the high level of precision and resolution capacities necessary to successfully capture the extremely slight, faint or sometimes invisible (to the naked eye) 2D and 3D impression evidence located on the surface of the insoles for the enhanced digital enhancement and visualization needed to extract the desired podiatric data. Thus, with all the factors outlined above in mind, I concluded that 3D structured light scanning was the best non-contact 3D imaging method for the various requirements and goals of this thesis project.

The following chapter continues the topic of the use of 3D imaging methods in archaeology with an extensive survey of the applications of 3D structured light scanning in Roman archaeological research projects from the last two decades, organized into five

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30 See Crowther et al. 2021 for a novel forensic podiatric study using SLS to scan impressions on modern shoe insoles. In addition, I personally conducted a feasibility study in early 2022 to test if 3D SLS in conjunction with post-processing techniques could be used to successfully capture foot impressions on modern shoe insoles, including several leather insoles, with considerable success.
self-made categories based on the type(s) of application and major project goal(s) of the project. Within this survey, I evaluate the limitations, advantages, and disadvantages of the different types of project goals, methodologies and analytical techniques used by these research projects. Then I discuss what kinds of approaches are currently missing in the field of Roman archaeology at present, and how this relates to the methodology of the research presented here. The discussion on the state of 3D structured light scanning applications in Roman archaeology leads into the next section of the chapter, showcasing a selection of research projects from non-classical archaeology, vertebrate ichnology, and forensic footwear impression analysis, which have heavily inspired the methodologies of the project presented in this thesis. Chapter three introduces the research questions and analytical goals of the project and introduces the site of Roman Vindolanda, the leather footwear assemblage found at the site, and the preservation and conservation contexts of the leather artefacts used for the project’s methodology and analysis. This is followed by an explanation of the materials, case studies, and technical methodologies used in the project. Finally, chapter four presents the results of the project’s case studies and my analyses and interpretations of the data and concludes with a discussion of the significance of the data results for expanding our current knowledge of the age, sex, health, and socio-cultural contexts of the Roman population at Vindolanda, and our understanding of Roman communities in military and provincial settings. The 3D data obtained and presented in this project represents the most comprehensive and precise Roman podiatric data to date, and the first time enhanced visualization of ancient footprint impressions has been possible.
Chapter 2: Literature Review

2.1 Introduction to 3D Structured light Scanning in Roman Archaeology

The increased use of 3D structured light scanning (3D SLS) to digitize and analyze archaeological objects has resulted in the development of a subset of categories for methodologies regarding 3D SLS applications within archaeology and cultural heritage management, providing new avenues for the examination of artefacts. Roman archaeology has also developed the same subset of categories for 3D SLS approaches, albeit generally slower than non-classical archaeology and with a significantly smaller number of applications. When doing the initial research for this thesis project and looking for inspiration for my own methodology, I was able to find only seventeen major applications of 3D SLS in Roman archaeological research projects. The limited number of 3D SLS applications found in Roman research projects in comparison to other archaeological sub-disciplines, particularly anthropological archaeology, can be partly attributed to Roman archaeology’s size and specificity as a discipline, smaller than many other archaeological sub-disciplines. However, more critically, it seems to be a result of the general reluctance until recently within the field to adopt new, innovative 3D imaging techniques as a standard practice in favour of more traditional, well-established, and less costly methods (e.g., 2D photography, illustration, or photogrammetry). This reluctance

32 With only limited research, I was able to find more than sixty ‘case studies’ utilizing structured light scanning in non-classical archaeological disciplines in significant ways. Many of these were anthropological archaeological studies. Some of these ‘case studies’ are discussed in 2.1.3 below.
33 Within only thirty minutes of searching, I was able to find more than 34 Roman archaeological studies that use photogrammetry, double the amount of those I could find for 3D SLS with a significant amount of research.
is more apparent when compared with the use of 3D SLS in non-classical archaeological disciplines and scientific-based disciplines, such as medical sciences, engineering, and forensics. These disciplines have generally applied 3D imaging systems in conjunction with digital processing software for enhanced visualization and analysis techniques in considerably more innovative and analytical ways in the last decade. It seems that many of the studies that use 3D SLS in Roman archaeology, as will be evident through the analysis conduct below, have hesitated to use the technology to its full technical potential as a facilitator of enhanced visualization and analytical methods until the last few years. However, the studies conducted thus far are critical for understanding the growing development of the use of 3D imaging and 3D SLS by researchers and scholars within the discipline, and are important for setting the ground work facilitating the research of new scholars such as myself who are interested in taking 3D analytical research within the discipline further.

To facilitate a comprehensive but concise literature review and analysis, I have categorized the seventeen Roman case studies using 3D SLS mentioned above into five categories based on their primary project goals and methodologies: conservation, restoration, and preservation; public dissemination and outreach; comparative studies; documentation and recording; and qualitative and quantitative analysis. Many of the projects discussed in this paper have objectives and methodologies that fit into multiple categories simultaneously, but due to the limited scope of this literature review I have generally limited my categorization to one per case study, with the exception of two select case studies whose methodologies I wish to highlight in greater detail for their
importance in influencing my own methodology.\textsuperscript{34} The case studies are presented in chronological order under each category heading, starting with the oldest to the most recent, with the added intention of highlighting changes in the application of 3D scanning technology within the discipline over the last decade or so. For each case study examined, I will briefly summarize the primary objectives relevant to their assigned category, the materials scanned, appropriate methodologies, and any significant results and conclusions. Additionally, I follow the summary portion of my discussion for each case study with a short assessment of the significance of the project’s objectives and results, and whether the project has successfully used 3D SLS to augment their analysis, engagement, and understanding of the object(s) of study, with a particular focus on any limitations, advantages, disadvantages, or noteworthy omissions in their methodologies and analyses. Then, I will discuss the positive and negative influences of some of these studies on my own project goals and methodologies. Finally, to conclude the literature review, I offer a brief summary of the general trends evident in the utilization of 3D SLS illustrated in these case studies and in the discipline of Roman archaeology as a whole. I finish by drawing some general comparisons between 3D scanning applications in Roman archaeology and non-Roman archaeological disciplines, highlighting the types of applications largely missing within Roman archaeology, and shifting the discussion towards how certain non-Roman and non-classical research projects have strongly influenced my thesis project.

\textsuperscript{34} For example, many projects incorporated both public dissemination and documentation objectives & methods, or even documentation and conservation or comparative studies, so for each project I have chosen whichever category I believed to be the most significant and fruitful for analysis.
The following chapter, while serving as a literature review outlining the current state of the use of 3D SLS in the Roman archaeological field, also importantly serves to highlight the innovativeness and importance of the thesis project presented here for introducing new and unique methodologies to the toolkits available to researchers and advancing our knowledge of the material within the field. Unlike some other projects within Roman archaeology and even some other classical archaeological disciplines, which could not be included due to the limited scope of this literature review, the thesis project presented here seeks to extract and collect meaningful data from a statistically significant material dataset. The goal is not merely to document and publish this material, as many studies below seek to do, but critically, to visualize and analyse the material in a new and improved manner and gain a new understanding of the materials and our knowledge of the demographic and socio-cultural world of the Romans. The following case studies will stress that this kind of critical research approach has been generally lacking within Roman archaeology until recently and how that has driven my desire to create a project that attempts to fill in some of the gaps. More, this review will show how certain elements of the methodologies of some studies provided ideas for aspects of the methodology early in its creation, presented in chapter three.

2.2 Case Studies: Structured Light Scanning in Roman Archaeology

2.2.1 Conservation, Restoration, and Preservation

The first category I have established for the analysis of 3D structured light scanning applications in Roman archaeology is conservation, restoration, and preservation. Any

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35 For clarity of categorization and analysis, I have chosen to define these terms in accordance with the definitions given by The American Institute for Conservation (AIC). They define conservation as “the
of the seventeen case studies that utilized 3D SLS with the main or one of the main objectives of any combination of these three types of conservation applications, was included in this category for analysis.

The single study attributed to the conservation category is the Bacchus Conservation Project, established in 2013 and concluded in 2020. This project was a 3D digitization and conservation project conducted by the North Carolina Museum of Art (NCMA) to study the collection’s famous “Statue of Bacchus.” At the time of the project’s commencement, the “Statue of Bacchus” was comprised of a 2nd century CE Roman marble torso, a head from a different 1st-3rd century CE marble statue, and limbs, hair, berries, and leaves which were added in the late 16th or early 17th century. The project aimed to study how the statue was put together and the history of its modification, and at least initially, to complete the de-restoration of the statue that was begun decades prior. In order to do this, one major aspect of the project was the 3D structured light scanning of the statue and its decorative fragments in collaboration with Scansite 3D.

According to Rocheleau, the director of research and curator of ancient art for the NCMA, the 3D data created using SLS was used to manipulate and experiment with the profession devoted to the preservation of cultural property for the future. Conservation activities include examination, documentation, treatment, and preventive care, supported by research and education. Restoration is defined as ‘treatment procedures intended to return cultural property to a known or assumed state, often through the addition of non-original material.’ Finally, preservation is defined as “the protection of cultural property through activities that minimize chemical and physical deterioration and damage and that prevent loss of informational content. The primary goal of preservation is to prolong the existence of cultural property.” “Conservation Terminology,” American Institute for Conservation (AIC), https://www.culturalheritage.org/about-conservation/what-is-conservation/definitions.

38 I could not find any additional information from the project publications regarding the particular SLS used or any methodological specifics, but the Scansite 3D website states that they use two SLS scanners: an ATOS 3D SLS scanner and the Breuckmann Stereoscan® 3D SLS. Scansite 3D, “3D scanning Services,” https://scansite.com/3d-scanning-services/; Rocheleau, “Bacchus under Structured Light,” 2018.
separate fragments of the statue virtually, which allowed them to figure out how the re-created antique fragments fit together in a virtual space before they attempted to handle the real objects.\textsuperscript{39} Additionally, the 3D data in conjunction with structural engineering post-processing software was used to analyze the structural integrity of the statue parts, including weak points or pressure points, as well as the weight bearing capacity of the legs of the statue before any de-restoration work was conducted.\textsuperscript{40} After conducting unspecified ‘structural analyses’ using the 3D data and other various un-identified scientific, analytical and compositional techniques, the project found that the statue contained more fragments made from ancient marble quarries than previously thought. Thus, the project decided instead of de-restoration, they would re-restore and consolidate the statue.\textsuperscript{41}

Unfortunately, any technical information regarding the 3D data acquisition process, software used, or the specific methodologies conducted by this project are absent, most likely a result of the heavily public facing nature of the project. Thus, it is difficult for me to analyse the exact methodologies and analytical results of the project with much significance here. However, with the information available it is evident that the project did utilize 3D SLS and digital analytical tools in a creative and interdisciplinary manner, adapting analytical techniques from structural engineering to the study of cultural heritage to enhance their understanding of the physical characteristics of the statue. Thus, the project did use the technical benefits that 3D SLS provides for high quality and accurate digital visualization, manipulation, and analysis of

\textsuperscript{39} Rocheleau does not specify how this was conducted or with what processing and post-processing software this process was carried out. Rocheleau, “Bacchus under Structured Light,” 2018.
\textsuperscript{40} Once again, Rocheleau does not specify the software used or any methodological specifics, most likely due to the fact that it is a public facing publication & project, and the project was not published academically as far as I can find. Rocheleau, “Bacchus under Structured Light,” 2018.
the morphological and morphometric characteristics of different objects. The interdisciplinary aspect of the project and their skillful use of the analytical and visual characterization potential of 3D SLS were useful when constructing the objectives of the thesis project and the 3D SLS methodology used.

2.2.2 Public Dissemination and Outreach

The second category established for the analysis of 3D structured light scanning applications in Roman archaeology is public dissemination and outreach. This category is rather straightforward, but for the sake of clarity I have generally included any case study whose primary objective was the creation of 3D models using 3D SLS for dissemination to a completely or principally public, non-academic audience, using online open access viewing platforms (e.g., Sketchfab)\(^42\) or publicly available collection databases. I also included case studies incorporating public exhibitions, either online or in person, as well as interactive demonstrations and 3D displays designed to engage the public with archaeological artefacts using virtual reality displays or 3D printed replicas (created with the data obtained from 3D SLS).

The first case study assigned to the category of public dissemination and outreach is the “Pottery Goes Public” project, authored by Opgenhaffen et al. 2018.\(^43\) This project had two primary objectives, the first of which was to engage the local public audience with the study of ancient pottery techniques and involve them in the process of carrying

\(^{42}\) Many museums and public collections have published 3D models of their artefacts to this online, public platform for international viewers in recent years. To learn more about Sketchfab, see https://sketchfab.com/about.

\(^{43}\) Opgenhaffen et al. 2018, 62-80.
out research on these vessels.\textsuperscript{44} To achieve this objective, the authors chose to use 3D SLS and digital visualization techniques as tools for communication and interaction with the public audience by performing live archaeological analysis and 3D printing replicas of the digitized pottery for people to engage with hands-on.\textsuperscript{45} The project ultimately aimed to create a public exhibition consisting of a guided tour through archaeological excavations, a hands-on experience with ancient pottery using 3D printed replicas, and a virtual 3D museum.\textsuperscript{46} In addition, the project aimed to make all the acquired 3D data accessible to the public through a comprehensive, online platform. The results of the project was the creation of a 3D printed stamp punch using the 3D SLS model of the stamped decoration on a bowl in the study to illustrate one of the production processes of pottery to the visitors and let them experience this firsthand by allowing them to stamp clay with the 3D printed stamp.\textsuperscript{47} The 3D models of the ceramics produced in the analysis portion of the project were also displayed on a touchscreen display as part of the exhibition, allowing visitors to manipulate the vessels and help them understand the geometry of the vessels in greater detail. Finally, the 3D printed replicas of some of the black-gloss pottery shapes gave visitors a tangible experience of the artefact’s geometry from all angles and up close.\textsuperscript{48} Interestingly, the authors admitted that the 3D printer,

\textsuperscript{44} Opgenhaffen et al. 2018, 62.
\textsuperscript{45} The pottery digitized in the project consisted of fine ware ceramic assemblages from mid-to-late Republican contexts of the central Tyrrenian region, specifically Italian black gloss pottery. Opgenhaffen et al. 2018, 62-3.
\textsuperscript{46} The project chose two different case studies; a set of complete stamped bowls recovered from the Secca di Capistello Shipwreck near Lipari, Italy, and a group of fragments of bowls with stamped decoration found at the site of Satricum, Italy. Opgenhaffen et al. 2018, 62, 64.
\textsuperscript{47} Opgenhaffen et al. 2018, 69, 71-3.
\textsuperscript{48} Opgenhaffen et al. 2018, 73-4, 77.
their printed replicas and the 3D touchscreen drew the most attention from visitors, but not many were interested in the 3D scanners and their software.⁴⁹

The project by Opgenhaffen et al. is unique in that it incorporates 3D SLS and digital analytical research with public outreach objectives in a productive way, facilitating both public engagement and their own analyses at the same time. Thus, despite having a significant portion of the project dedicated to public dissemination and outreach objectives, the project did not necessarily compromise research and analytical goals like some other projects involving public outreach. However, similar to many other outreach-oriented projects, public interaction and learning is heavily oriented towards the 3D printed replicas, not the 3D SLS technology and digital techniques for the visualization of key features.

The following case study is the “Newcastle University Digital Heritage” project established in 2014 by Prof. Ian Haynes and Dr. Rob Collins at Newcastle University under the Frontiers of the Roman Empire Digital Humanities Initiative and in coordination with the Great North Museum: Hancock (GNM), Newcastle.⁵⁰ The authors of the paper, Dolfini and Collins, state that the project was a pilot study with the primary goal of making use of 3D imaging methods for cultural heritage documentation, teaching, and public engagement activities. In order to fulfill these goals, the project’s first objective was to identify a suitable 3D imaging method to digitize the various sizes and materials of the artefacts at the Great North Museum while retaining the high-resolution

⁴⁹ Opgenhaffen et al. 2018, 77.
and high-fidelity of the original objects.\textsuperscript{51} Additionally, they sought a method that offered the best ratio of cost efficiency, investment of labour and equipment, and data quality. Ultimately, the project chose 3D SLS as the most suitable 3D imaging method to achieve their objectives within these outlined parameters.\textsuperscript{52} The project scanned more than 60 artefacts and the authors concluded that the 3D structured light scanning of the Roman stone monuments in the museum was “extremely successful and exceeded expectations,” but they did not elaborate on how they determined what was successful.\textsuperscript{53} The authors concluded that the project was able to identify appropriate methods for future work supporting research, teaching, and engagement activities, but did not specify what kinds of activities would be conducted using the 3D models.\textsuperscript{54} Thus, in order to facilitate a more comprehensive analysis, I sought out further information online. The project created an open-access website online containing a searchable catalogue of the high-resolution 3D models of the objects captured at the Great North Museum, described above.\textsuperscript{55} The 3D models available on the website have had their point clouds decimated (lowering their file sizes, but also quality) to facilitate online publishing and access, reducing the quality

\textsuperscript{51} Two categories of artefacts were selected for 3D digitization: small finds and stone monuments. The stone monuments included Roman tombstones, altars, sculptures, and inscriptions ranging in size from 300mm to 1.3 m in height and were selected for 3D SLS. Dolfini and Collins 2018, 44.

\textsuperscript{52} The structured light scanner used was the Artec EVA handheld scanner and its accompanying proprietary processing software. The scanner has an accuracy of at least 100 microns and captures up to 16 frames per second. The small finds were scanned with a combination of laser scanning and photogrammetry, and therefore, not discussed here. Dolfini and Collins 2018, 43-4.

\textsuperscript{53} Dolfini and Collins 2018, 46.

\textsuperscript{54} Dolfini and Collins 2018, 43, 46.

\textsuperscript{55} See NU Digital Heritage, http://www.nu-digitalheritage.com/about-us/. In addition to the website, there are two videos posted on YouTube featuring animation of the 3D models scanned in the project. Wessex Archaeology (UK) also has a series of public facing blog posts featuring some of the 3D models created during the project with contextual information on the object scanned and the some of the process of 3D scanning using 3D SLS. The videos were produced by John McCarthy of Wessex Archeology, UK. See https://www.youtube.com/watch?v=J5DjzWCzgr0 for the second video featuring some of the Roman stone monuments scanned using SLS.
of the 3D models that are available publicly.\textsuperscript{56} Finally, some of the 3D models produced by the project were used as teaching resources in Newcastle University’s free online, open course “Hadrian’s Wall: Life on the Roman Frontier.”\textsuperscript{57}

The NU Digital Heritage project used 3D SLS for an exploratory documentation and public dissemination project, and thus, their project objectives and parameters for the selection of 3D SLS were intentionally unspecific. The project was primarily focused on creating adequate 3D models for public dissemination and teaching purposes, signalled by the lack of significant metadata and paradata in the online 3D catalogue, as well as the reduced quality of the published 3D models. However, this project provided a valuable example early in the thesis process for the importance of carefully choosing a 3D imaging method with a suitable set of the artefacts and establishing realistic and clear logistical parameters for the project.

A similar case study to Opgenhaffen et al. 2018 is that of Williams et al. 2019, presented in the paper \textit{3D Imaging as a Public Engagement Tool: Investigating an Ox Cranium Used in Target Practice at Vindolanda}.\textsuperscript{58} In this paper the authors present a pilot study for the 3D digitization, 3D printing, and interactive public demonstration of an Ox cranium from the Roman Vindolanda Museum in the UK. The primary goal of the study was to confirm the potential of 3D models produced using 3D SLS and their 3D printed replicas for public engagement with the Roman military and the site, and for direct interaction with artefacts that is otherwise not possible with the originals.\textsuperscript{59} An Ox

\textsuperscript{57} For more information regarding this course, see “Hadrian’s Wall: Life on the Roman Frontier,” FutureLearn, https://www.futurelearn.com/courses/hadrians-wall.
\textsuperscript{58} Williams et al. 2019, 1-16.
\textsuperscript{59} Williams et al. 2019, 1, 5.
cranium used for archery target practice excavated from the site was chosen as the main case study to test the project’s goals, and was scanned on site using an HP 3D structured light scanner Pro S3 with a single camera setup.\textsuperscript{60} Additionally, a range of weaponry suspected to have been used on the cranium, including iron arrowheads, lance heads, and ballista bolts were also scanned and 3D printed.\textsuperscript{61} The textured 3D model of the cranium was posted on the public-access online collection service Sketchfab for public dissemination, and both the 3D models and 3D printed replicas of the cranium and weaponry were used for interactive workshops held at the site museum.\textsuperscript{62}

Similar to the comments made by Opgenhaffen et al., the authors noted that visitors were not really interested in scan accuracy or technical aspects of the 3D models.\textsuperscript{63} They did conclude, however, that contextualising the difficult information of trauma analysis using textured 3D models and 3D printed replicas of the Ox cranium and weapons was an effective method of public education in a museum setting. When attempting to explain to visitors how certain trauma sites on the Ox cranium showed that the cranium was held up above the Roman archers for target practice, the study found that using the 3D models demonstrated this activity more clearly than hard to follow text-based descriptions.\textsuperscript{64} The authors also found that using the 3D models and replicas as part of an interactive display was effective in contextualizing how Roman archery practices can appear as evidence on bone, and educating the public on the power of Roman archers at Vindolanda.\textsuperscript{65}

\textsuperscript{60} Scans were registered using the proprietary software HP 3D Scan Pro 5, and image capture, surface cleaning and simplification was conducted using the post-processing software MeshLab. Mesh cleaning was conducted using the Geomagic studio 12 software. Williams et al. 2019, 5-6.
\textsuperscript{61} Williams et al. 2019, 5-6.
\textsuperscript{62} Williams et al. 2019, 7.
\textsuperscript{63} Williams et al. 2019, 7.
\textsuperscript{64} Williams et al. 2019, 8-9.
\textsuperscript{65} Williams et al. 2019, 10.
Additionally, the display allowed the audience to engage, regardless of age, with the complex information presented by handling and visualizing the evidence on the 3D models themselves. Overall, the authors concluded that the 3D models and 3D printed replicas created in the pilot study were extremely successful at contextualizing complex information in a creative and effective manner for public learning of all age groups, as well as allowing the public to engage directly with the material culture in an accessible and interactive manner.

The project by Williams et al. 2019 used 3D SLS models and their 3D printed replicas in a more advanced and purposeful manner than some other studies in the public dissemination category, cleverly taking advantage of the scanner’s ability to visualize high levels of subtle detail regarding the characteristics of objects to augment understanding of analytical practices, as well as to understand better the socio-cultural practices of the ancient Romans. The project used 3D printing to further enhance the features revealed by the 3D model and to further facilitate their educational and engagement capabilities. The use of 3D SLS in this case study to augment the visualization and analysis of the small surface details on artefacts provided inspiration early in the formulation of this thesis research to use the technology similarly on the surface of Roman leather insoles. The use of the online platform Sketchfab does slightly restrict the quality of engagement and learning for the audience online as it has a limited capacity for archaeological context, metadata and paradata. Moreover, the 3D models have to be reduced in quality on Sketchfab for size capacities and are usually edited for the sake of being visually appealing to a wider audience. Thus, at least regarding the

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66 Williams et al. 2019, 10.
67 Williams et al. 2019, 7-8, 11.
Sketchfab 3D models, much of the analytical benefits provided by 3D SLS models, as highlighted in the interactive activities, are reduced in this context. However, the 3D models made during the project can be used in future research if desired, and it is clear that a certain amount of trauma analysis has already been conducted on this 3D model.

A particularly unique and interdisciplinary case study in the public dissemination and outreach category is Rossi et al. 2019, *A lead-framed glass mirror from a Roman woman’s grave in Padua/Patavium (north-eastern Italy)*. In this project a small, fragmented Roman mirror dating to the second half of the 2nd century CE was digitized using 3D SLS, analyzed, and then digitally reconstructed using a multidisciplinary approach. In addition to conducting their various analyses, which will be discussed in greater detail later in the chapter, their second objective was to publicly display the accurate reconstructed high-resolution 3D model of the mirror in a museum setting. According to the authors, 3D SLS was used as a tool to reconstruct the shape of the artefact in “the clearest, most comprehensible and differentiated way for different classes of viewers who may appreciate the complexity of the find, in particular its decorations, which would otherwise be unclear.” A particular emphasis was placed on capturing the decorations of the artefact because they were extremely small and hard to visualize with the naked eye in a traditional display. The final 3D model was disseminated through a virtual reality display that allowed visitors to handle it and visualize their own reflections.

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68 Rossi et al. 2019, 94-105.
69 The mirror was scanned and printed by AuRum 3D (Open Technologies). The authors do not specify the model of the scanner used in the study but specify that it captured the object with 10 μm resolution accuracy and 30 μm precision accuracy. Data processing was conducted using Optical RevEng software. Rossi et al. 2019, 97.
70 Rossi et al. 2019, 94, 103.
71 Rossi et al. 2019, 103.
in the mirror in a virtual world.\textsuperscript{72} The 3D data collected and analysed in the study was also used to virtually reconstruct the optical properties of the mirror. Using this information, the project created a graphic simulation on a virtual display that showed visitors what the reflection of the Roman woman would have looked like in the mirror, engaging the audience with both the value of the object and the Roman woman who used it.\textsuperscript{73}

The project presented by Rossi et al. 2019 stands out in the public dissemination and outreach category as it successfully combined the project’s public outreach and analytical goals without sacrificing the quality or the quantity of meaningful data extracted. The authors used 3D SLS and novel digital, analytical and visualization tools in an innovative way, taking full advantage of the advanced capture capabilities of 3D SLS and digital tools for enhancing small, subtle features and decoration, and using the accompanying data as the basis for the reconstruction of the artefact. Thus, the project used 3D SLS and its resulting 3D models in a manner that advanced both scholarly and public understanding of the artefact. Additionally, their use of a combination of the 3D model and virtual reality was a creative and meaningful way to enhance the public’s tactile engagement with the details of the artefact, its optical properties, and its Roman user while maintaining emphasis on the capabilities of the scanner and its models instead of 3D printed replicas. The project’s use of 3D SLS to enhance and visualize the small and hard to see details of the decorations of the artefact that could not be viewed well with the naked eye was a big inspiration for this thesis research and helped confirm early on in the

\textsuperscript{72} Rossi et al. 2019, 103.
\textsuperscript{73} Rossi et al. 2019, 104.
creation of my methodology that 3D SLS was a suitable technology for the thesis’s analytical objectives.

The penultimate case study examined is the 3D digitization campaign of the archaeological park and museum of the Domus Romana of Rabat, Malta conducted in 2019 as part of the larger *Melite Civitas Romana* project. The authors of the paper discuss the 3D scanning methodologies, technical challenges, data curation, results, and dissemination strategies of the digitization campaign conducted by the University of South Florida’s Institute for Digital Exploration (IDEx). The digitization campaign consisted of two primary objectives, one of which was the 3D scanning of 128 Roman and Muslim artefacts from the museum of the Domus Romana using both 3D SLS and digital photogrammetry. All of the 3D models digitized by the project were decimated (this makes the file size smaller) and published on Sketchfab as a collection. Each individual 3D model in this collection has accompanying metadata consisting of inventory number, names of contributors, date of data collection and 3D model creation, 3D digitization method, equipment used, and paradata. The authors of the paper note, however, that due to the metadata limitations of the Sketchfab platform, its role as a platform for the public dissemination of the 3D models from the project is currently acceptable but temporary. Thus, the authors state that they are creating an alternative,
dedicated website with a customized interface and database functionalities linked to the
3D models stored on Sketchfab. The project plans to include with each 3D model
annotations of relevant features of the object, metadata, paradata, and historical and
archaeological contextualization.\textsuperscript{79}

Unfortunately, the proposed website mentioned by the authors for the dissemination
of the 3D models produced by the project has not been made public as of the date of
writing, limiting my examination to the information presented by the paper only. The
project by Tanasi et al. 2021 used 3D SLS (and photogrammetry) for a straightforward
but substantial digital documentation and public dissemination campaign, similar to that
presented by Dolfini and Collins discussed above. It is notable that the project
acknowledges the limitations of Sketchfab and attempts to remedy some of the
limitations of Sketchfab by providing additional contextual information, metadata, and
paradata. This digitization campaign was influential in my selection of 3D SLS because it
demonstrated that 3D SLS was a suitable 3D imaging method for digitizing a large
collection of artefacts (50+), which was a necessity for the large material dataset in this
research. Furthermore, 3D SLS was only used to scan a certain subset of the objects in
the collection, including pottery, statuary, and tombstones, and thus, 3D SLS was used on
most optimal objects for the technology, resulting in successful 3D models. This decision
stressed for my own research the importance of using a 3D imaging method optimized for
the materials of my research.

The final and most recent case study examined in public dissemination and outreach
category is “Digging up Memories,” an online exhibition conducted in 2019 in

\textsuperscript{79} Tanasi et al. 2021, 78-80.
partnership with the Teesside University Bioarchaeology (TUBArch) group, showcasing the results of the 3D digitization campaign of some of Vindolanda’s wooden artefacts.\(^80\) The primary goal of the virtual 3D exhibition was to enhance the public’s experience with the objects using accurate and manipulatable 3D models. The authors claim that these 3D models provide the public with a unique opportunity to visualize and engage with the small features and intricacies of the objects in a detailed manner not possible in traditional museum settings. The objects were digitized using an HP 3D structured light scanner Pro S3 with a single camera setup in quality mode.\(^81\) The compressed (decimated) versions of the 3D models were published on Sketchfab and the models hosted there were embedded as a 3D viewer in the pages dedicated to each chosen artefact in the online exhibition for viewing and manipulating.\(^82\) As the authors have importantly noted, Sketchfab acts as a viewing platform for 3D models devoid of any meaningful interpretation and isolated from their museum contexts, and thus, the project’s online exhibition was carefully curated with interpretation and context as core objectives leading the 3D scanning campaign.\(^83\) Therefore, for each page the exhibition also provided additional information regarding the object and other relevant contextual information.\(^84\) The authors of the project concluded that 3D SLS models (and 3D printed

\(^80\) The wooden artefacts scanned for the exhibition were chosen by the Vindolanda research team and volunteers based on their personal favourites from the museum collection, including notable objects such as a toy sword, peacock decorated lid, toilet seat, bath clog, and others. See Hackenbroich and Williams 2022, 27-28 for 3D models of additional artefacts included in the exhibition. For all the objects included in the exhibition, see “Digging Up Memories,” Vindolanda Charitable Trust, https://www.vindolanda.com/listing/category/digging-up-memories.

\(^81\) Williams notes that all 3D models were imported into MeshLab for post-processing cleaning and simplification in order to reduce file sizes for online publication, and objects with holes in their mesh were fixed using Geomagic Studio in preparation for 3D printing. For a complete methodology see Hackenbroich and Williams 2022, “Capturing 3D Scans and 3D printing,” 26.

\(^82\) Hackenbroich and Williams 2022, 28.

\(^83\) Hackenbroich and Williams 2022, 29-31.

replicas) were an extremely valuable tool for public archaeological learning and engagement without having to risk any damage to the original artefacts.\textsuperscript{85}

The “Digging up Memories” project successfully used the technical ability of 3D SLS to produce high-resolution 3D models that enabled the visualization of small and subtle details of the artefacts in a detailed, close-up manner, and the public dissemination of these models through the online exhibition pages provided the necessary contextual information and meaningful interpretations that other projects in this category do not provide. As the authors acknowledge, the use of Sketchfab does not enhance the engagement or education of the public, but the curation of a custom exhibition website makes up for the limitations of Sketchfab. Additionally, as established, Sketchfab models are compressed and in reduced quality, but the project notes that full-sized 3D model formats can be requested by researchers for academic purposes, a significant factor allowing analytical research to be conducted in the future by researchers.

2.2.3 \textit{Comparative Studies}

The third category I have created for the application of 3D structured light scanning in Roman archaeology is comparative studies. I have limited this category to case studies primarily concerned with comparing 3D SLS technology and its 3D data outputs with other types of 3D imaging techniques in order to determine the best method to achieve their project goals, or which attempt to integrate two or more kinds of 3D imaging techniques (including SLS). In addition, I have also included any project that compares

\textsuperscript{85} Hackenbroich and Williams 2022, 31-2.
3D SLS with traditional 2D methods such as plaster casts, photographs, hand-made illustrations, and/or manual measurement and analysis techniques.

The first case study in this category is presented by Hess et al. 2018, conducted by a group of researchers and professionals in the European network, Colour and Space in Cultural Heritage (COSCH) between 2014-2016. This study applied several different multi-modal 2D and 3D imaging methods and analytical techniques to two Roman silver denarii to evaluate the types of imaging methods that could enhance the visualization and analysis of the physical features and properties on ancient coins. I have limited my analysis to the comparisons made between optical, non-destructive 2D and 3D imaging techniques. The project conducted a quantitative topological and geometrical comparison of the 3D surface models created with the various imaging methods with 3D vertices/triangles, maximum diameter, shape factor, surface area, volume, and measured weight and density of the coins as indicators. They also compared the convergence and RMS errors of the alignment between the 3D models, as well as their deviation values.

The authors found that the 3D imaging techniques were valuable tools for the documentation, study, and improvement and automation of the analysis of coins. More significantly, they concluded that 3D digital models enabled the extraction of additional

86 Hess et al. 2018, 1; Bentkowska-Kafel et al. 2017, 35.
87 Hess et al. 2018, 1, 9; Bentkowska-Kafel et al. 2017, 50-1. These comparisons included 2D photography, Reflectance Transformation Imaging (RTI), and focus stacking, as well as 3D digital photogrammetry and SfM, photometric stereo, laser scanning, and 3D structured light scanning. For a summary of the systems and methodologies used by the study, see Hess et al. 2018, 4-11. For a more comprehensive description of the 3D digitization process and post-processing techniques of the data in the study, see Bentkowska-Kafel et al. 2017 and MacDonald et al. 2017.
88 Four post-processing software, CloudCompare, Geomagic Control, MeshLab, and Polyworks, were used to conduct topological and geometric measurements of the 3D models, as well as for alignment and comparison between 3D models. Hess et al. 2018, 11; Bentkowska-Kafel et al. 2017, 51-2.
object features for characterization not possible using traditional 2D methods, such as deviation of surface morphology, 3D surface area and volume measurements, cross-section views and quantitative characterization and analysis.\textsuperscript{90} Most important for our purposes, however, are the results showing that the 3D models produced using laser scanning and SfM were not able to reach the highest quality of 3D data made using the 3D structured light scanners.\textsuperscript{91}

The project conducted by Hess et al. 2018 presented clear-cut research and analytical goals and conducted a comprehensive, interdisciplinary imaging campaign. The comparative analysis uses an incredibly wide range of 3D imaging techniques from multiple fields of research in order to carefully and purposely evaluate the best methods to achieve the project’s goals. The data acquisition outcomes from each technique was well presented and illustrated, and comparative analyses were conducted qualitatively and quantitatively and illustrated through graphs, charts, colour depth maps, and 3D models. Despite having well-constructed methodologies and tangible, quantitative and qualitative results, some of the conclusions regarding optical 3D imaging and 2D imaging were rudimentary and confirmed many of the conclusions made previously in other numismatic studies before 2018. Regardless, this case study was incredibly valuable to the early stages of this thesis research, as it reaffirmed that 3D SLS was the best 3D imaging method for the advanced visualization and analysis of small and indistinct surface features and subtle topographies, even on very small objects such as coins. I figured that if 3D SLS was successful at visualizing these details on such a small object,

\textsuperscript{90} Hess et al. 2018, 11, 19.
\textsuperscript{91} Hess et al. 2018, 15.
that it was a feasible 3D imaging method for extracting fine, subtle features on medium sized insoles.

The survey campaign conducted by Mongelli et al. 2019 on the “Corsini Throne” in the Corsini Gallery in Rome shows similar results to that of Hess et al. 2018 above regarding the benefits of 3D SLS. This project, however, involved both the comparison and integration of Structure from Motion (SfM) photogrammetry and 3D SLS. The advantages of each technique and the potential of their integration revealed during the survey campaign were discussed in this paper. The 3D models produced using both imaging techniques were directly compared with regards to 3D shape accuracy, texture quality, digitization and processing time and price. The authors concluded that 3D SLS produced much higher-resolution and more detailed 3D models than SfM photogrammetry, particularly for capturing geometric and iconographic features. Ultimately, the project decided to merge the 3D models of both techniques to produce a semi-high definition 3D model with the most detail in the relief area for study, and also more manipulatable with a reduced file size. Overall, the study concluded that despite the results proving that 3D SLS provided the best 3D data, SfM photogrammetry provided the best compromise between portability, cost, and quality.

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92 The artefact is a late Roman Republican marble copy of a princely Etruscan throne from the late 5th century BCE. Mongelli et al. 2019, 166.
93 For a description of the SfM photogrammetry acquisition methods and post-processing work, see Mongelli et al. 2019,167-8.
94 The throne was digitized using an AICON smartSCAN 5M pixel SLS system with an M-300 optic & OPTOCAT software was used for post-processing. For a full description of the acquisition methods and post-processing work, see Mongelli et al. 2019, 168-9.
95 Mongelli et al. 2019, 166, 169-171.
96 The models produced by both techniques were merged using the post-processing software MeshLab. For a full description of the merging process, see Mongelli et al 2019, 170.
97 Mongelli et al. 2019, 171.
The project presented by Mongelli et al. 2019 comes at a surprisingly late date considering several comparative analyses between photogrammetry and 3D SLS methods have already been conducted in the last decade, and the various benefits and limitations of each technique for artefact digitization has already been demonstrated within archaeology and cultural heritage. However, this project and other similar comparison studies have significant value because they provide quantitative and qualitative comparative results that other researchers can look towards to inform their own research projects and determine whether either 3D imaging methods are suitable for similar applications or contexts. Thus, the comparative results of this study reaffirmed the suitability of 3D SLS for the parameters outlined in this research early in the thesis process.

Instead of conducting a comparative analysis between 3D SLS and photogrammetry, Papas et al. 2021 present the results of a qualitative and quantitative comparison between 3D laser scanning and 3D SLS, using a Roman vase from the city of Thessaloniki, Greece as the benchmark for comparison.98 The comparison included all production steps leading to the final 3D model, including data acquisition, manipulation of the point clouds, and final meshing algorithms. The artefact was scanned with every possible setting on each scanner, but only one configuration for each imaging method was selected for the final comparison.99 The criteria for the final selection of the two 3D models was based on the proximity in the number of points and polygons produced and thus, the best 3D

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98 The vase is a broken, two-handed wine cup found in the palace of Galerius, dated to the late 1st-early 2nd century CE. Papas et al. 2021, 111.
99 The vase was scanned using a Next Engine™ laser scanner and a Scan in a Box™ structured light scanner. For a full description of the digitization methods, technical specifications of each system, and comparative statistics and tables, see Papas et al. 2021, 111-115.
reconstruction of the vase. The results of the comparative study showed that the laser scanner achieved the highest accuracy and acquired information from the less accessible areas of the object, but that the structured light scanner could produce a model of almost identical accuracy but in a significantly shorter time frame. The comparison of the two 3D models also revealed that for a mesh of a predefined and approximate number of polygons, the 3D SLS required a significantly shorter scanning time and data size for the final model. The authors, Papas et al., stated that the 3D mesh created by SLS was more detailed than the actual vase, but had a larger number of topological errors than laser scanning. In contrast, the 3D mesh from the laser scanner was less detailed than the actual vase, but the topology had almost no errors. Thus, the study concluded that 3D SLS achieved the optimal combination of scanning quality, accuracy, and acquisition time.

The project examined here is a good example of a comprehensive comparative analysis based on a set of clear and meaningful quantitative and qualitative parameters. The comparative analysis conducted was primarily focused on the quality and accuracy of the 3D data (models) and incorporated comparison not only between the 3D models produced by each technique, but also between the 3D models and the original artefact as seen by the naked eye. The results provided by the comparative analysis were also thorough and meaningful. Similar to the study conducted by Hess et al. 2018, the comparative results of this study were valuable in the early stages of this thesis research as I was still in the process of choosing a suitable 3D imaging method. 3D laser scanning

100 Papas et al. 2021, 111.
101 Papas et al. 2021, 115.
102 Papas et al. 2021, 115.
103 Papas et al. 2021, 111, 115.
and 3D SLS were both prime candidates for the 3D imaging method used in this thesis research, but the quantitative and qualitative comparative results of studies such as this one ultimately led me to the conclusion that 3D SLS was the most suitable method for the various objectives and parameters of the project. In particular, the results demonstrating the ability of 3DSLS to produce high-quality and accurate 3D models in a relatively short time frame and with reasonable data sizes was a significant factor in the decision to use 3D SLS over other imaging methods.

2.2.4 Documentation and Recording

The fourth category I have established for the examination and analysis of 3D structured light scanning applications in Roman archaeology is documentation and recording. I have included case studies whose main objective is the 3D digitization and thus, documentation of an artefact or collection of artefacts using 3D SLS, typically for the purpose of creating an online database or collection. These online collections, unlike those found above under the public dissemination and outreach category, are designed to facilitate research by exclusively or primarily academic audiences and are generally characterized by a more limited access than those designed with public outreach in mind.

An early and fairly straightforward case study in this category is the 3D digitization of the lower half of the “Weary Herakles” statue located in the Antalya Museum, Turkey, using 3D SLS and presented by Akca et al. 2006.\footnote{A Roman marble statue of Herakles identified as belonging to the “Herakles Farnese” type, dating to around the 2\textsuperscript{nd} century CE. It is a copy of an original bronze statue sculpted around 330-320 BCE by the Greek master Lysippos. Akca et al. 2006, 14-15.} The paper presents the entire 3D digitization process of the statue, including data acquisition methods and post-processing
workflow consisting of registration, editing, texture mapping and visualization.\textsuperscript{105}

Scanning was conducted in 2005 in the Antalya Museum with a Breuckmann optoTOP-HE coded structured light scanner, and a total of 67 scans were required to fully capture the statue.\textsuperscript{106} The authors concluded that 3D SLS met the project requirements “satisfactorily,” and had distinct advantages over 3D laser scanning for digitizing marble statues, such as its high-resolution 3D data, faster acquisition speeds, and less speckle noise.\textsuperscript{107}

The project by Akca et al. 2006, similar to other Roman studies with documentation-based objectives, centers on the straightforward 3D digitization of the statue and the feasibility of 3D SLS for achieving this goal. The paper does not outline any 3D digitization parameters for the project and the authors state that the digitization results met the project’s requirements “satisfactorily,” but do not elaborate on what was considered satisfactory or unsatisfactory. It should be noted, however, that this study was conducted very early on in the adoption of 3D imaging techniques within the discipline, especially 3D SLS, and thus many studies from this time period were still very exploratory and centered on testing the feasibility of the new technology for digital documentation within cultural heritage compared to other more established or less costly

\textsuperscript{105} The work was conducted by researchers and professionals from InfoTRON Co., Breuckmann GmbH, the Division of Photogrammetry of Yildiz Technical University, and the Group of Photogrammetry and Remote Sensing of ETH Zurich. Akca et al. 2006, 14.

\textsuperscript{106} All of the 3D modelling and post-processing procedures were conducted using Geomagic Studio version 6, but the visualization of the final 3D model was done with the IMView module of Polyworks, and the textured version of the 3D model was visualized using the viewer in the VCLab’s tool. For the complete description of the entire data acquisition process and a technical overview of the SLS system used in the study, see Akca et al. 2006, 15-17. For a complete description of the post-processing pipeline and specifications, see Akca et al. 2006, 17-18.

\textsuperscript{107} Speckle noise is a phenomenon that occurs in all coherent imaging systems (e.g., radar, ultrasound, laser) in which the superposition of acoustical echoes in random phases and amplitudes produces an interference pattern that reduces the image’s contrast and obscures and blurs details, resulting in a reduction in imaging quality and reliability. Akca et al. 2006, 18; Michailovich and Tannenbaum 2006, 1-2.
methods. Therefore, although not too useful to my own research today, projects such as this were necessary to set the groundwork for future research using 3D SLS in Roman archaeology.

The following case study, conducted by Zambanini et al. 2009, presents the results of the 3D digitization of a collection of selected historical coins using 3D SLS and evaluating its benefits over traditional 2D photography.108 Twenty five historical coins, 16 of which were ancient Roman coins, were scanned using a Breuckmann stereoSCAN 3D SLS.109 According to the authors, the 3D models provided highly detailed surface topographies of both sides of the coins, and they found that 3D models created using SLS allowed for more accurate visualization and a more informative impression of their features and structures than 2D imaging, such as focus stacking or reflectance transformation imaging (RTI). Thus, the results showed that accurate 3D models of historical coins was feasible using 3D SLS despite their small sizes and specular surfaces.110 The authors also found that sufficient documentation of the coin edges was only possible using the 3D models from the SLS, allowing specialists to recognize production processes or counterfeits. In addition, the models allowed them to view the coins or certain details at any viewpoint and in any scale, providing better representations than plaster casts or drawings.111 The authors presented the digitization results of a Roman coin from the study, illustrating that 3D models were useful for detecting changes on the coin surfaces, such as deep cuts, and creating plots of the coins’ profile for further

109 The Roman coins digitized included several different denarii, aurei and antoniniani from the 2nd to 3rd centuries CE. For a complete overview of the digitization methods see Zambanini, Schlapke, and Kampel 2009, 2.
analysis. They also found that 3D models helped identify coins in a more efficient way than the inspection of traditional 2D images or the original object, because the high-resolution close-up 3D model allowed for the visualization of small, subtle details like the punches of letters of inscriptions or symbols. Additionally, they note that the ability to change light sources on the 3D model virtually using modelling software allowed them to visualize the stamping better than 2D images. Overall, the project authors concluded that the accuracy of 3D models of historical coins produced using 3D SLS is more than high enough to meet the requirements of improved numismatic documentation and analysis.

Similar to Acka et al. 2006, the case study examined here by Zambanini et al. 2009 is a preliminary digitization case study testing the benefits of 3D SLS over traditional 2D methods such as focus stacking and RTI and provides somewhat vague documentation goals and technical parameters. Once again, this can be attributed to the early date the study was conducted (2009), which was rather early in the adoption of 3D SLS in archaeology broadly, especially in Roman archaeology. Thus, most studies at this time were focused on establishing the benefits and limitations of the technology for different archaeological applications and materials, such as numismatics. Notably, however, the study examines the distinctive capabilities of 3D SLS for enhancing numismatic documentation and analysis and provides some preliminary examples of the types of visualization and analyses that can be conducted using the 3D data from SLS. Thus, considering the date of publication, this study produced significant results that advanced the tools and digital techniques available for numismatic digitization and analysis at that time. The study was valuable to the development of the methodology of my thesis.

research for several reasons. First, the results confirming that 3D SLS was successful on the small and specular surfaces of coins reaffirmed that 3D SLS could successfully work on the specular surfaces of conserved Roman leather footwear, and could capture incredibly fine surface details, two factors that were necessary for the success of the thesis’s methodology. The qualitative results presented by the authors preliminary analyses were also informative in the formation of the thesis’s methodology, showing that the advanced visualization of small, subtle details on the surface of tiny objects such as coins was feasible, and thus, should also be feasible for the surfaces of medium sized objects, such as footwear and their impression evidence. Finally, their use of a digital, manipulatable light source for better visualization of certain features (in addition to its use by other studies in non-Roman studies not described here) was a significant inspiration for its use in my own methodology.

The case study conducted by Bunsch et al. 2012 presents similar results to that of Zambanini et al. 2009 above. The study consisted of the 3D digitization of a Roman grave stele from the Roman province of Moesia Inferior using 3D SLS in order to document the characteristic features on the surface of the stone.\textsuperscript{114} The project used its own newly developed 3D SLS with a 0.1 mm sampling density to digitize the Roman stele, with the entire scanning and data processing pipeline for the final 3D model taking 4 days to complete.\textsuperscript{115} The 3D model revealed that 3D SLS allowed the researchers to visualize the surface shape and appearance of the stele from different angles and with

\textsuperscript{114} The stele is 1.4 m high x 0.9 m wide, adorned with carved decoration and Latin inscription (Wilanow Palace Museum inv. No 96/93w). The project was conducted by the Warsaw University of Technology (WUT) Mechatronics Faculty in cooperation with the Wilanow Palace Museum, Warsaw, Poland. Bunsch et al. 2012, 633, 635.

\textsuperscript{115} For more technical details of the custom structured light scanner used, see Bunsch et al. 2012, 633-4.
changing light direction using digital post-processing software, which ultimately helped them verify some of the decorative details of the stele. The authors also found that the 3D model could facilitate the identification and measurement of the tooth chisel used on the stele, as well as the characteristic path of small, delicate tool marks on its surface, which had been very difficult to document previously using traditional methods.\textsuperscript{116} Thus, the project concluded that the 3D digitization of the Roman stele using 3D SLS was successful in completing the primary objective of the study.\textsuperscript{117}

Similar to the two projects discussed above, Bunsch et al. 2012 focused on digitizing an object using 3D SLS and evaluating its potential over traditional 2D methods for future documentation and analysis. The authors of this project did not elaborate on any specific technical parameters for digitization, but state they wanted to capture characteristic features on the surface of the stele and verify un-specified ornithological investigations of its bird decorations, suggesting that this project also acted as an experimental digital visualization study. Unfortunately, they do not elaborate on the significance of verifying the decorative details or any visual analysis that may have been or will have been conducted using the 3D model created in the study. The authors, Bunsch et al., do however, significantly discuss some of the benefits 3D SLS data has for advancing the visualization and analytical tools for studying that class of artefact. They also provide some examples of digital tools and techniques that could augment knowledge of the artefact and its manufacture, such as shape analysis, oblique lighting, characterization and measurement of tool marks, but they do not conduct any of these in this study. Just as Zambanini et al. 2009 above, the study’s use of digital post-processing

\textsuperscript{116} Bunsch et al. 2012, 635-6.
\textsuperscript{117} Bunsch et al. 2012, 636.
light manipulation contributed to the incorporation of this digital tool in my own methodology. Additionally, their conclusion that a combination of 3D SLS and digital post-processing tools could facilitate the digital visualization and measurement of incredibly fine features, such as tool marks, was inspiration for applying a similar combined methodology on the Roman leather footwear in this thesis research and reaffirmed the feasibility of using 3D SLS to capture and extract subtle features such as impressions.

The following case study examined in this category, presented by Quatember et al. 2013, takes a slightly different approach than the studies discussed above. The project investigated the building history and architectural features of Hadrian’s Temple, located in the city center of Roman Ephesus, using 3D imaging techniques to produce an accurate, up-to-date 3D documentation of the building.\textsuperscript{118} The temple was scanned with two types of 3D scanners due to its large size; a laser triangulation scanner was used to scan the entirety of the building, but all of the individual, highly ornamental architectural pieces were scanned using two separate 3D structured light scanners due to the requirement of high-resolution capture for their smaller details.\textsuperscript{119} One of the primary objectives for the 3D digitization of the building, according to the authors, was to create a highly detailed, stone-by-stone documentation (aka. ortho-projections) of all of the building’s elements, including cuttings, tool marks, and architectural ornamentation, for future archaeological publications. Thus, they state their 3D digitization was dictated by

\textsuperscript{118} This is one of two project’s conducted in the ancient city of Ephesus, Turkey in 2009 by the Austrian Archaeological Institute (OAI). Quatember et al. 2013, 217-19.
\textsuperscript{119} The laser triangulation scanner was a phase-shifting laser scanner (Z + F IMAGER® 5006i), and the structured light scanners used were a smartSCAN-3D (FoV 600mm) and a triTOS (FoV 1.400 mm). Quatember et al. 2013, 217, 219, 227.
the desire for this type of documentation, which could easily fit into monographs or books.\textsuperscript{120} In addition to the creation of detailed ortho-projections, the project also used the 3D data captured to facilitate the digital reconstruction of the complex roof structure of the temple.\textsuperscript{121} Some of the 3D models of the ornamental decoration of the temple’s relief blocks were illustrated in the paper, but the aforementioned ortho-projections and 3D virtual reconstruction of the building were not included or discussed further.\textsuperscript{122} The authors of the project concluded that the 3D data captured in the study eliminated subjective factors of documentation while containing enough information for researchers to draw interpretative conclusions regarding complex architectural questions of the building, and thus, concluded that 3D scanning had clear advantages over traditional forms of documentation, such as hand-made drawings.\textsuperscript{123}

As Quatember et al. admit themselves, their methodology for the digitization of the building was dictated by their desires to publish the results in monographs and books, converting their 3D data into 2D ortho-projections to achieve this aim. This, in my opinion, weakens much of the technological benefits of 3D SLS and the 3D data, but ultimately, the study was successful at accomplishing their stated research objectives. The authors conclude that 3D scanning the building gave them enough information to draw conclusions regarding complex architectural questions, but they do not specify what the information given was, what conclusions were made, or what questions were asked in the first place. Thus, it is difficult to examine the significance of the project for the application of 3D SLS in architectural research within the discipline.

\textsuperscript{120} Quatember et al. 2013, 220-221.
\textsuperscript{121} Quatember et al. 2013, 221.
\textsuperscript{122} Quatember et al. 2013, 220-221.
\textsuperscript{123} Quatember et al. 2013, 221, 227.
The last case study in the documentation and recording category is Tanasi et al. 2018, *Best Practices for 3D Digital Recording and Global Sharing of Catacombs from Late Roman Sicily*. The project was a 3D digitization campaign conducted during the excavations of the late Roman Catacombs of St. Lucy at Siracusa, Sicily from 2013 to 2015. The first and main objective was the 3D digitization of excavation data and creation of 3D models of selected areas of the catacombs using various 3D imaging methods, including 3D SLS, for facilitating future scholarly research. The three areas of the site digitized using 3D SLS were the excavation trench in Room A, the trenches of tombs 2006-2009 in Room L, and Crypt VI in region C of the catacombs. In the first area, the excavation trench of the *formae* opened on the floor of Room A and the complex stratigraphy of tombs 2043, 2044, and 2045, were digitized using an infrared SLS. A 3D model of the four internal walls of Room A was made as well. The same scanner was also used to digitize the stratigraphy of the trenches of tombs 2006-2009 in the southeastern side of Room L, and characterize the stratigraphic relationship between the three tombs and others nearby through an un-textured, high-resolution 3D model. Finally, a low-cost infrared SLS made using a Microsoft Kinect was used to digitize the entirety of Crypt VI, whose documentation at the time of the project was outdated and incomplete.

Despite some technological limitations and the structural complexity of many aspects of

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125 The project also utilized laser triangulation scanning and digital photogrammetry for certain areas and objects of the site, but only the areas digitized using structured light scanning are discussed here. Tanasi, Gradante, and Hassam 2018, 60.
126 The authors don’t specify the model of this SLS, but state that it used an occipital structure sensor, which is a sensor device that attaches to mobile devices to allow them to 3D scan objects. Tanasi, Gradante, and Hassam 2018, 69.
127 The authors don’t provide any information on their 3D SLS or post-processing methodologies but do note that all processing was conducted using the MeshLab software. Tanasi, Gradante, and Hassam 2018, 69.
128 Tanasi, Gradante, and Hassam 2018, 68-9, 72.
the site, a 3D model of most of the crypt complex was obtained.\textsuperscript{129} The authors noted that Corridor B1 and the western flooded area of the Crypt were documented for the first time, and the whole 3D data outcome represented the best documentation of Crypt VI available at the time of writing.\textsuperscript{130} The project concluded that the 3D data and models obtained during the digitization campaign would be helpful for future post-excavation studies as the catacombs are typically inaccessible outside of periods of fieldwork.\textsuperscript{131}

As established previously, 3D structured light scanners are optimized for capturing small to medium sized objects or the smaller details of larger objects, and thus, are not optimized for or typically used to capture the entirety of large spaces.\textsuperscript{132} Thus, in my opinion this project uses 3D SLS in a rather disadvantageous manner and does not take advantage of the capabilities that 3D SLS has for capturing small details in close-range. Additionally, using 3D SLS to primarily capture flat, 2D surfaces such as walls and stratigraphic layers (where only one side can be captured) is an inefficient use of the technology because it is primarily beneficial over other 3D imaging techniques or traditional 2D techniques because of its ability to characterize 3D features and geometries of objects with extreme accuracy. Thus, this study reaffirmed the importance of carefully choosing a 3D imaging system optimized for the specific materials and environments and logistics of the research project.

The final two projects examined above, Quatember et al. 2013 and Tanasi et al. 2018, served as examples early in the thesis process of the kind of research project I did not

\textsuperscript{129} Tanasi, Gradante, and Hassam 2018, 72-4.
\textsuperscript{130} Tanasi, Gradante, and Hassam 2018, 73-4.
\textsuperscript{131} Tanasi, Gradante, and Hassam 2018, 78.
\textsuperscript{132} See 1.3. Laser triangulation scanners are typically used to capture the entirety of large architectural features and buildings, such as in Quatember et al. 2013 discussed above.
want to conduct in this thesis. These studies were vital exploratory 3D digitization campaigns that have firmly established the benefits of using 3D SLS to strengthen archaeological fieldwork and architectural research within the discipline. However, in my opinion, these two projects used 3D SLS and its 3D data outputs in disadvantageous or inefficient ways, by either using the scanner on sub-optimal environments or by reducing its 3D data output to a 2D plane.\textsuperscript{133} By using 3D SLS in these ways, these two projects only inhibit the scanner’s capabilities as a cutting-edge 3D visualization and analytical tool. In this thesis research, I sought to use 3D SLS in the most advantageous manner possible in order to capitalize on the unique strengths of 3D SLS for the digital visualization, measurement, and analysis of themorphological and topographical features of 3D objects. The technology was carefully and deliberately chosen based on its optimization for the artefacts of interest and fulfilling the pre-established research-objectives and parameters laid out by the project.

2.2.5 Qualitative and Quantitative Analysis

The final category in my examination and analysis of 3D structured light scanning applications in Roman archaeology is qualitative and quantitative analysis, which I have further divided into three sub-categories: enhanced visual analysis, digital metric analysis, and other analyses.\textsuperscript{134}

\textsuperscript{133} In Tanasi et al. 2018 above, the authors of the project use 3D SLS to scan the entirety of large rooms and/or spaces, including flat, 2D stratigraphic layers. Quatember et al. 2013, use 3D SLS to capture the decorative features and details on architectural pieces, but then convert this 3D data into 2D ortho-projections.

\textsuperscript{134} I consider enhanced visual analysis or ‘visualization’ to be the use of 3D SLS in conjunction with post-processing software tools and techniques to enhance the characterization of topological and morphological features of an object not visible using traditional 2D techniques, and to augment visual analyses of the artefact. For digital metric analysis, I include projects whose primary objectives involve the use of 3D SLS data and digital post-processing software tools and/or algorithms to precisely measure the artefact(s) and/or
The first case study in this category is by Lapp and Nicoli 2014, and is the only study attributed to the enhanced visual analysis sub-category. The project included two relevant objectives: First, the application of 3D SLS and post-processing to enhance visualization of the small and subtle topological surface features and molded decorations on ancient clay lamps. Second, the digital visualization and extraction of ancient fingerprints on the surface of ancient clay lamps to identify individual lamp makers.\textsuperscript{135} Lamp 1 was selected as a case study for 3D scanning a complete lamp and examining how accurately surface relief decoration could be visualized, and Lamp 2, a base fragment of a lamp, was selected in order to test the effectiveness of 3D scanning for visualizing fingerprint impression on the surface.\textsuperscript{136} The authors found that the 3D model of lamp 1 enhanced with pseudo-line drawn shader tools in post-processing was extremely successful at visualizing all of the small, subtle decorative reliefs on the surface of the lamp with a high degree of accuracy. Additionally, the 3D model enabled them to effectively visualize and analyze the material properties, structure, and manufacturing techniques of the clay lamp.\textsuperscript{137} For example, the digitally matted 3D model of lamp 1 facilitated the visualization of defects and surface “terrain” features on the surface caused by clay preparation, firing, usage, and decorative molded reliefs.\textsuperscript{138} The use of enhanced visual shader tools (both matte and pseudo-drawn) on the 3D model was also successful at

\textsuperscript{135} Three ancient clay lamps were selected as case studies, including two Roman-period clay lamps of the “Classic Nabatean” lamp type from the first century CE. Lapp and Nicoli 2014, 36.

\textsuperscript{136} Each lamp was scanned using a Steibichler Comet L3D Blue Light Scanner with a 2-megapixel camera and 65 μm accuracy. For the complete methodology conducted in the study, see Lapp and Nicoli 2014, 39-40.

\textsuperscript{137} Lapp and Nicoli 2014, 40.

\textsuperscript{138} Lapp and Nicoli 2014, 40.
visualizing the details of a fingerprint on the interior surface of lamp 2, confirming that 3D SLS could be used to successfully extract fingerprint data from ancient clay lamps for analysis.\textsuperscript{139} The high resolution and accuracy of the 3D scan data enabled the authors of the study to identify the fingerprint on the lamp as a patent print. Additionally, they were able to conclude that the fingerprint followed the lateral-pocket loop pattern, suggesting it was a left-handed thumbprint.\textsuperscript{140} Thus, the project concluded that the high accuracy and high-resolution 3D data produced by SLS in combination with post-processing visualization tools were successful at enhancing the visibility of a variety of topological surface features such as slips, paint, molded reliefs, cracks, breaks, and even fingerprints for visual analysis.\textsuperscript{141}

The project examined here is particularly noteworthy, as it has fully integrated both documentation objectives with visualization and analytical objectives, and these clear, pre-determined research goals drive the methodologies conducted in the project. The methodologies and techniques are carefully used to augment their analysis, and their innovative use of new enhanced visualization techniques to extract subtle fingerprint details in particular is impressive, especially considering the study was conducted eight years ago as of writing. The successful extraction of the fingerprints on the objects and the subsequent analytical results has greater consequences for the discipline, as it not only enhances the available knowledge for these kinds of artefacts, but also adds a new and advanced tool with which researchers in the discipline can augment their own analyses in the future. This project has inspired the methodologies presented in this thesis research,

\begin{flushleft}
\textsuperscript{139} Lapp and Nicoli 2014, 34, 42-43.
\textsuperscript{140} Lapp and Nicoli 2014, 43.
\textsuperscript{141} Lapp and Nicoli 2014, 43.
\end{flushleft}
particularly the second aspect of the project involving the visualization of fingerprints. The successful application of 3D SLS and digital, visual shader tools on the 3D model resulting in the enhanced visualization and extraction of the intricate details of fingerprint led me to believe that a similar methodology could also be applied successfully on footprints and impressions on the surface of leather footwear, as they are similar types of impressions. Additionally, the project’s successful visualization and analysis of irregularities and different surface features suggested that similar results could be obtained on leather footwear to distinguish impression evidence and possibly illuminate other irregularities on the surface of the insoles.

The following case study, conducted by Tolksdorf et al. 2017, falls into the second sub-category, digital metric analysis. The project digitized 37 ancient Roman coins with Publius Varus (VAR) countermarks using high-resolution 3D SLS and conducted a combination of Procrustes analysis,\textsuperscript{142} metric statistics, and use-wear analysis to attribute countermarks to different wear-stages of the same specific die, and to reconstruct a chronology of the countermarks.\textsuperscript{143} The coins were scanned using a Breuckmann SmartSCAN-HE blue SLS and all 3D models were visualized as greyscale shaded relief images using the software TroveSketch to enhance the minuscule surface features and subtle topography of the coins.\textsuperscript{144} First, the project conducted a generalized Procrustes

\textsuperscript{142} Procrustes Analysis is defined by Donald A. Jackson as “A method of comparing two sets of data…the method is based on matching corresponding points (landmarks) from each of the two data sets. When dealing with morphometric data, these landmarks represent points or physical locations.” Donald A. Jackson, “Procrustes Analysis,” Jackson Lab, http://jackson.eeb.utoronto.ca/procrustes-analysis/.

\textsuperscript{143} The authors of the study focused their analysis on a group of VAR-countermarks of the Werz 227 1/1 type, which were conclusively attributed to die S13, as well as another group of well-preserved VAR countermarks from other dies. Tolksdorf et al. 2017, 400-402.

\textsuperscript{144} A blue light structured light scanner was chosen for this study because the wavelength of blue light (460 nm) avoids inaccuracies caused by reflective, shiny surfaces such as on coins. They note that the average resolution of the final 3D-models was 29 μm and all 3D data was processed using the proprietary software OPTOCAT (AICON). Tolksdorf et al. 2017, 403.
analysis on the countermarks, a process that compares the geometry of a set of defined landmarks on the 3D model, in order to determine if the dies could be separated based on their individual geometry. Next, having successfully identified the group of countermarks assigned to die S13, the project conducted a use-wear analysis on this subset to identify features related to use-wear and recutting of the die, consisting of the digital measurement of the width and depths of the incised letters and the sizes of the raised areas inside the letters A and R of the VAR countermark. The coins not belonging to the S13 die group or that stood out in the metric analyses were qualitatively compared using digital elevation maps, and coins assigned to the S13 die group were similarly compared, but with a focus on micro-wear features. Ultimately, the study used ten coins with use-wear characteristics that could be attributed to a particular use-wear phase together with the results of their metric analysis to reconstruct a relative chronology for the countermarks, as well as a spatial analysis. Most significantly, the study concluded that 3D SLS combined with metrical, geometric, and visual use-wear analysis was a powerful tool for establishing a refined chronological division of countermarked Roman coins.

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145 The project defined a set of 12 landmarks covering the entire area of the imprint (the letters VAR) using the R-package geomorph. The authors note that a complete set of landmarks was recorded for only 32 countermarks with sufficiently preserved outlines. Tolksdorf et al. 2017, 403-4.

146 The authors note that all 3D-models were aligned manually to a horizontal plane using OPTOCAT. To facilitate the use-wear analysis, digital slope maps of the raised areas of the die were also calculated using the 3D data and the software Surfer. Tolksdorf et al. 2017, 404.

147 Elevation maps were created from the 3D models with a shared elevation colour scale starting from the lowest point of the VAR imprint. Tolksdorf et al. 2017, 404.

148 The results of their combined analysis suggested that since the latest countermarks with the most use-wear were found in the Rhine area, the chronological position of the S13 die should be placed somewhat before the last military campaign of Varus in 9 CE. Tolksdorf et al. 2017, 404, 409.

149 Tolksdorf et al. 2017, 409.
This project combines 3D SLS and digital post-processing analytical techniques in a meticulous and innovative manner, incorporating several types of analytical techniques used in different scientific disciplines to achieve a set of preestablished research objectives for advancing our understanding of the artefacts and their historical contexts. The project presents a thorough methodological workflow consisting of both qualitative and quantitative analyses. Their use of 3D SLS takes full advantage of the ability of the technology to capture extremely small, subtle details in high resolution and with extreme accuracy to facilitate precise, digital metric and comparative analyses on the countermarks that would not be possible using other techniques. They also make use of some enhanced visualization techniques to augment surface features in order to conduct more accurate analyses. Their analytical results were concrete and meaningful, and provided new analytical tools available to augment the analysis of Roman coins.

The second primary objective of the “Pottery Goes Public” project conducted by Opgenhaffen et al. 2018, discussed previously in the public dissemination and outreach category, was to evaluate the potential of 3D visualization and analytical tools for enhancing the quality and quantity of information regarding technological aspects of ancient pottery manufacturing.\textsuperscript{150} The methodology conducted by the project was twofold. First, it included the quantification of potting techniques and gestures using 3D macro trace analysis of surface features, and the geometric analysis of shape morphology on a subset of vessels from Satricum. Second, it involved the 3D visualization, measurement and comparison of impressed stamp decorations on a subset of vessels from the Secca di Capistello shipwreck.\textsuperscript{151} The first part of the methodology used a

\textsuperscript{150} Opgenhaffen et al. 2018, 62, 64.
\textsuperscript{151} Opgenhaffen et al. 2018, 64-5, 69.
combination of digital analysis techniques, such as contours, curvature analysis, surface normal, and smoothing and decimation algorithms, to extract and enhance several types of surface features on the vessels.\footnote{Opgenhaffen et al. 2018, 64.} The results showed that integrating 3D SLS data with digital 3D macro trace analysis enabled the authors to visualize the vessel’s surface topographies more systematically and in greater detail than the naked eye or other 2D techniques. It also showed that additional features, such as stamp depth and orientation, could be recorded with much greater detail and precision.\footnote{Opgenhaffen et al. 2018, 64-5, 70.} The macro trace analysis provided the authors of the study with valuable information enabling them to identify different forming techniques and operational frameworks. Additionally, digital 3D geometric analysis on vessels of the Satricum assemblage revealed that the rims, bases, body shape and thickness, and finishing of the bowls were less homogenous than previously thought.\footnote{Opgenhaffen et al. 2018, 75-6.} The second part of the methodology consisted of a comparative analysis, which was completed by digitally aligning and overlapping the 3D scans of the different impressed stamp decorations of the vessels. This analysis involved both quantifying (using cloud-to-model distance computation) and visualizing the differences between the stamp erosion, angle, depth, and motif details to determine if the stamps were identical.\footnote{The comparative analysis and aligning of 3D data was conducted using the open-source software CloudCompare, which allows for the measurement of differences between large quantities of 3D data at once. Opgenhaffen et al. 2018, 70.} The comparative analysis enabled the visualization of the locations of stamp wear and differences in depth, angle, and motifs. Finally, a color depth map was used to enhance the differentiation between the 3D overlaps of the impressions.\footnote{Opgenhaffen et al. 2018, 75.} The results of the comparative analysis confirmed that none of the impressed stamp
decorations perfectly overlapped and that all of the petals of the rosette decoration were different, and thus, came from different stamping tools. Further quantitative analysis using the post-processing software CloudCompare reaffirmed these conclusions.\textsuperscript{157}

I have analysed a portion of this study above under the public dissemination category, so I am focused on the analytical portion of the study here. This project has clear and meaningful research objectives that effectively combine enhanced digital visualization techniques and several types of interdisciplinary analyses for the purpose of enhancing their understanding of the manufacturing processes behind the artefacts of study. Their digital analytical workflow was thorough, and they used the 3D data and post-processing software in an effective manner that facilitated more accurate analysis. The results regarding the comparative analysis between stamp impressions were illustrated both quantitatively and qualitatively, and their conclusions had significant impact on the understanding of the artefacts and enabled them to advance their construction of the chaîne opératoire for the production of stamped ware. However, the results for the geometric and macro trace analyses are a bit vague and are not elaborated as much as their other analyses, reducing the impact of their results for this specific aspect of the study. The successful use of 3D SLS data for visualizing and analysing the fine surface topographies of the pottery and the shallow impression depths made by stamps acted as another study demonstrating the effectiveness of 3D SLS for this type of application, and its potential for successfully visualizing the subtle depths of foot impressions on leather footwear.

\textsuperscript{157} Openghaffen et al. 2018, 75-6.
The project by Rossi et al. 2019, similar to Opgeenhaffen et al. 2018, incorporated both public dissemination and quantitative and qualitative analytical objectives. The project’s analytical objective was to 3D scan the Roman glass mirror using 3D SLS and analyse and quantify the morphologic, iconographic, and morphometric characteristics of the mirror in order to accurately reconstruct its optical properties. A series of digital measurements and metric analyses were conducted on the 3D model to calculate the center of the mirror circumference, center of the spherical cap circumference, and the center of the sphere, thus facilitating a full reconstruction of the glass sphere from which the small mirror was cut. These calculations showed that the mean radius of the glass sphere was about 9 cm, and this measurement was used for further metric analysis. The results of their metric analysis showed that the mirror would have provided the user with a field of view wide enough to mirror an entire face at a distance of 30cm and a maximum incidence angle of 33.7%, providing an effective overall field of view of 40.14 cm at face level. This data enabled the study to digitally reconstruct the complete optical properties of the mirror and conclude that the mirror was used as a makeup tool. In addition to their metric analyses, the authors found that the extremely high-resolution 3D model enabled the analysis of both the manufacturing techniques and iconographic features of the mirror as the smallest, subtlest details of the frame decorations were clearly visible. Thus, using digital measurement on the 3D model in post-processing software, the authors could precisely calculate the sizes and distances between the

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158 For a summary of the projects public dissemination objectives see the public dissemination and outreach category above.
159 Rossi et al. 2019, 94, 97.
160 For the complete technical methodology conducted here, see Rossi et al. 2019, 97-8, 100-102.
161 Rossi et al. 2019, 94, 100, 102.
162 Rossi et al. 2019, 97.
compositional and iconographic elements of the mirror, facilitating future comparisons with similar artefacts. Finally, a general geometric and decorative analysis of the elements of the mirror’s frame, enabled by the high accuracy data of the 3D model, confirmed that it belonged to group C of M. Buora’s frame classification.\textsuperscript{163}

The project combined 3D SLS, post-processing techniques and analytical methods in an innovative and creative manner, incorporating different interdisciplinary, digital measurement and morphometric analytical techniques to achieve well-defined and precise research objectives. The project takes full advantage of the high-resolution and accurate 3D data produced by SLS to facilitate advanced analyses and enhance the knowledge of the functionality of the artefact. The authors present a comprehensive methodology and illustrate their analyses quantitatively and qualitatively. The results of the study were concrete and consequential, enabling not only categorization, but a full reconstruction of the mirror and its optical properties, and thus advancing our understanding of roman technical processes and socio-cultural practices while at the same time providing a methodology for similar studies.

\textbf{2.3 Overview of Applications of Structured Light Scanning in Roman Archaeology}

Even without conducting a more thorough comparative analysis of the case studies above, certain trends in the use of 3D structured light scanning in Roman archaeology and their primary digitization objectives are apparent. Out of the seventeen case studies examined in this chapter, the majority of the case studies were categorized under the public dissemination and documentation categories, with six case studies and five case studies

\textsuperscript{163} Rossi et al. 2019, 97.
respectively. There were also several other case studies not categorized under those two categories that incorporated some form of public dissemination or documentation objectives, but I determined that they were not a significant enough part of the project for my analysis.\textsuperscript{164} In striking contrast to public dissemination and documentation, only four projects were categorized under the broad quantitative and qualitative analysis category, despite being arguably the most significant category for the utilization of advanced 3D imaging techniques and development of new digital research tools in the discipline. Surprisingly, there was only one Roman project that used 3D SLS for conservation purposes, despite the advantages it has for visualizing surface features in high-resolution, such as external damage, cracking, and natural and unnatural weathering and wear. Within the public dissemination category, many of the projects did not use the full potential of 3D SLS technology in innovative or advanced ways but used the technology to create 3D models suitable for public sharing on online platforms such as Sketchfab. Although the public dissemination of artefacts for open access by the public audience is incredibly important for archaeology and cultural heritage in its own ways, for my own purposes, these types of projects were not as valuable for influencing my own research goals and methodologies as other categories.

Most of the projects within comparative studies compared 3D imaging techniques such as SLS with traditional 2D techniques and demonstrated the benefits of 3D SLS over other methods, which by the writing of this thesis, has been well established. However, these studies provided comparative results that were useful when initially deciding my own project methodologies. In the documentation category, most of the

projects utilize SLS for straightforward or exploratory 3D digitization campaigns to test the feasibility of 3D SLS for documentation purposes. However, it is notable that four of five case studies under documentation were conducted in the earliest case studies from 2006-2013, as this was a period when we see the first uses of 3D SLS in the discipline as a relatively new method, and many projects were testing its digitization potential before adopting it fully as a 3D imaging tool and extending to analytical research. Finally, despite having only four case studies within the quantitative and qualitative analysis category, the studies that were included generally used 3D SLS and digital post-processing tools in innovative and consequential ways, and established clear, well-defined research objectives and methodologies that fully utilized the various advantages 3D SLS has for visualization and analytical research. They also generally produced significant results that contributed to the advancement of knowledge and analytical tools within their sub-fields.

Overall, it seems that the discipline of Roman archaeology seems to be more reluctant than other disciplines to utilize 3D SLS as standard practice in favour of traditional or less costly methods. When Roman researchers do adopt 3D SLS for various purposes, they use the technology mostly for digitization and public dissemination objectives, and thus as a whole, the discipline has not taken full advantage of the powerful visualization and analytical capacities of 3D structured light scanning and the versatility of different research avenues that it offers until more recent years. The discipline has also largely lacked the adoption of innovative 3D visualization and analytical methodologies conducted in anthropological archaeology and scientific-based disciplines such as medical science or engineering, whose strengths lie in their expansion
and refinement of the analytical tools available for researchers within their fields in order to enhance the quality and quantity of information that can be extracted. Several of the studies I researched within these non-classical disciplines during the thesis processes creatively applied 3D SLS and several interdisciplinary digital post-processing software tools to enhance the analysis and complete 3D characterization of objects and in innovative and meaningful ways, a task more difficult using traditional 2D visualization and analytical techniques.\textsuperscript{165} Thus, case studies using 3D SLS from non-classical or non-archaeological disciplines provided significant influence on the research objectives and methodology in this thesis project early in the process, particularly case studies from vertebrate paleoichnology and forensic podiatry.

2.4 Applications of 3D Imaging and 3D SLS in Vertebrate Paleochnology and Forensic Podiatry

The 3D scanning and digital analysis of leather Roman insoles for the purposes of capturing and visualizing footprint impressions on their surfaces has no precedent within the discipline of Roman archaeology. Thus, when looking for inspiration for the most suitable 3D imaging method for the research objectives outlined in chapter 1 and creating the methodology conducted in chapter 3 and 4, I looked for comparable applications from several disciplines. Ultimately, the closest comparable applications I found were the use of 3D imaging methods, including 3D SLS, for capturing and digitally analyzing

\textsuperscript{165} Some of these traditional 2D techniques include, but are not limited to, manual or digital illustration, photography, 2D scanning (such as flatbed or overhead scanners), 2D GIS (Geographic information system), microscopy, x-radiography, or RTI (Reflectance Transformation Imaging).
footprint impressions, tracks, and trace fossils in forensic science and vertebrate paleoichnology.

Vertebrate ichnology refers to the study of trace fossils and tracks made by vertebrate organisms on various substrates, such as animals, dinosaurs, and prehistoric humans. Paleoichnology is a sub-discipline of ichnology and palaeontology involving the description, classification, and interpretation of ancient ‘trace fossils’ or ‘ichnofossils.’

In the last two decades or so, researchers have adopted various 3D imaging systems for the precise capture and digital 3D morphological and morphometric analysis of the size, shape, depth, arrangement, and patterns of these trace fossils, which can often be damaged and/or very shallow in relief. Thus, I believed that the application of 3D imaging systems to capture trace fossils in substrates, particularly hominin footprints, and the digital enhancement and analysis of these tracks using post-processing software tools could be similarly applied to footprint impressions on insoles. The digital enhancement, visualization and morphological and morphometric analyses conducted by several iconological studies were particularly influential to the construction of the post-processing methodology conducted in this thesis, described in detail in chapter 3. Several studies used the 3D data and perspective manipulation capabilities in post-processing software to visualize, measure, and compare the changes in the depth of the tracks (even very shallow ones) in order to analyse the plantar pressure points made on the substrate by the foot during the walking gait cycle of the organism.

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166 Catuneanu 2022, 44.
167 These studies typically use photogrammetry or laser triangulation scanning, not 3D SLS, most likely due to outside environments for scanning and the necessity to scan large surface areas of substrates. 3D SLS was the most optimized method for the indoor scanning of medium sized objects such as shoes.
168 For examples of some studies conducted on hominin footprints and tracks, see Bennett et al. 2013, Bennett et al. 2016, Gierlinski et al. 2017, Bennett et al. 2020, and Helm et al. 2023.
between the depths of trace fossils in substrate and the very shallow impressions found on insoles, I chose to adopt a similar approach to my own post-processing visualization and analysis with the goal of identifying similar topographical changes in impression depths on the Roman insoles. Furthermore, many ichnological studies utilized manipulatable virtual light sources, particularly low-angled light or oblique lighting, to improve the visibility of subtle surface features and topographical changes of low relief tracks under different perspectives and analyze all aspects of the tracks that may be hard to see under regular conditions.\(^{169}\) I believed that the successful use of a changing virtual light source and oblique lighting on low relief 3D track data to visualize subtle surface features could be used successfully on the subtle impression depths of Roman insoles and included it as a major aspect of my digital, post-processing enhancement and visualization methodology. Finally, several studies used rendering tools and expressive visualization tools found in post-processing software to enhance the visualization of certain track features, such as elevation, edges and slopes, 3D morphology and topographic changes.\(^{170}\)

The Screen Space Ambient Occlusion and Lambertian Radiance Scaling tools in particular were popular for improving the visualization of the 3D morphologies of the tracks and enhancing surface details, as well as characterizing shallow and/or faint track impressions. Considering that enhancing the fine surface details of the surface of the insole and visualizing faint impressions was the primary goal of my thesis research, I decided to implement both these tools in my post-processing methodology along with several other tools.

\(^{169}\) Lallensack et al. 2022, 10-11.

\(^{170}\) Lallensack et al. 2022, 1-2.
Similar to vertebrate ichnology, forensic podiatry is concerned with extracting and analyzing trace footprint impression evidence left behind in crime scenes on various surfaces or within discarded footwear. The increasing application in the last decade of 3D imaging methods for the capture and digital analysis of forensic footwear and footprint impression evidence on modern insoles had a significant influence in the early stages of the creation of the methodology conducted in this research. These impression analysis applications shared nearly identical objectives to my thesis research and the most comparable material samples to the Roman leather insoles in the dataset that I could find. The case study conducted by Crowther et al. 2021 was particularly influential for this thesis research and contributed to my decision to use 3D SLS. Crowther et al. 2021 conducted a feasibility study to test whether 3D structured light scanning could accurately capture footprint impressions on the surfaces of modern insoles for digital forensic measurement and analysis. The study used the digital post-processing software MeshLab to view and digitally measure the 3D models of the insoles. Similar to several studies conducted in ichnology, as described above, the study utilized the changing virtual light source tool to enhance their visualization of impression evidence. The study concluded that 3D SLS was successful at capturing footprint impression evidence to a sub-millimetre standard and could be used in conjunction with digital post-processing for visualization and measurement successfully. Thus, the results of the case study heavily inspired me to use a similar methodology on the ancient Roman

171 Thompson and Norris 2018, 1; Crowther et al. 2021.
173 Crowther et al. 2021, 82-3.
174 Crowther et al. 2021, 86.
insoles in my dataset, particularly the incorporation of 3D SLS and the software MeshLab for digital enhancement and visualization.

The comprehensive literature review conducted in this chapter examining the applications of 3D structured light scanning in Roman archaeological research has not only cohesively summarized the research conducted in the last two decades, but more importantly, highlighted the types of research projects that have not been sufficiently explored within the discipline, such as enhanced visualization, augmented quantitative and qualitative analyses, and digital metric analyses. This thesis research was formed around filling some of these gaps present within applications of 3D SLS in the discipline, and carefully used the research objectives, methodologies, and conclusions of the studies examined in this chapter as models from which to inform the creation of the research’s primary objectives and methodology, both negatively and positively. However, the most substantial inspiration for several aspects of the methodology conducted came from research within non-classical disciplines, particularly forensic podiatry and vertebrate ichnology. A detailed description of the full 3D scanning and digital post-processing enhancement methodology conducted in this thesis research is given below in chapter 3.
Chapter 3: Materials and Methods

3.1 Introduction

3.1.1 Roman Vindolanda

This research project uses material from the Roman period site of Vindolanda located in northern Britain. The site is a Roman military auxiliary fort and settlement and is a part of the northern frontier system of the Roman province of Britannia (Britain), roughly one and a half miles south of Hadrian’s Wall. It was occupied from the first through sixth centuries CE.\textsuperscript{175} Vindolanda is located in the central sector of the ‘Stanegate frontier,’ a line of Roman military forts stretching east to west along the Roman ‘Stanegate road’, built along the original ‘frontier’ line of the River Tyne and Solway Firth in the late 1\textsuperscript{st} century CE, with the Roman fort Coria (Corbridge) at the eastern end, and Luguvalium (Carlisle) at the western end (fig. 3.1).\textsuperscript{176} In the late 1\textsuperscript{st} century CE, the ‘Stanegate frontier’ was a simple system of communication and defense, consisting of a linear series of forts and watchtowers. It did not develop into a systematic or comprehensive frontier system, however, until after 105 CE, when the Romans withdrew from Scotland and established the new frontier along the Stanegate.\textsuperscript{177} It was around this period when many of the Roman sites along the Stanegate, including Vindolanda, Carlisle, and Corbridge, saw new fortifications built and permanent settlements develop. Finally, in the early 120s CE Hadrian’s Wall was built just north of the Stanegate, running east to west across the province as the official frontier line, accompanied by defensive measures including forts,

\textsuperscript{175} The fifth and six centuries are the post-Roman period at Vindolanda and will not be discussed here. R. Birley 2009; A.R. Birley 2002; Greene 2019, 311.
\textsuperscript{176} Greene 2013, 18; A.R. Birley 2002, 49, 54; Birley and Alberti 2021, 8; Greene 2019, 311.
\textsuperscript{177} Greene 2013, 18; A.R Birley 2002, 52.
milecastles and turrets. Vindolanda occupied a strategic position not only as a suitable stopping point for those travelling east-west along the frontier, but also acting as a north-south control point for the junction of the Allen and Tyne valleys and river systems and their native British inhabitants.178

Figure 3.1. The ‘Stanegate’ northern frontier in the late first century CE in northern Britain (© Andrew Birley/The Vindolanda Trust).

The site of Vindolanda was first occupied in the mid 80s CE and almost continuously occupied until the end of the 4th century CE by several different Roman auxiliary regiments, non-citizen infantry or cavalry units originating from other conquered provinces of the Roman empire.179 In addition to the soldiers, their male and female non-combatant dependents were also present at the fort. Vindolanda was occupied for a significant period of time, standing as one of the longest continually occupied sites

178 Birley and Alberti 2021, 8; Greene 2013, 18.
179 Primarily from northwestern Roman provinces such as Gallia Belgica and Germania Inferior, from which the main cohorts of Vindolanda, the Tungrians and the Batavians, originated. However, for some periods (VIA, VIB, & VIIIA), the garrisons occupying the site have not been positively identified. R. Birley, 2009, 141-168; Greene 2013, 18; A.R. Birley 2002, 42, 45-6; Greene 2019, 311; Birley and Alberti 2021, 10.
along the Roman frontier in Britain, aside from large urban centers. Because the stratigraphic sequence and dating of the site is well understood, the successive phases of the military fort in the same location can be examined in great detail. The occupation of Vindolanda is divided into several periods (or phases) from I (ca. 85 CE) to VIII (ca. 300-367 CE), which mark either the abandonment and re-occupation of the fort or the re-building of the fort in the same settlement location on a different alignment using slightly different construction techniques (see table 1). Between ca. 85 and 213 CE, at least nine forts were built at the site, of which the first five forts (ca. 85-130 CE) were made of timber and included external defensive ditch systems. A visitor to Vindolanda during its occupation by the Ninth Cohort of the Batavians in period III (ca. 100-105 CE) would have been first greeted by the west gate and the massive ramparts of the fort topped by palisades. As they continued inside along the via praetoria they would have immediately seen rows of soldiers’ barracks separated by small streets, and in the center of the fort a series of buildings including the granaries, a hospital (valetudinarium), the commander’s residence (praetorium), and the fort headquarters (principia).

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180 According to Andrew Birley (2016, 149), few of the successive forts and extramural settlements were the exact same size or shape, resulting in some of the site being covered by all nine periods of construction, while other areas were only intermittently part of the intramural and/or extramural areas of the site.
181 Birley and Alberti, 2021, 7-8; Greene 2019, 311; R Birley 2009; Buck et al. 2019, 2.
182 The layout of the Batavian fort at Vindolanda faced west, from where the via praetoria ran eastwards to intersect the north-south via principalis. A.R. Birley 2002, 49-50, 55.
Table 1: Periods of occupation at Vindolanda and occupying garrisons (© A. Birley/The Vindolanda Trust).183

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>DATE</th>
<th>GARRISON / POPULATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>AD 85-90</td>
<td>Coh. I Tungrorum</td>
</tr>
<tr>
<td>II</td>
<td>AD 90-100</td>
<td>Coh. I Tungrorum, Coh. VIII Batavorum</td>
</tr>
<tr>
<td>III</td>
<td>AD 100-105</td>
<td>Coh. VIII Batavorum</td>
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<tr>
<td>IV</td>
<td>c. AD 105-118</td>
<td>Coh. I Tungrorum + Vardulli cavalry</td>
</tr>
<tr>
<td>V</td>
<td>c. AD 120-130</td>
<td>Coh. I Tungrorum</td>
</tr>
<tr>
<td>VI</td>
<td>c. AD 140-160</td>
<td>Coh. II Nerviorum</td>
</tr>
<tr>
<td>VI A</td>
<td>c. AD 160-200</td>
<td>Garrison unknown</td>
</tr>
<tr>
<td>VI B</td>
<td>c. AD 200-212</td>
<td>Garrison unknown</td>
</tr>
<tr>
<td>VII</td>
<td>c. AD 213-275</td>
<td>Coh. IV Gallorum</td>
</tr>
<tr>
<td>VIII</td>
<td>c. AD 300-367</td>
<td>Coh. IV Gallorum</td>
</tr>
<tr>
<td>VIII A</td>
<td>c. AD 367-408</td>
<td>Garrison unknown</td>
</tr>
<tr>
<td>IX A</td>
<td>c. AD 409-600</td>
<td>Brigomaglos Warband</td>
</tr>
<tr>
<td>IX B</td>
<td>c. AD 600-800</td>
<td>Population unknown</td>
</tr>
<tr>
<td>X</td>
<td>AD 800+</td>
<td>Population unknown</td>
</tr>
</tbody>
</table>

By the late 2nd century CE, the forts at Vindolanda began to be made from stone constructions instead of timber, and the Romans built two stone forts on top of each other between ca. 140-213 CE (stone fort one from period 6-6A, a Severan fortlet in 6B, and stone fort two in period 7), and a third modification of the second stone fort in the late 3rd century CE (period 8). Each of the different forts at Vindolanda also would have had a series of defensive ditches surrounding the walls of the fort proper, and an active extramural settlement (*vicus*) occupied both by combatant and non-combatant civilians and infrastructure.184 The extramural settlement at Vindolanda was located just outside the western wall of the fort proper along the primary roadway branching southeast from the main Stanegate to the west gate of the fort (*porta principalis sinistra*) (fig. 3.2). The

183 Table taken from Birley and Alberti 2021, 10.
184 Recent excavations and finds from the extramural settlements at Vindolanda suggest that there were active extramural settlements in all periods at Vindolanda, and that early extramural settlements may have been occupied by a mix of local and non-local inhabitants. Birley, Meyer, and Greene 2016, 6; Birley and Alberti, 2021, 7, 10; Greene 2019, 311; A.R. Birley 2002, 55; Buck et al. 2019, 2.
settlement also contained a complex series of interconnected roads, including main ‘A’ roads, secondary, connecting ‘B’ roads, and unlabelled side streets and alleys. The various structures of the extramural settlement had a range of residential, commercial, industrial, religious, service and storage functions. By the end of the 3rd century CE, between ca. 280 and 300 CE, the extramural settlement at Vindolanda was abandoned permanently, and the civilian populations of the extramural settlement began to occupy the interior of the newly built and reorganized fort. There is evidence that the fort itself was still densely occupied by a mixed population of combatant and non-combatants into the 4th century CE, but the site might have been briefly abandoned in the late 3rd century with re-occupation inside the walls of the fort from the 4th century onwards. Although the settlement of the site of Vindolanda continued into the 800s CE, the last Roman military garrison (currently unknown) occupied the site from ca. 367 to 408 CE, around the time when Roman control over Britain ended. The official end of the Roman military occupation of Britain and its part as a province of the Roman empire is generally attributed to 409 CE, when Britain suffered from renewed Saxon attacks and the Diocese of Britain revolted against the Western Roman emperor Constantine III. What exactly happened to the Roman garrisons stationed in the northern regions is uncertain, but Robin

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185 Blake 2014, 25, 27-8, 55.
186 According to Bidwell & Hodgson, the change from extramural civilian settlement to intramural settlement was a typical feature of the Roman frontier towards the end of the 3rd century CE as garrison sizes shrank and/or policies shifted. From the early 4th century CE, the inside of the fort was modified to include domestic dwellings, homes for combatants and their families, commercial buildings, workshops, and religious and social spaces. Birley and Alberti 2021, 7; Bidwell & Hodgson 2009; 29-34; Birley, Meyer, Greene 2016, 2.
187 Evidence for the abandonment of the extramural settlement comes from a significant decrease in the quantity of coins after ca. 280 CE, and the complete absence of 4th-century pottery from the extramural settlement. The use of coins and pottery continue within the fort in the 4th century. Andrew Birley 2016, 150; Birley, Meyer, and Greene 2016, 2; Brickstock 2013, 121-125.
Birley has suggested that they were either ordered south, or gradually drifted away due to a lack of pay and supplies. However, in the absence of the Roman military, a substantial post-Roman population, consisting of at least some Christians and Anglo-Saxons, continued to occupy the old fort site of Vindolanda in the fifth to seventh centuries, and possibly after that.\footnote{For a general discussion on post-Roman activity at Vindolanda, see chapter 13 of R. Birley 2009. For the most detailed report on evidence of post-Roman occupation and activity at Vindolanda, see Birley and Alberti 2021. For evidence of post-Roman activity in the extramural settlement in particular at Vindolanda, see Blake 2014. R. Birley 2009, 169-172; A.R. Birley 2002, 15.}

![Figure 3.2. Vindolanda period VII fort (ca. 213-300 CE) and extramural settlement (vicus) of the third century CE (© Andrew Birley/The Vindolanda Trust).](image)

3.1.2 The Inhabitants of Vindolanda

This thesis research is primarily concerned with refining and expanding the podiatric data that can be extracted from the leather footwear of the inhabitants of Vindolanda, thereby
augmenting our understanding of the local demographic variables of the populations at
the site, both within and outside the fort walls. Thus, it is necessary to establish our
current understanding of the demographic population of the site at Vindolanda,
particularly that of the children, adolescents, and adult males and females from which the
leather insoles analyzed in this research belonged.

The presence of a substantial number of Roman military combatants within the
walls of the fort at Vindolanda from the 1st to 4th century CE is well attested and
indisputable. Vindolanda was garrisoned after ca. 85 CE by several different Roman
auxiliary regiments recruited from the other Roman provinces of the Empire, primarily
from the Celtic and Germanic speaking provinces of Gallia Belgica and Germania
inferior and superior (see table 1).190 It has been traditionally understood that wives,
children, and families of the soldiers and other non-combatants connected with the
garrisons would have lived in the extramural settlements of the Roman military forts of
the northwestern provinces. However, the work of Carol van-Driel Murray, P.M Allison,
and Lindsay Allason-Jones on the presence of women, children, and families in Roman
provincial military communities over the last three decades has definitively shown that
there was a considerable presence of women, children, slaves, and extended family
networks within the Roman military communities of the northwestern provinces.191 More
recently, the work of Elizabeth Greene on the socio-cultural aspects of this has
illuminated the presence and lives of women, children, and extended family networks at

190 For a more comprehensive examination of the various regiments that garrisoned Vindolanda see A.R.
Birley 2002; Birley and Alberti 2021.
Vindolanda, not just in the extramural settlements, but also within the fort walls itself. Evidence for the active presence of women, children, and families of various social ranks and cultural identities within the walls of Roman forts from the early stages of occupation in the northwestern provinces onwards has come from a range of sources, such as Latin literature, writing tablets, military diplomas, inscriptions, funerary epitaphs, archaeological assemblages and artefact distribution analyses. The categories of artefacts used to demonstrate the presence and habitation of adult women in Roman military forts, including within the praetoria, centurion quarters, soldier barracks and other intramural habitational spaces, have included ‘female artefacts’ such as spindle whorls, jewelry such as bracelets, decorative brooches, necklaces and beads, hairpins, and footwear. Artefacts indicative of the presence of children, such as infant remains and footwear, have also been found in these intramural, habitational spaces, and by proxy,

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192 Traditionally, historians contended that the wives and families of soldiers stationed in Roman military forts in the western provinces dwelled in the extramural settlements only, and that the space inside the fort walls were a heavily male-centered and military space. Greene 2013b, 17; Greene 2014, 29; Greene 2015, 125-6. For more on the topics of women in the military, see Greene 2012, 2013a, 2013b, 2014, 2015a, 2015b, 2016, 2017, 2020, and Allason-Jones, van Driel-Murray, and Greene 2020.

193 Several Latin authors, such as Cassius Dio, Julius Caesar, and Vegetius, describe a variety of non-combatants following the Roman army on their march, including women, children, and slaves. Writing tablets and concordances, particularly from Vindolanda, provide evidence for the wives, children, and slaves of commanding officers and centurions, and tablets with greetings and invitations to and from wives, siblings, friends, parent-in-laws, children, and others illustrate the presence of strong female and extended familial social networks along the frontier in Britain and at Vindolanda. Military diplomas from the 1st to 3rd c. CE record information about soldiers and their families. Greene’s work on Roman military diplomas has shown that it was more common for wives in military communities to come from the same tribe as their husbands or from the immediate military community itself, rather than from local tribes, although this occurred as well. Greene 2013a, 369, 371-380; Greene 2015, 125, 143; Greene 2017; Allason-Jones 2012, 475; Allason-Jones 2005, 51.

194 Numerous stone inscriptions and funerary epitaphs from Britain provide evidence for the wives, mothers, and siblings of commanding officers, centurions, and soldiers, as well as their children. Allason-Jones 2012, 472; Allason-Jones 2005, 50-1, 54, 57.


betray the presence of women and family units.\textsuperscript{197} At Vindolanda, almost all of these kinds of artefacts have been found in substantial amounts within the walls of the fort in various habitational spaces, not only corroborating the habitation of various women, children, and family units, but also aiding scholars in understanding the socio-cultural lives of these non-combatant groups within a provincial military community setting. In particular, the spatial analysis conducted by Andrew Birley on the deposition of specific artefacts from the 3\textsuperscript{rd} century CE extramural and intramural settlements at Vindolanda that betray the presence of male combatants and female non-combatants has shown that there is significantly more evidence for non-combatant adult women in intramural contexts than has previously been known.\textsuperscript{198} The intramural distribution of spindle whorls in particular, has shown that the majority of finds were from the domestic spaces of the barracks and \textit{praetorium}, and both spindle whorls, hairpins and beads were highly concentrated in the north-western barrack quadrant within the fort.\textsuperscript{199} This work has further proved that non-combatant women composed a significant part of the military communities at Roman forts like Vindolanda, and actively occupied spaces within the walls of the forts that have been traditionally seen as strictly ‘military’ and ‘male’ spaces, such as the barracks.

Apart from ‘gendered artefacts,’ Roman leather shoes are a particularly noteworthy category of artefacts that concretely demonstrate the widespread presence of women, children, and family units living inside the walls of the fort at Vindolanda. In the

\textsuperscript{197} Allison 2013, 65-108; Greene 2014, 29; Greene 2015, 136.
\textsuperscript{198} In this study, Birley used the deposition of socketed weapons and swords, military kits, crossbow brooches, shield bosses, helmet fragments, armour, and scabbard fittings as representative of the presence of male combatants. Depositional evidence for non-combatants as exemplified by adult women included spindle whorls, bracelets, hairpins, and beads. A. Birley 2016, 158-170.
\textsuperscript{199} A. Birley 2016, 159, 162, 170.
1990s, van Driel-Murray’s seminal works on the shoes excavated from inside the walls of the fort at Vindolanda in earlier periods of its occupation, including the 2\textsuperscript{nd}-century barracks (1993, 1995, 1998), was the first to demonstrate that shoes in these habitational spaces could be attributed to males, females, children and infant wearers, substantiating her argument that the intramural spaces of military forts were not ‘male only’ spaces. More recently, the work of Greene on footwear evidence from all periods at Vindolanda has further highlighted the presence of shoes belonging to women and children throughout all the habitational layers within the fort, including a substantial number found in the early occupational layers of periods 1, 3 and 4 (ca. 80s, 100-120 CE).\textsuperscript{200} The presence of shoes belonging to women and children within the fort is particularly important for this thesis work because of the important role footwear plays in strengthening our understanding the demographic populations of the site, including combatant and non-combatant men, women, and children. By extracting data from foot impressions on the insoles of Roman leather shoes, this research seeks to refine our knowledge of the sex and age of individuals wearing shoes found at the site, and how these individuals wore certain styles of shoes.

3.1.3 \textit{The Leather Footwear Assemblage at Vindolanda}

The leather footwear assemblage from Vindolanda constitutes the largest assemblage of archeological leather from any single site in the ancient Roman Empire, with over 4000 shoes found during archaeological excavations, dating from ca. 85 to 300 CE.\textsuperscript{201} The

\textsuperscript{200} Birley 2016, 158; Allason-Jones 2012, 473; Greene 2013b, 18-19; Greene 2014, 29; Greene 2015, 136.\textsuperscript{201} Roman footwear is found at several other sites in the northwest Roman provinces (See Groenman-van Waateringe 1975; Charlesworth and Thornton 1973; van Driel-Murray 1993, 2011, 2012; van Driel-Murray and Gechter 1983; Hoevenberg 1993; van Driel-Murray and Plicht 2016), but the assemblages found at
enormous size and range of shoe types in the assemblage provides the most comprehensive corpus available for the intense examination of the development of the styles of Roman shoes over a long period of time at a single, relatively isolated site. The assemblage also provides valuable insight into demographic questions regarding the sex, age, and health of their individual wearers in the well-defined historical context of a Roman provincial community. Due to the anaerobic and waterlogged conditions of the environment of the site, organic materials such as leather artefacts are often preserved extremely well in a stratified, securely dated archaeological sequence for the full period of Roman occupation. This situation provides a fruitful dataset of complete leather insoles from which to extract valuable podiatric and demographic data, offering a much more complete understanding of the Roman population at Vindolanda than is typical from most archaeological sites. Since the 1990s, the leather footwear assemblage at Vindolanda has also been used by scholars to determine the stratigraphic sequences of excavations with leather preservation, examine the construction techniques of Roman shoes and the possible existence of leather workshops on site, investigate the use of iron hobnails on shoe soles, and examine podiatric interventions and health outcomes.

these sites are much smaller than Vindolanda, with only a few dozen or at the most, a few hundred examples. Thus, their small assemblages do not have the same statistical significance to make overarching conclusions about shoes, unlike Vindolanda, but comparison with the assemblage at Vindolanda could assist in making convincing generalizations.

The abundance of textual and epigraphic evidence also aids in examining the economic, industrial, and social contexts relevant to interpreting the footwear assemblage. van Driel-Murray 1993, 30; Greene 2014, 29; Greene 2019, 310, 313-14.

Anaerobic, or anoxic, waterlogged environments have significantly reduced oxygen or oxygen-free conditions, denying the fungi and bacteria responsible for biological decay of organic objects the oxygen they need to function, and thus protecting them. Spriggs 2014, 202-205. For a more detailed explanation of the anaerobic and waterlogged conditions at Vindolanda, see ch. 3.2.1 below.

Van Driel-Murray 2001, 186.

As mentioned previously, in 1993 van Driel-Murray published her preliminary report on the Vindolanda footwear assemblage, the first of several of her seminal works on archaeological shoes in the Roman world, which has provided much of the information we have about actual Roman shoes.\textsuperscript{206} Using her research on the technologies used in the manufacture of the shoes from the Vindolanda leather footwear assemblage and other Roman site assemblages in the northwestern provinces, she determined Roman footwear could be classified into six main categories: Single piece, un-nailed shoes (e.g. Carbatinae), nailed bottom unit constructions, sewn bottom unit constructions, sandals (single layer or multi-layer nailed and/or sewn), wooden soles (e.g. clogs), and fibre sandals.\textsuperscript{207} At Vindolanda in particular, van Driel-Murray distinguished thirteen individual styles of shoes, each with four or more occurrences in the entire assemblage. In addition, from the late second century onwards, she identified an increase in styles occurring only once or twice in the assemblage. Thus, at Vindolanda it is possible to discuss the concept of evolving ‘fashions’ in relation to the rapid succession of new styles of footwear.\textsuperscript{208} In her 1993 report, van Driel-Murray examined the leather footwear evidence for all periods in the assemblage and identified the changes that occurred generally in shoe styles at the site, and the types of individuals who wore these styles. For period I, despite the limited evidence available to her at the time, she identified a trend of large, wide, and ‘rather shapeless’ soles, closely resembling those of period II.\textsuperscript{209} The majority of footwear from period III were nailed with ‘round nosed’ soles a little ‘shapelier’ than those from period II. She noted that period III included a significant

\textsuperscript{207} Van Driel-Murray 2001, 186; van Driel-Murray 2007, 345, 347.
\textsuperscript{208} Van Driel-Murray 2001, 186-7, 191.
\textsuperscript{209} Period II shoes had the full variety of Roman shoe categories. van Driel-Murray 1993, 31.
amount of well-preserved footwear belonging to women and children and were usually *carbatinae* and sandals. In contrast to the other periods, the footwear from period III was also notable for their “distinctive feet” and clustering of smaller sizes.\textsuperscript{210} The soles she examined from period IV were similar to those of period III, which she described as relatively natural shaped and round nosed, but the large wide shapeless soles of periods I and II were gone. The shoes from period V were mixed and mostly followed the styles from previous shoe types, but van Driel-Murray identified a later shift towards pointed soles and broader sandals typical of the stone fort I ditch fill (final dates of period VI).\textsuperscript{211} The shoes found in the stone fort I ditch fill were relatively homogenous in character, and sandals became more common in general and now found in male sizes. She also noted that sandals were broadened significantly in the front area of the sole. Thus, despite a lack of evidence available to her for the transitional Antonine period, van Driel-Murray identified a shift from early sandals, characterized by their natural shape, cut-out toes, and use by women, and later sandals, characterized by exaggerated wide soles at the top and adoption by men.\textsuperscript{212} She noted that the exaggeration of the width of soles at the top reaches its most extreme by ca. 240 CE, and by the late second century, the diversity of shoe styles increases greatly.\textsuperscript{213} During this period (ca. mid second century onwards), she also noticed an increase in the number of sewn soles. Nailed soles from this period tended to be natural and pointed, and extremely pointed, often swayed style soles begin to appear and become more common in larger male sizes. In fact, van Driel-Murray commented

\textsuperscript{210} Van Driel-Murray 1993, 31-2.  
\textsuperscript{211} Van Driel-Murray 1993, 33, 35.  
\textsuperscript{212} Van Driel-Murray 1993, 36.  
\textsuperscript{213} She also notes a new experimentation with cutting patterns and fastening methods, and the appearance of completely closed shoes and fashionable slippers with raised soles. Van Driel-Murray 1993, 36.
that it was notable that almost all of the more exaggerated and elaborate styles of footwear seemed to belong to adult males, and female sized shoes tended to be more ‘restrained’ with more naturally shaped soles, except for when straight, very narrow soles became popular towards the end of the second century CE. Finally, she noted that soles became more straight with a wide blunt shape in the late 3rd to 4th century CE. 214 In van Driel-Murray’s 2001 article on the dating of Roman footwear at Vindolanda and 2007 chapter on Roman footwear in the northwestern provinces, she discusses the evolution of sandal styles and sole shapes in particular, with the knowledge of the footwear evidence found at Vindolanda since the 1980s and 1990s.215 The development of sandal styles and sole shapes are particularly important for this thesis, as sandals compromise a significant portion of the insoles 3D scanned and analyzed in the following case studies, and the impact of certain sole shapes on how an individual’s feet would have been placed inspired a significant portion of the goals driving the research presented in this thesis, presented in more detail below.

3.1.4 Introduction to Thesis Case Studies

The research goals presented in this thesis, introduced in chapter one, center around addressing the gap in the demographic data that can be extracted from Roman leather footwear with ambiguous ownership. Up until this point, demographic information collected from Roman shoes, primarily that of age and sex, has been manually measured from the total lengths of the insole of the shoe, resulting in an ambiguous and overlapping

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range of sizes attributed to men, women, adolescents, and children (table 2).\textsuperscript{216} For shoes at Vindolanda, insoles with relative sizes between 120-189 mm (small) can be confidently attributed to young children anywhere between 5 and 11 years old, but insoles with relative sizes between 190-210 mm (medium) and waist widths between 31 and 50 mm can be attributed to either a larger child, adult female (18 years and older), or growing adolescent male probably under the age of 14. Additionally, insoles with relative sizes between 211-250 mm (large) can be attributed usually to an adult male (18 years and older), but sometimes may represent a larger adult female. Insoles with relative sizes above 250 mm (extra-large) can be confidently attributed to adult males.\textsuperscript{217} The current methodology provides a relatively good overarching picture of the demographic variables (e.g., age, sex, and health) of the local isolated community at this site, but the use of total length measurements and the overlaps in many shoe size ranges has made it difficult to attribute proper ownership of certain individual shoes with certainty. Furthermore, different styles of shoes (e.g., nailed with uppers or sewn shoes) and insole shapes such as pointed, rounded or wide upper areas affect the overall lengths and widths of the sole, masking the true size of the wearer’s foot and obscuring accurate ownership.\textsuperscript{218}

Thus, in order to fill the gaps in shoes with ambiguous ownership and refine the demographic data extracted from Roman shoes, this research uses 3D structured light

\textsuperscript{216} See Groenman-van Waateringe 1978, van Driel-Murray 1993, 43, van Driel-Murray 2007, 360 for the origins of established Roman foot size and age estimates. The length of the sole, especially the insole, is the closest guide to the actual foot size of the wearer, but it is not directly equivalent to actual foot length. Additionally, measurements of the widths of the waist of insoles may help to distinguish between female and male wearers, as females tend to have narrower feet than men. Note that the size ranges used in this research for the shoes at Vindolanda are based on conservative post-conservation leather measurements, allowing for potential shrinkage up to 2cm. van Driel-Murray 1993, 42; Greene 2014, 30-31.

\textsuperscript{217} Van Driel-Murray 1993, 42-44; Greene 2013b, 22; Greene 2014, 30-31.

\textsuperscript{218} Nailed shoes with closed uppers tend to be much tighter than sewn shoes, soft adjustable carbatinae, or open sandals, and thus, appear to be made for a larger foot size than the actual size of the wearer’s foot. van Driel-Murray 1993, 42, 44; van Driel-Murray 2001, 2007, 360.
scanning to capture and visualize footprint impression evidence on three different but interrelated case studies using three different datasets from the leather footwear assemblage at Vindolanda. The first case study examines sandals with identifiable toe thongs, the second examines insoles with prominent pointed toes, and the third examines insoles currently attributed to young children. The clear and accurate visualization of the foot impressions, their size, shape, and placement on the insoles chosen for these case studies, and future work digitally measuring this podiatric data digitally and precisely according to anthropological and bioarchaeological measurement systems, will provide a much more accurate picture of who the Roman individuals wearing these shoes were and how they wore specific styles of Roman leather footwear. The following section discusses the preservation and conservation contexts of the footwear assemblage at Vindolanda and outlines the dataset of insoles scanned for each of the three case studies chosen for this research.

**Table 2: Relative insole sizes and possible ownership for footwear in the Vindolanda leather footwear assemblage.**

<table>
<thead>
<tr>
<th>Relative Insole Size (mm)</th>
<th>Possible Ownership</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small (120-189)</td>
<td>Young child (walking age to ca. 11 years old)</td>
</tr>
<tr>
<td>Medium (190-210)</td>
<td>Female/Adolescent (ca. 12 years to 18 years)</td>
</tr>
<tr>
<td>Large (211-250)</td>
<td>Adult Male (ca. 18 years and above)</td>
</tr>
<tr>
<td>Extra Large (250 +)</td>
<td>Adult Male (ca. 18 years and above)</td>
</tr>
</tbody>
</table>
3.2 Materials

This research project centers on 3D structured light scanning insoles from the leather footwear assemblage at Vindolanda. The unique preservation contexts at Vindolanda and the conservation treatments applied to the shoes have both contributed to the present conditions of the shoes scanned in the dataset. The conditions of the surfaces of the insoles, the focus of scanning, are particularly important to consider for their potential negative effects on the quality of the scans and thus, the ability to extract foot impressions from the 3D models. Therefore, an examination of the preservation contexts and conservation processes of the shoes included in this research, ranging in date from the 1970s to 2010s, is necessary to identify whether these factors have any impact on the scanning results and digital, post-processing enhancement conducted in the study.

3.2.1 Preservation Contexts at Vindolanda

The excellent preservation of leather footwear found at Vindolanda is in part due to the natural anaerobic, waterlogged conditions of the site’s burial environment, preserving organic material remains in excellent conditions in many areas of the site. Anaerobic, or anoxic, burial conditions are formed by the complete or almost complete exclusion of oxygen from the burial medium (e.g., soil, clay) through water saturation. The exclusion of oxygen denies the micro-organisms (fungi and bacteria) that are responsible for biological decay of organic materials the oxygen they need to metabolize and function. Thus, these ‘oxygen-free’ or oxygen ‘reduced’ burial conditions provide excellent protection against the decay of organic materials and corrosion of metals such

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as copper, lead, and iron due to oxidation processes.\textsuperscript{220} Anaerobic, waterlogged conditions in particular, are most prominent in the sediment layers at the bottom of rivers, lakes, in fenlands, marshlands, and peat bogs, and in urban contexts where the natural water table is raised artificially through centuries of deliberate dumping of organic debris.\textsuperscript{221}

Artefacts made of organic materials such as leather, wood, animal and plant fibers, can survive burial in anaerobic conditions for thousands of years if sufficiently sealed with their chemical equilibriums undisturbed, and their surfaces can retain a significant level of their pre-burial detail.\textsuperscript{222} Generally, the preservation level of leather excavated from anaerobic, waterlogged burial conditions is dependent on a combination of pre-and post-depositional factors such as the methods of manufacture, wear and tear from use, the extent of decay during burial, as well as tanning quality and the animal species and body area from which the leather was derived.\textsuperscript{223} The tanning method used by the Romans, ‘true tanning’ using vegetable extracts, allows the leather to survive particularly well in wet, anaerobic conditions because the tanning process makes the collagen fibers of the leather structure resistant to hydrolysis.\textsuperscript{224} Waterlogged preserved leather is typically black or almost black/dark brown in colour, including the leather

\textsuperscript{220} Spriggs 2014, 202; Orr et al. 2021, 2.
\textsuperscript{221} Spriggs 2014, 202; Orr et al. 2021, 2.
\textsuperscript{222} This is particularly true for the leather footwear in the Vindolanda assemblage, which is generally preserved exceptionally well compared to many other Roman sites without anaerobic burial conditions. Spriggs 2014, 203.
\textsuperscript{223} Roman leather footwear was made of several different animal leathers. Thick, specially treated cow hide was used for the soles of shoes, goat and calfskin was used for the uppers, sheepskin for the linings, and fine, soft leathers such as deerskin was used for luxury slippers. This research deals only with leather insoles, and thus, thick cow hide leather is particularly important here. Van Driel-Murray 2007, 339-340.
\textsuperscript{224} Hydrolysis is the chemical breakdown of a compound due to the reaction with water. Cameron, Spriggs, and Wills 2006, 245; van Driel-Murray 2007, 337; Spriggs 2014, 203.
found at Vindolanda, due to the saturation with humic matter in the burial medium and the by-products of the chemical reactions between iron salts and tannins in the leather.\(^{225}\)

In addition to the natural anaerobic and waterlogged conditions of the site environment, human-made anaerobic, waterlogged layers were produced by the systematic levelling, raising, and rebuilding over the same areas of the site between each period of Roman occupation discussed in 3.1. Between each of these occupation periods, the wooden and then later stone buildings were deliberately demolished and the ground levels of the entire site were sealed with thick layers of turf and clay (sometimes up to half a metre in depth) to create a clean, gradually raised foundation on which new buildings for that period were erected, forming several sealed layers over time in which oxygen was excluded from the material underneath. This waterlogging above the dense clay layers led to the formation of anaerobic preservation layers, preserving the old foundations, floorboards, debris, artefacts that lay in or near the old buildings, or were deliberately dumped in fort ditches, including leather shoes.\(^{226}\) According to Andrew Birley, this type of levelling, raising, and rebuilding made the post-depositional movement of objects by humans or animals from one stratigraphic layer to another, less probable, thus creating well-secured stratigraphic sequences. By the end of the 4\(^{th}\) century CE, some parts of the site had risen above the pre-Roman ground level by more than 6 metres.\(^{227}\)

The exceptional levels of preservation found at Vindolanda are due to a combination of natural, environmental factors producing exceptional anaerobic and

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\(^{225}\) Cameron, Spriggs, and Wills 2006, 245; van Driel-Murray 2007, 340.
\(^{226}\) Orr et al. 2021, 1; A. Birley 2016, 149; Greene 2019, 311; R Birley 2009, 42.
\(^{227}\) A. Birley 2016, 149; R. Birley 2009, 51.
elemental conditions, and human produced anaerobic, waterlogged contexts. As a result, the most well-preserved leather artefacts are typically found in the waterlogged levels of ditches from all periods and the backfilled and raised levels of the site, as well as in areas where soil is preserved under thick layers of ground clay.\textsuperscript{228} Orr et al. studied the unique chemical and microbial conditions of the anaerobic, waterlogged environment of the site that led to the increased archaeological preservation of organic artefacts.\textsuperscript{229} In this study, natural environmental conditions were identified as the first factor contributing to the unique anaerobic conditions of the site, including the fact that the site was situated on the Alston formation, a calcium carbonate sedimentary bedrock, overlaid by loamy and ‘clayey soils,’ resulting in a local geochemistry and hydrology promoting preservation.\textsuperscript{230}

In addition, they also highlighted the appearance of a hydrated iron (II) phosphate mineral called Vivianite (\(\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}\)), produced in the anaerobic layers at the site as a result of the microbial community within the soil, which is associated with instances of good preservation of artefacts at the site.\textsuperscript{231} Furthermore, they proposed that the changes in moisture conditions at Vindolanda “may allow reactions with organic material within the soil, which facilitates a natural ‘tanning’ process.” Thus, in regard to chemical and microbial environmental factors promoting the preservation of organic artefacts at the site, the authors of the study concluded that the soil contains distinctive chemical and

\textsuperscript{228} van Driel-Murray 2001, 186; van Driel-Murray 2007, 337; Orr et al. 2021, 2; Greene 2019, 311-12.
\textsuperscript{229} Orr et al. 2021, 1.
\textsuperscript{230} They state that anaerobic soil rich in organic material are more likely to show reduced biological oxidation of leather. The geochemical and hydrological factors impacting artefact preservation include redox reactions, such as Fe(III) reducing to Fe(II), and formations of Vivianite through combinations of Fe(III) and phosphate, microbiological decrease of Proteobacteria, Actinobacteria and Firmicutes, pH values, conductivity and oxidation-reduction potential, and the decomposition material surrounding highly organic matter, including those rich in phosphates. Orr et al. 2021, 1, 5-6.
\textsuperscript{231} They propose that the high concentrations of iron and phosphorus within locations showing preservation could suggest why increased levels of vivianite are observed here. Orr et al. 2021, 2, 5.
microbial communities dominated by *Firmicutes, Bacteroidetes* and *Proteobacteria*, which were associated with layers that show increased preservation of organic/inorganic artefacts. They also suggest that the specific conditions of the soil potentially allow the microbial production of *Vivianite* and *Methylophilus*, which may lead to enhanced preservation of artefacts in anaerobic conditions.\(^{232}\)

In her 1993 report on the leather footwear assemblage from Vindolanda, van Driel-Murray commented that the leather was generally well-preserved and that the exceptional burial conditions in which they were found did not seem to affect the pre-depositional state of the leather “very much.” Thus, importance was placed more on the pre-depositional condition in which the leather entered the soil, which she noted showed signs of original wear and deformity from use by their Roman wearers.\(^{233}\) This observation remains true today based on my own observations, and it is evident that the preservation conditions of a significant number of the leather shoes in the assemblage have not significantly altered their pre-depositional shape or surface conditions. Many shoes still retain almost all their surface details and topographical features from their pre-depositional state.\(^{234}\) Thus, the exceptional preservation contexts and conditions of the leather shoes in the assemblage provided the best collection of samples with which to apply the research’s methodology successfully. Most of the insoles selected for the three case studies in this research were registered as in ‘excellent’ or ‘good’ preservation conditions in the assemblage database, with a few notable exceptions (discussed below).

\(^{232}\) Orr et al. 2021, 1, 6-7.
\(^{233}\) She also noted that the footwear available at the time from the first four periods of the site seem to have been sealed quite rapidly after being discarded, and thus, were in ‘markedly’ better conditions than the footwear from the two later ditches (outer ditch, period VI and inner ditch, period VII, VIII). van Driel-Murray 1993, 2.
\(^{234}\) This is especially true for the thick cow hide leather from which Roman insoles were made, making the insoles selected in this study a significantly well-preserved dataset. Greene 2019, 312.
in order to have the best quality dataset for 3D structured light scanning and digital analysis. In doing this, I hoped that the insoles that were preserved exceptionally well would yield the best 3D scanning results and thus, the best odds for extracting and visualizing footprint impression details. A more detailed discussion on the selection criteria for insoles for each case study will follow in sections 3.2.3 to 3.2.5.

3.2.2 The Conservation Process of Roman Archaeological Leather at Vindolanda

The wet leather footwear excavated from Vindolanda is generally unstable once taken out of the ground due to their waterlogged state. Thus, the conservation processes conducted at the site, just as at other sites with organic, waterlogged artefacts, aim to transform the leather artefacts from unstable to stable conditions in a process known as ‘remedial conservation.’ This is generally achieved through ‘interventive’ conservation treatments designed to remove the water from the leather artefact, while limiting any damage from the effects of drying on the weakened cell and fibre structures of the leather. The entire conservation process of waterlogged leather materials at Vindolanda normally consists of five phases: Initial storage before treatment, washing, chemical treatments, drying, and long-term storage. The first phase, initial storage, occurs immediately after the leather is removed from the ground. The wet, waterlogged leather requires wet storage immediately in order to avoid irreversible shrinkage and embrittlement caused by uncontrolled drying. This is achieved by placing the wet leather, still dirty from the ground, in perforated polythene bags and then storing it in plastic

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235 Historic England 2018, 34.
boxes or tubs containing tap water with airtight lids in cool, dark storage conditions.\textsuperscript{236}

The initial on-site treatment begins with the preliminary washing of the leather artefact in tap water with soft brushes or sponges to remove the surface dirt.\textsuperscript{237} The following phases of the conservation process, primarily the laboratory chemical treatments and drying of the leather, have changed since the initial processes of the early 1970s, and differ in several ways from the conservation methods used by other conservators and institutions in Britain. This is partly due to the unique size of the leather assemblage at the site, requiring an unusually large number of artefacts that need to be conserved, making the process significantly more costly and time consuming than other sites. Thus, the conservation process used at Vindolanda needed to be efficient, cost-effective, and able to be conducted on site, and different from techniques used at other sites with fewer leather objects or big institutions with more complex infrastructure, such as the British museum. The conservation processes conducted on the leather insoles since the 1970s, especially the chemical treatments applied, is significant for this research because of the potential effects it may have on the shape, size, and surface conditions of the insoles and how these conditions might affect the ability of the 3D structured light scanner to capture the small, subtle details necessary for the purposes of the project.

In the early 1970s, leather conservation was not conducted on site, but rather sent to the Department of Archaeology at Manchester University for conservation, including

\textsuperscript{236} The leather should be placed in reduced light levels or ideally, dark storage environments to stop microbiological growth and keep temperatures down. Keeping the storage environment cool also reduces temperatures, slows decay rates, and stops microbiological growth. Historic England 2018, 25, 35; Cameron, Spriggs, and Wills 2006, 246; Jackman 1989.

\textsuperscript{237} Historic England 2018, 38; Cameron, Spriggs, and Wills 2006, 246; Jackman 1989; van Driel-Murray 1993, 2.
the so-called Lepidina sandal. Generally, early 1970s conservation treatments for waterlogged leather in Britain involved the gradual replacement of the water in the artefact with oil, such as castor oil. From personal correspondence with the current curator for the Vindolanda Trust, Barbara Birley, however, I learned that the laboratory conservation treatment at this time involved the impregnation of an early form of Carbowax™ Polyethylene Glycol (PEG) wax into the leather, which replaces the excess water and gives the degraded structure of the artefact dimensional stability for subsequent freeze-drying treatment. In my personal experience handling some of the early 1970s PEG-treated leather shoes in the Vindolanda assemblage, the shoes treated in this manner are noticeably stiffer and heavier than more modern, non-PEG treated shoes, exceptionally darker in colour (typically black), and the surfaces of the insoles were noticeably glossier compared to the non-PEG insoles. Thus, insoles treated with this early form of PEG will most likely negatively affect the 3D scanner’s ability to precisely capture their surface and their subtle topographical features. Thus, for researchers interested in 3D scanning leather shoes with SLS, I argue it would be more fruitful and efficient to scan shoes that have not been treated with early forms of PEG.

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238 James Jackman (1989) commented that the leather artefacts conserved externally in the early 1970s were noticeably dark in colour and heavily impregnated with lanolin, which tended to obscure some of the fine surface details.
239 Cameron, Spriggs, and Wills 2006, 247.
240 Bruno Muhlethaler (1973) notes two different treatment methods using Carbowax™ PEG. The first method immersed Roman leather placed between glass-plates in a bath of molten Carbowax™ 750 wax, a methoxy-polyethylene glycol with a melting point of 30 degrees Celsius. The second method, utilized by the British Museum Laboratory at the time, immersed leather in a bath of molten Carbowax™ 1500 (a mixture of equal parts Carbowax™ 300 and 1540) with a melting point of 40 degrees Celsius, and left the leather immersed in the molten wax until the water had been replaced with the wax. It is probable that one of these two methods, or a similar method, was employed on the leather artefacts from Vindolanda conserved with Carbowax™ PEG in the early 1970s. A lower molecular weight PEG, PEG-400, is still commonly used in modern conservation treatments in Britain. Personal correspondence with Barbara Birley 03/02/2023; Cameron, Spriggs, and Wills 2006, 248; Historic England 2018, 35; Muhlethaler et al. 1973, 66-67.
The conservation process of early 1970s leather from Vindolanda also included freeze-drying the leather.\textsuperscript{241} During freeze-drying, the PEG in the leather acts as cryoprotectors, and afterwards, as lubricants and humectants. The appearance of the leather afterwards is generally dry, and the finer details of decoration, manufacture, and wear is highly visible.\textsuperscript{242} Despite the fact that PEG and freeze-drying conservation treatments were considered successful at the time, the whole process was lengthy, taking over six weeks, and required more storage tanks and equipment than there was space available at the time. Thus, the Director of excavations for the Vindolanda Trust at the time, Robin Birley, looked for a relatively simple, quick, but effective way of conserving the large amount of leather in the assemblage on site at Vindolanda.\textsuperscript{243}

By August of 1975, a new conservation process and set of chemical treatment methods for leather artefacts began to be used on-site at Vindolanda. The chosen treatment method was a modified version of the “Rector method” established by W.K Rector at the conservation laboratories of the Guildhall Museum, London. This modified method was composed of three stages: initial on-site treatment, chemical treatment, and dehydration and lubrication (For the full process and chemicals used see appendix A). During the chemical treatment stage, the leather was placed in a bath of 2% acetic acid for 1 hour. This treatment apparently did not create as pronounced of a lightening effect on colour of the leather as the original Rector method, but it was found to be more “in keeping with the condition of the leather.”\textsuperscript{244} Furthermore, during the dehydration and

\textsuperscript{241} Personal correspondence with Barbara Birley 03/02/2023; Historic England 2018, 35.
\textsuperscript{242} Overall, freeze-drying was and is still used commonly today in Britain as it eliminates traditional drying stresses and large quantities of material can be stabilised relatively quickly. Historic England 2018, 35; Cameron, Spriggs, and Wills 2006, 248.
\textsuperscript{243} Jackman 1989.
\textsuperscript{244} Acetic acid is a synthetic carboxylic acid with antibacterial and antifungal properties. Jackman 1989; Cameron, Spriggs, and Wills 2006, 247; “PubChem Compound Summary for CID 176, Acetic Acid,”
lubrication stage, a two bath acetone dehydration treatment was applied to the leather, which removes the water from the cellular structure of the leather while maintaining the original shape and flexibility of the leather. Finally, a leather dressing solution was applied to the leather to protect it from natural degradation processes, plump up the surface, and improve the leather’s dry appearance. At first, a leather dressing called the ‘Guildhall Leather Dressing’ was used on many of the leather finds from 1975 to the around the mid 1980s, but shortly before 1989 Vindolanda shifted to using the ‘British Museum Leather Dressing’ (BMLD). The ‘Guildhall Leather Dressing’ reportedly caused minimal colour changes, but could achieve quick penetration, sufficient and stable lubrication, and protection against fungal growth, and “had a good feel to the finished artefact upon drying.” The leather artefacts treated with the ‘British Museum Leather Dressing’ (BMLD) are generally darker in colour than those treated with the ‘Guildhall Leather Dressing.’ Cameron et al. note that some levels of shrinkage “were always experienced with these leather dressing treatments (typically 5-10% linear reduction), but the properties of texture, feel, flexibility and weight were all considered satisfactory.”
If this is true for some of the leather insoles scanned in this research, the shrinkage shouldn’t significantly alter the ability to visualize and enhance footprint impression evidence on the insoles, nor the measurements of the foot impressions, which are separate measurements from the length of the insoles themselves.

The conservation treatment method used on the leather at Vindolanda since August 1975 was slightly modified once again sometime between 1989 and 1993 at Vindolanda, noted by van Driel-Murray in her 1993 Vindolanda report.249 The conservation treatment used from 1993 onwards, including the modifications made between 1989 and 1993, is given in detail in Appendix B. Generally, the laboratory treatment in the modified Rector method was not as strictly timed or controlled as the newly reported method from 1993. Additionally, the use of glass plates and tissue paper during the drying process was a new addition to the conservation process.250

Barbara Birley relates that not much has changed in the conservation process and treatment methods outlined by Jackman in 1989 and Van Driel-Murray in 1993. Birley noted that current conservation practices only call for the use of glass plates to gently flatten shoes during the air-drying process if there is any significant warping or folded areas on the shoe, and that this practice typically has a minimal effect on the surface and shape conditions of the shoe from its original preservation conditions. She also commented that if any potential shrinkage or minor shape changes occurred during the conservation process, it would happen during the acetone solution bath treatment, but she argues that changes seem to be very minimal and rather negligible, especially for the purpose of this research. Finally, she noted that in addition to the application of the first

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249 Van Driel-Murray 1993, 2.
leather dressing, the shoes chosen to be placed in the display cases at the Vindolanda site museum have an additional leather dressing solution applied to them. Greene 2014 states that the conservation processes applied to the leather shoes of the assemblage at Vindolanda “do not alter the shoe dramatically,” and that modern calculations of conservation techniques regarding leather show only a small amount of shrinkage (3-5%), which would result in an overall difference in shoe size of less than 1.0 cm. In her professional experience working on the conservation process at Vindolanda, Barbara Birley remarked that overall, very minimal changes occur during the conservation treatment process in the physical conditions of the leather shoes from their original preservation conditions (incl. size, shape, surface details), and that no further glossiness or high surface reflection should happen during this process that could significantly affect the quality of the 3D scans in a negative way. In my own personal experience handling over eighty leather shoes from different time periods in the assemblage, I agree with the comments made by B. Birley, and will add that all the shoes I handled were robust, flexible and stable enough to be handled and moved around by hand for personal examination, photography, and 3D scanning without any issues.

The shoes I ultimately chose for the three case studies of this research were in various physical conditions, but 71 of the 81 (87.65%) shoes chosen were characterized

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251 This leather dressing solution is the “Leather Restoration Conditioner” produced by Preservation Solutions®. Unfortunately, Preservation Solutions® does not state the ingredients and composition information anywhere due to trade secrets, and thus, I was only able to determine that it does not contain water, but rather contains a solvent with no sulphur content, and is non-toxic and contains low VOCs. Personal correspondence with Barbara Birley 03/02/2023; “Leather Restoration Conditioner,” Preservation Equipment Ltd, https://www.preservationequipment.com/Catalogue/Cleaning-Products/Cleaning-Agents/Leather-Restoration-Conditioner-P993-0800; “Leather Product Directions,” Preservation Solutions, https://preservation-solutions.com/pages/leather-product-directions/.

252 According to Greene, for shoes between 180-210 mm, shrinkage would only amount to a roughly 0.5 change. Greene 2014, 30.
as in excellent or good conditions in the museum database.\textsuperscript{253} These shoes were completely intact and appeared well-preserved, dry in appearance and in various shades of brown and black, with small, subtle surface details of decoration, manufacture, and pre-depositional wear and tear from use highly visible with the naked eye.\textsuperscript{254} Generally, I observed that these shoes had only a few minor instances of wrinkling, cracking or warping, some small areas with minor tears, light scratches or other instances of minimal damage, and some with slight discolouration in certain areas or rust around stud holes. Apart from the majority of shoes in excellent or good condition, only nine insoles were characterized as in mediocre condition, and one as in poor condition.\textsuperscript{255} The shoes in mediocre condition generally had more warping, tearing, folding, and damaged or missing areas of the insoles than the rest. I observed that some of them had noticeable areas with small scratches, some wrinkling and cracking, and some had minimal colour discolouration and rusting of various degrees. Although the goal in choosing specific insoles for the case studies and 3D scanning was to choose the insoles in the best-preserved conditions, some insoles in mediocre condition were chosen either for notable features, or to test if the 3D scanning and digital post processing methodology conducted in this research could be successful on less well preserved insoles. A more in-depth discussion on the conditions and surface details for the specific insole chosen for each of the three case studies will be conducted below in 3.2.3 to 3.2.5.

\textsuperscript{253} 26 out of 30 insoles in case study one, 33 out of 35 insoles in case study two, and 21 out of 25 insoles in case study three.
\textsuperscript{254} These characteristics were the main reason these specific insoles were picked for the case studies, aside from their appropriate construction or size.
\textsuperscript{255} 3 mediocre condition and 1 poor condition insoles in case study one; 2 mediocre condition insoles in case study two; and 5 mediocre condition insoles in case study three. The insole in poor condition was chosen specifically for my additional interest in visualizing the inscription present on the insole more clearly.
3.2.3 Case Study One: Pointed Toe Insoles

The first case study conducted in this research consists of a dataset of 30 insoles with swayed or tapering sole shapes and narrow pointed toe shapes (see appendix C for dataset). The insoles in this case study were not limited to a particular size range or ownership category. Fourteen insoles had relative sizes between 211-250 mm (large), a size range typically attributed to adult male ownership, and six insoles had relative sizes between 190-210 mm (medium), typically attributed to female/adolescent ownership category.\textsuperscript{256} Five insoles had relative sizes above 250 mm (extra-large), attributed to adult male ownership, and finally, five insoles had relative sizes between 120-189 mm (small), attributed to ownership by a child. It should be noted that two of the insoles within the large size category are attributed to female/adolescent ownership and three are attributed to adult female ownership, because either the insole measurements or style indicated a non-adult male ownership, or both together conclusively indicated a female ownership.\textsuperscript{257} Additionally, one insole within the medium size category is attributed to adult female ownership, because it is in the upper size range (195 mm) and has a very narrow waist.\textsuperscript{258} The primary research objective directing the first case study was determining where exactly the individual’s foot, particularly the toes, lay on insoles with particularly narrow, pointed toe shapes. Would the individual’s foot sit further back in the shoe to avoid squeezing their toes in the narrow, pointed toe area? Or would the individual indeed wear

\textsuperscript{256} Insoles within this size range are assigned to female/adolescent because adolescent boys grow through the female size range.


\textsuperscript{258} L-2003-395-A.
the shoe with their toes squeezed into the narrow, pointed toe area? As mentioned previously, foot length estimates, relative sizes, and subsequently ownership for all insoles in the Vindolanda assemblage are based on the measurement of the entire insole length from seat to toe, resulting in potentially incorrect data and ownership attribution for shoes with narrow pointed toe shapes. Using a combination of 3D structured light scanning and digital post-processing visualization techniques, the goal was to obtain clear footprint impression data, successfully visualizing exactly how these particular sole shape styles were worn regarding the position of the foot on the insole. With this impression data, I can gain accurate individual foot length measurements and assign more precise ownership of the individual insoles in the dataset.

There are three insoles of particular note in the dataset for case study one (see appendix C). The first, L-1992-3416, is the only insole chosen for this research that has been designated as in ‘poor’ condition, primarily because it is broken into two pieces. I chose to include this insole in my research for two reasons. First, I wanted to see if the proposed methodology would work on insoles in less ideal or ‘poor’ conditions and thus, could be applied to a larger dataset in the future or to assemblages with worse preservation contexts than Vindolanda. The second notable insole, L-2003-395-A, was chosen because the entire length of the insole was incredibly narrow in comparison to the rest in the dataset, and I was interested in determining where the foot would sit on a very narrow waist and if it would show impression evidence. If impressions were visible on this insole, I wanted to obtain accurate foot measurements to give a better determination of the individual who wore this particular shoe. Finally, L-2007-94-A, was chosen because it was unclear whether it was an insole or outer sole (without hobnails), and I
determined that it would be worthwhile to see if I could visualize any foot impressions, thereby confirming it as an insole or outer sole. If the methodology was successful, it could be applied to other ambiguous soles in the assemblage in the future to confirm what part of the sole construction they belonged to.

3.2.4 Case Study Two: Sandal Insoles

The second case study conducted in this research consists of a dataset of 35 sandal insoles with identifiable toe thongs (see appendix D for dataset). The insoles in this case study were not limited to a particular size range or ownership category, nor to any particular time period or sole shape. Eighteen insoles in the dataset had relative sizes between 211-250 mm (large), a size range typically attributed to adult male ownership, and six insoles had relative sizes between 190-210 mm (medium), typically attributed to female/adolescent ownership. Another six insoles had relative sizes above 250 mm (extra-large), assigned to exclusively adult male ownership, and five insoles had relative sizes between 120-189 mm (small), assigned exclusively to ownership by a child. However, two insoles with relative sizes between 211-250 mm (large) were assigned adult female ownership because their insole measurements, especially the narrowness of the waist, and styles strongly suggested ownership by a woman. Additionally, one insole within the medium size category was assigned to an adult female for the same reasons. The primary research goal directing the case study was determining where exactly the individual’s foot sat on the insoles of Roman sandals that have their toe

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260 L-1992-3464. It should be noted that the seat of this insole is missing, so insole length and seat max. width measurements are estimates, which has impacted the reliability of this insole’s relative size and ownership category.
thongs located very high up on the insole near the top edge of the toe area. It is currently uncertain whether the individual’s foot sat further up on the insole and their toes hung off the front edge of the shoe, or if the foot sat further back on the insole and their toes rested at the edge of the toe area instead. Visualization of foot impressions on the insoles in the dataset would allow me to precisely determine where the individual’s foot, particularly their toes, was placed on sandals with toe thongs. I am also interested in determining if the different sandal sole shapes and cut-out toe patterns found in the dataset have any meaningful impact on the placement of the foot on the insole.

There is a singular insole of note in this dataset (see appendix D): L-2003-392-A. Similar to insole L-2003-395-A in the first case study, this insole was chosen because of its very narrow waist, which provided an opportunity to determine if footprint impression evidence could be extracted from such a narrow waist, potentially indicating how the individual foot was placed on a shoe of this style.

3.2.5 Case Study Three: Children’s Insoles

The third and final case study conducted consists of a dataset of 25 insoles (see appendix E for dataset) with relative sizes between 120-189 mm (small) or 190-210 mm (medium), and ownership attributed to young children from the age of 5 to 11 years old. There is one insole of exception, however, with a relative size between 190-210 mm (medium), currently assigned to a female/adolescent.261 The insoles chosen for the dataset were not limited to a specific type of shoe or sole shape, but with the exception of one secondary test carbatina, none of the insoles chosen had uppers that could significantly

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261 L-1994-4252. Visualization of a foot impression and the extraction of more accurate measurement data will help clarify whether this insole belongs to a child, adolescent or female.
obstruct the 3D scanner’s view of the insole surface.\textsuperscript{262} The primary research goal for this case study was determining whether some shoes currently assigned to ownership by a young child actually belong to small-footed adolescent male or female ownership by visualizing their foot impressions. As noted earlier, insoles with relative sizes between 120-189 mm (small) and 190-210 mm (medium) can be assigned potentially to three ownership groups: young children, female/adolescents, and adult females. These indeterminate range of sizes and ownership categories are the result of the current limitations in manually collecting foot measurements from the entire insole. Thus, by visualizing foot impressions, much more precise foot measurements can be extracted from each insole and then assigned more accurate ownership. More accurate ownership assignments will also assist in gaining more accurate demographic information on the populations living at the site.

There is one insole of note in this dataset (see appendix E), L-2002-282-A, which I have already noted above is the only \textit{carbatina} in the entire study. There are some uppers present on the right and back side of the shoe, but the uppers were flexible enough to peel back so the scanner could still capture a significant portion of the interior surface. This \textit{carbatina} was chosen as a singular test sample to see if foot impressions would be visible on a singular construction shoe of this style.

\textsuperscript{262} L-2002-282-A. 3D structured light scanners cannot penetrate through mediums, and therefore, can only scan what is directly in view. This is the reason why single-piece construction shoes or soles with their uppers preserved were generally not chosen for this research.
3.3 Methods

3.3.1 Data Acquisition: 3D Structured Light Scanning at Vindolanda

3D structured light scanning was conducted in June 2022 at the Vindolanda site museum in the UK. A total of 81 insoles were scanned over the course of roughly three full working days. The 3D scanning itself was conducted by Dr. Rhys Williams, a lecturer in forensic science at Teesside University, UK, who has previously conducted 3D structured light scanning at Vindolanda and kindly agreed to provide and operate all the necessary equipment on-site, as well as to process the 3D models. Due to COVID-19 complications preventing me from being on-site for the week of the scanning process, Dr. Elizabeth Greene oversaw the entire scanning process and aided Dr. Williams with carefully handling the shoes during the scanning. The structured light scanner used was an HP 3D Structured Light Scanner Pro S3 (formerly the DAVID SLS-3) with a projector and a single industrial HDMI camera with a high quality lens mounted on a stationary, sliding rail (for technical specifications see table 3). The scanner was first calibrated during an initial test scan using the proprietary HP calibration board, and the projector and camera were ultimately calibrated to 120 mm when scanning the leather insoles in order to capture smaller and finer details on the surface of the insoles. The insoles were scanned in a room with dim, diffused lighting in order to pick up darks and lights better, and the projector was set to a brightness of 173 lumens. Shutter speed was set to 1/30th of a second for the shoes in medium shades of brown, and 1/10th of a second shutter speed was used on the shoes in darker shades of brown and black in order to pick up more light.

263 The projector was in focus on the artefact, and the camera was in focus with the projector. Personal concordance with Dr. Rhys Williams 09/2022.
on the surface of the insoles.\textsuperscript{264} The shoes were rotated until all visible surfaces were scanned. Overall, it took approximately 10-14 scans to scan all the surfaces of the shoe and approximately 10-15 minutes to scan each shoe.\textsuperscript{265}

The scans for each shoe were then registered together and processed into 3D models by Dr. Williams using the proprietary HP 3D Scan Pro 5 software (formerly DAVID V5). The first step in this process was the free alignment of separately captured scans for each shoe using the ‘pairwise fine registration’ tool, which uses surface features as guidelines to align the captured scans automatically and sequentially. Next, after all separate scans were aligned, the ‘global fine registration’ tool was run (80 iterations) in order to convert all of the 3D frames (or captures taken during scanning) into a single coordinate system.\textsuperscript{266} Finally, ‘sharp fusion’ was used to fuse the scans into one 3D model (resolution=1500, sharpness=1 mm, and close holes= 1\%).\textsuperscript{267} After the initial processing of the 3D models was complete, Dr. Williams imported all of the 3D models into the post-processing software MeshLab© for image/texture capture, surface cleaning and mesh simplification of the 3D models (quadratic edge collapse decimation).\textsuperscript{268}

\begin{flushright}
\textsuperscript{264} More light is picked up with a faster shutter speed, which was particularly useful for capturing details on darker coloured shoes. Personal correspondence with Dr. Rhys Williams 09/2022.
\textsuperscript{265} Personal correspondence with Dr. Rhys Williams 09/2022.
\textsuperscript{267} Fusion is a process that creates a polygonal 3D model by ‘melting’ and ‘solidifying’ the captured and processed frames. Sharp fusion is an algorithm that perfectly reconstructs fine features and sharp edges in a higher level of detail than other fusion algorithms. Personal correspondence with Dr. Rhys Williams 09/2022; “Data Processing,” Artec Studio 12 documentation, 2017, http://docs.artec-group.com/as/12/en/process.html.
\textsuperscript{268} Mesh simplification compresses the file sizes of the 3D models to make them more manageable. Personal correspondence with Dr. Rhys Williams 09/2022; Ranzuglia et al. 2013.
\end{flushright}
Finally, the finished 3D models for each shoe were exported and sent to me as .obj, .mtl, and .png files for further digital post-processing enhancement.

Table 3: Technical specifications for the HP 3D Structured Light Scanner Pro S3 (formerly DAVID SLS-3).

<table>
<thead>
<tr>
<th>HP 3D Structured Light Scanner Pro S3 (formerly DAVID SLS-3)</th>
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<tbody>
<tr>
<td><strong>Projector</strong></td>
<td>LED 3D Acer K132 (1280x800 resolution)</td>
</tr>
<tr>
<td><strong>Camera</strong></td>
<td>HP 3D HD Camera Pro (2.3 Megapixels)</td>
</tr>
<tr>
<td><strong>Max resolution</strong></td>
<td>0.05 mm (50 microns)</td>
</tr>
<tr>
<td><strong>Max point accuracy</strong></td>
<td>0.05 mm (50 microns)</td>
</tr>
<tr>
<td><strong>Colour &amp; texture capture</strong></td>
<td>Full colour and texture capture</td>
</tr>
<tr>
<td><strong>3D mesh density</strong></td>
<td>2,300,000 vertices per scan</td>
</tr>
<tr>
<td><strong>Object size</strong></td>
<td>60-500 mm</td>
</tr>
<tr>
<td><strong>Scanning time</strong></td>
<td>2 seconds per scan</td>
</tr>
</tbody>
</table>

3.3.2 Digital Post-Processing Enhancement and 3D Visualization

The processed 3D models of the insoles in this research come in two different versions; one version has photo-realistic, coloured 2D textures applied and the other has texture coordination turned off, displaying the 3D model without these 2D coloured textures applied in default greyscale. I found that for the purposes of visualizing and analyzing impression evidence, the 3D models without texture coordination (un-textured) significantly reduced the busyness of the surface & provided the best visibility of the topographic features, decorative details, contours, shapes, and use-wear on the insole’s surface. The un-textured model was also the best version for visualizing any surface irregularities or intricate surface details that were obscured by the realistic, coloured 2D
textures, a problem inhibiting detailed analysis of the insole with the naked eye.

Furthermore, with texture coordination off, I found that it was easier to visualize the effects of lighting and shading on the surface topologies and geometric features of the insoles, which made visualizing impression evidence possible. Thus, the 3D models without texture coordination were chosen for all the digital post-processing enhancements conducted in this research.\(^{269}\)

The 3D-mesh processing and post-processing software used to conduct all enhancement and visualization was MeshLab (v.2022.02).\(^ {270}\) I chose to use MeshLab for several reasons, the first being that it is an open-source, free software, and thus, more accessible than some other commercial 3D processing software.\(^ {271}\) More significantly, MeshLab has also been used successfully by several different kinds of archaeological, cultural heritage and forensic studies, and thus, has a precedent within relevant disciplines, not only indicating its potential usefulness for this research, but also providing relevant methodological data.\(^ {272}\) These studies have made use of some of the powerful 3D expressive visualization techniques and rendering tools offered by the software. The tools and techniques used for the 3D enhancement and visualization conducted in this research included the manipulation of a virtual light source and the

\(^{269}\) In addition to texture coordination= off, the basic settings used for each 3D model were Back-Face= single, Colour= Mesh, and Shading= Face.

\(^{270}\) An advanced 3D model processing software for processing, editing, cleaning, inspecting and visualizing 3D models. The software can import and export a large variety of 3D mesh formats and point clouds. Cignoni et al. 2008; Ranzuglia et al. 2013; Vergne et al. 2012.

\(^{271}\) Open-source software are also made freely available for others to make custom modifications or add additional tools, which can be useful.

application of several advanced rendering tools, shaders, and plugins. MeshLab allows the user to freely manipulate the direction of a virtual light source, which reduces the impact of unwanted shadows on visible features, including insole footprint impressions, as discovered by Crowther et al. in their study on modern insoles. According to Crowther et al., the ability to change the direction of a virtual light source allows the user to find the optimum angle of light for visualizing footprint impression features on the surfaces of the insoles, such as toes, waist, heel, etc. For my own digital enhancement methodology, I chose to utilize the manipulation of a virtual light source in the same manner for each insole.

In addition to manipulating a virtual light source, I also used a set of various expressive 3D visualization rendering tools and shaders available on MeshLab. These tools generally exaggerate meaningful surface features according to the geometry of the 3D model, resulting in better shape characteristics. By emphasizing meaningful surface features in contrast to less meaningful surface features, these tools often create a better representation of the topography of the surface and remove possible ambiguities. Thus, rendering tools and shaders are incredibly useful for clarifying and exaggerating the visibility of certain features and closely examining topographical details and geometric shapes. The rendering and shader tools used in the methodology conducted here included Shadow mapping, Screen Space Ambient Occlusion, Cook-Torrance, Dimple, Lattice, Minnaert, Phong, Reflexion_lines, and Lambertian Radiance Scaling. I applied each

273 Crowther et al. 2021, 82-3.
274 Vergne highlights that lighting variations correlate to surface feature variations, so thus, the adjustment of light directions improves the distinction between concave and convex surface features. Crowther et al. 2021, 82-3; Vergne et al. 2012.
275 Vergne et al. 2012.
chosen rendering or shader tool individually to each insole 3D model one by one to determine their effectiveness at enhancing foot impression evidence. If I found that the specific tool applied enhanced my visualization of any kind of impression evidence on the insole, I took a screenshot and saved it for further visual analysis, and then proceeded to apply the next tool, and so forth. If I found that no impression evidence was visible using a specific tool, I would note it and move on to test the next tool. A technical explanation of each tool is outside the scope of this thesis, and this information is easily accessible and better explained elsewhere. In the following chapter, however, more specific detail will be given regarding the effects of each tool on the enhancement and visualization of foot impression evidence for the insoles in the datasets. Finally, the results of each primary case study described above will be presented and discussed in detail, along with the implications of these results for advancing podiatric data collection within the discipline.
Chapter 4: Results and Discussion

This chapter presents the results of the 3D structured light scanning and digital, post-processing enhancement and visualization methodology conducted in this research, described in chapter 3. It first presents the results obtained from the analyses conducted on the insoles in each case study without any accompanying interpretations or conclusions, in order to illustrate the results in their raw form. It is important to note that more analysis needs to be done in the future to examine the effects of some of the post-processing tools used in the methodology more closely on the objectivity of some of the qualitative results presented in the following chapter, but regularly recurring impression results and direct comparisons with modern podiatric in-shoe plantar pressure research validate the results overall. The results for each case study are followed by individual discussions with interpretations of the results for each case study and consideration of their significance and implication for the thesis research. The chapter finishes with a comprehensive discussion of the collective results of the analyses conducted in this research and their significance to the research objectives of the thesis as outlined in chapter 1. It concludes with the implications of these results for advancing podiatric analytical tools available to researchers within the discipline and expanding local demographic knowledge at the site of Vindolanda. Finally, it proposes future avenues for further research and analyses.
4.1 Case Study One: Pointed Toe Insoles

4.1.1 Results

As explained in chapter 3, a total of 30 insoles were scanned using 3D SLS and digitally enhanced and visualized using a set of various rendering and shader tools available in the 3D processing software MeshLab. Each insole model was carefully and meticulously visually analysed to identify any traces of 2D or 3D footprint impression evidence on the surface of the insole, including sweat stains, surface wear and indentations from chronic re-use. Out of 30 insoles in this case study, 23 insoles (N=23, 76.67%) revealed some form of identifiable footprint impression evidence, ranging from vague and faint to prominent and clear, and varying in location, size, and shape. Seven insoles (N=7, 23.33%) did not exhibit any identifiable impression evidence that could be confidently attributed to footprint impressions. Out of the 23 insoles with identifiable footprint impression evidence, 12 insoles (N=12, 52.17%) were characterized as exhibiting ‘good’ footprint impression evidence, and 11 insoles (N=11, 47.83%) were characterized as exhibiting ‘ok’ footprint impression evidence (Table 4). Due to the limitations of a master’s thesis, which prevents me from presenting the results for each of the insoles in this thesis research, only insoles characterized as having ‘good’ footprint impression evidence or insoles otherwise notable will be presented for each case study. The results for these select insoles will be presented in the order they appear in the case study dataset (see Table 4 and Appendix C). The terminology used in this chapter to label the different sections of the Roman insole are those previously established by van Driel-Murray (see Fig 4.1).276 For reference, the seat of the insole, otherwise known as the heel,

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276 Van Driel-Murray 2007, 345.
is the back section of the insole at where the heel of the foot is placed on the surface. The tread of the insole is the section on the upper half of the insole where the ‘ball’ of the foot is placed on the surface. The waist is the section between the tread and the seat/heel, corresponding to where the arch of the foot is placed, and the toe is the small section above the tread where the toes are placed.

Table 4: Case Study One: Footprint Impression Results.

<table>
<thead>
<tr>
<th>Insole #</th>
<th>Impression Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-1985-19</td>
<td>Good</td>
</tr>
<tr>
<td>L-1986-146</td>
<td>None</td>
</tr>
<tr>
<td>L-1986-158</td>
<td>Good</td>
</tr>
<tr>
<td>L-1986-164</td>
<td>Good</td>
</tr>
<tr>
<td>L-1986-174</td>
<td>Ok</td>
</tr>
<tr>
<td>L-1986-368</td>
<td>None</td>
</tr>
<tr>
<td>L-1986-464</td>
<td>Ok</td>
</tr>
<tr>
<td>L-1986-578</td>
<td>None</td>
</tr>
<tr>
<td>L-1986-579</td>
<td>Ok</td>
</tr>
<tr>
<td>L-1986-676</td>
<td>Ok</td>
</tr>
<tr>
<td>L-1986-679</td>
<td>Good</td>
</tr>
<tr>
<td>L-1986-682</td>
<td>Ok</td>
</tr>
<tr>
<td>L-1986-686</td>
<td>Good</td>
</tr>
<tr>
<td>L-1992-3416</td>
<td>Good</td>
</tr>
<tr>
<td>L-2001-231</td>
<td>Ok</td>
</tr>
<tr>
<td>L-2003-395-A</td>
<td>None</td>
</tr>
<tr>
<td>L-2004-36-A</td>
<td>Good</td>
</tr>
<tr>
<td>L-2004-115-A</td>
<td>None</td>
</tr>
<tr>
<td>L-2004-159-A</td>
<td>Ok</td>
</tr>
<tr>
<td>L-2005-27-A</td>
<td>Good</td>
</tr>
<tr>
<td>L-2006-51-A</td>
<td>Ok</td>
</tr>
<tr>
<td>L-2007-84-A</td>
<td>Good</td>
</tr>
<tr>
<td>L-2007-94-A</td>
<td>Ok</td>
</tr>
<tr>
<td>L-2007-158-A</td>
<td>None</td>
</tr>
<tr>
<td>L-2016-204</td>
<td>Good</td>
</tr>
<tr>
<td>L-2016-268</td>
<td>None</td>
</tr>
<tr>
<td>L-2016-358</td>
<td>Good</td>
</tr>
<tr>
<td>L-2016-373</td>
<td>Ok</td>
</tr>
<tr>
<td>L-2016-415</td>
<td>Good</td>
</tr>
<tr>
<td>L-2016-452</td>
<td>Ok</td>
</tr>
</tbody>
</table>
Figure 4.1. Terminology for Roman footwear. (Above) Labelled sections of a Roman insole. (Below) Labelled sections of a complete Roman shoe unit.277

Results: L-1985-19

Footprint impression evidence was successfully visualized on this insole by mimicking the oblique lighting technique used by forensic investigators on impression evidence with the virtual light source tool in MeshLab, without any additional rendering tools or shaders. I have characterized the footprint impression evidence for this insole as generally ‘good’. Footprint impression evidence was most prominent on the tread and

277 Image retrieved from van Driel-Murray 2007, 345.
upper waist areas of the insoles, associated with the darkest regions, with fainter impressions visible on the toe and heel/seat regions (fig. 4.3). A rough outline of the footprint impression can be traced from the heel/seat to the big toe print area on the upper medial side of the insole. The footprint impression evidence visible on this insole correlates well with in-shoe plantar pressure points (plantar pressure points=darker impression evidence on the insole) during normal walking gait, with the greatest pressure on the heel and metatarsophalangeal joints (MPJs), commonly known as the ‘ball’ of the foot, and the interphalangeal joint (IPJ), the big toe (see figure 4.4-4.7). On this insole it seems that the impression evidence on the heel/seat was centered primarily on the lateral heel, correlating with the plantar pressure on the lateral heel that occurs from the first point of touch on the ground during a normal walking gait. The heel impression, however, is not as deep or pronounced as the impression on the tread of the insole (the MPJs) and the big toe area (IPJ), potentially indicating an irregularity in the gait of this individual, or simply indicating a lack of impression evidence in the heel area for other unrelated reasons.

Figure 4.2. Photograph of insole L-1985-19.

Figure 4.3. Screenshot of MeshLab view showing footprint impression evidence on un-textured 3D model of insole L-1985-19, enhanced with an oblique virtual light source only. (Left) Visualization of impression evidence from the waist to the tread and toe area, and faint evidence on the lateral side of the seat/heel. (Right) Visualization of impression evidence from the toe area to heel/seat of insole.
Figure 4.4. Illustration of in-shoe plantar (sole) pressure during the major phases and events of a full gait cycle for a normal human (right heel strike to right heel strike). HS=heel strike, FF=foot flat, MSt = midstance, HO=heel off, TO=toe off, IS=initial swing, MSw=midswing.\textsuperscript{280}

Figure 4.5. Illustration representing the 10 anatomical regions of interest of the foot and peak plantar pressure points (in colour) during the normal human gait cycle. (1) Interphalangeal joint (IPJ); (2) Lesser toes; (3) Metatarsophalangeal joint 1 (MPJ1); (4) MPJ2; (5) MPJ3; (6) MPJ4; (7) MPJ5; (8) Midfoot; (9) Medial heel; (10) Lateral heel. The magnified area highlights the interphalangeal joint (IPJ) and

\textsuperscript{280} Taken from Wafai et al., 2015, 20393, figure 1.
metatarsophalangeal joints (MPJs) in regions 1, 3-7 of the foot, where significant pressure is placed.\textsuperscript{281}

Figure 4.6. 2D and 3D representation of in-shoe plantar (sole) pressure distribution in a healthy control during the stance phase of the gait cycle, from heel strike to heel off, and the average pressure distribution from four stances.\textsuperscript{282}

\textsuperscript{281} Taken from Wafai et al. 2015, 20396, figure 2.
\textsuperscript{282} Taken from Wafai et al. 2015, 20399, figure 3.
Figure 4.7. Diagram illustrating the different regions of the plantar surface (sole) of foot.\textsuperscript{283}

\textbf{L-1986-158}

I identified both 2D and 3D footprint impression evidence on this insole using a variety of digital, post-processing tools and techniques in MeshLab. I was able to detect 3D impression evidence on the insole by simply viewing the insole model from an oblique perspective, providing me with a better visualization of the subtle changes in the surface topography of the insole, and thus, allowing me to identify the physical indentations made by plantar (sole) pressure points during the gait cycle (refer to fig. 4.4-4.7). Using this technique, two areas with 3D impression indentations were immediately

evident on the heel/seat and tread of the insole (fig. 4.9), correlating with expected plantar pressure points from the heel and the metatarsophalangeal joints, (the ‘ball’ of the foot), during a normal walking gait cycle.\textsuperscript{284} I also identified more subtle 3D impression indentations that I associated with the big toe (IPJ) and some of the lesser toes of the foot just above the tread, in the upper regions of the insole close to the edge (see fig. 4.9). Having identified clear traces of 3D impression evidence on the insole, I continued my analysis by applying a set of various rendering tools, shaders, and a changing light source, as outlined in 3.3.2. I was able to identify 2D footprint impression evidence with several different tools and light sources, but I found that the “Dimple” shader and the “Lambertian Radiance Scaling” plugin were most effective at visualizing the entire footprint impression on the insole (fig. 4.10). The footprint impression visible using both the “Dimple” and “Lambertian Radiance Scaling” tools is nearly identical, but I found that “Dimple” was useful for clarity as it depicts the impression evidence in black/greyscale against a yellow surface colour for the insole (fig. 4.10, left),\textsuperscript{285} whereas the other is visualized in greyscale only (fig. 4.10, right).\textsuperscript{286} The 2D impression evidence visible with these two tools supplemented the findings of 3D impression indentations found on the heel/seat, tread, and toe areas, indicating additional areas with significant impression evidence (the darker areas=more pressure) on the lateral heel, waist, MPJ1 pad, and anterior MPJ6, and MPJ7 where the top of the ‘ball’ of the foot met the insole. Additionally, these tools clarified the placement of all five toes on the upper region of the insole, revealing that the individual’s toes were placed very close to the edge of the

\textsuperscript{284} Wafai et al. 2015, 20393-20399; Grew and de Neergaard 2002, 106; Swallow 1975, 28-9.
\textsuperscript{285} “Dimple” shader technical specifications: Density=0, LightPosition=55,0,5, Scale=0, Size=0.
\textsuperscript{286} “Lambertian Radiance Scaling” plugin technical specification: Enhancement=1.00, Invert Effect=off, Double side=off.
insole, against the wall of the uppers of the shoe (see fig. 4.10). Overall, a nearly complete footprint impression can be traced from the heel to the toes of the foot. The location of the darkest footprint impressions appears to indicate that the individual favoured the medial midfoot (see fig. 4.10). Thus, the impression may indicate an irregular or asymmetrical gait different from a normal gait cycle, but this cannot be confidently determined without further research and analysis. Additionally, the impression made by the midfoot is relatively wide, which may indicate more pressure was placed on the medial arch of the sole of the foot. It may also be simply due to a wider midfoot, which is possible as the relative size of the insole is large and is attributed to an adult male.

Figure 4.8. Photograph of insole L-1986-158.
Figure 4.9. Screenshot from MeshLab displaying 3D impression evidence visible on insole L-1986-158 from an oblique perspective.

Figure 4.10. Screenshot from MeshLab displaying impression evidence on insole L-1986-158. (Left) Impression evidence visible with “Dimple” shader. (Right) Impression evidence visible with “Lambertian Radiance Scaling” Plugin with 1.00 enhancement.
L-1986-164

Similar to insole L-1986-158 above, I began my analysis by identifying any 3D impression evidence using a combination of a changing virtual light source and an oblique perspective. Using this technique, I was able to identify both 3D impression indentations and 2D impression evidence on the tread and toe of the insole, correlating with average plantar pressure points made by the MPJs, IPJ (big toe), and lesser toes of the foot during a normal gait cycle (fig. 4.12, left). The 3D impression indentation made by the IPJ (big toe) is particularly deep, and the impression indentations of the lesser toes are deeper than on many other insoles in this research, and once again sit right at the edge of the insole (fig. 4.12, left). In order to emphasize the 3D impression indentations identified using this technique, the rendering tool “Shadow Mapping,” was applied to the insole model and viewed from a direct top-down perspective. This tool applies shadows based on the surface topography of the model, and thus, helps visualize different depths. With this tool enabled, the 3D impression indentations made by the anterior MPJ pad (anterior ‘ball’ of the foot), the IPJ (big toes), and the lesser toes were highlighted and better visualized (fig. 4.12, right). To obtain a better view of other impression evidence on the rest of the insole below the tread, I applied a series of rendering and shader tools. I found that the “Reflexion_line” shader tool provided the best overall view of the 2D impression evidence extending from the heel/seat to toe (fig. 4.13).287 The impression evidence on the heel/seat is relatively centralized and indicates that the individual’s heel was placed against the rear edge of the shoe. The impression evidence on the waist seems to favour the medial insole slightly and is fairly wide, similar to L-1986-158, which as

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287 “Reflexion_line” shader technical specifications: ScaleFactor=0, Shading=max, Smoothing=0.
stated previously, could be the result of an asymmetrical pressure distribution, or simply that the insole was worn by an adult male with a wider midfoot. The 2D impression evidence on the tread and toe of the insole correlates with much of the same 3D impression evidence seen in figure 4.13, with significant impression evidence made by the first two MPJs and the IPJ (big toe), and the lesser toes in particular (fig. 4.13).

Similar to L-1986-164, the lesser toe impressions lie close to the edge of the insole, but here the big toe impression lies further down from the tip of the narrow toe area of the insole. Overall, a relatively complete footprint impression is visible and can be roughly traced from the heel to toes.

![Figure 4.11. Photograph of insole L-1986-164](image-url)
Figure 4.12. Screenshot from MeshLab displaying impression evidence on insole L-1986-164. (Above) 3D impression indentations visible using a changing virtual light source and oblique perspective. (Below) 3D impression indentations emphasized with “Shadow mapping” rendering tool enabled.
This sole was included in the case study dataset because it was uncertain whether it was an insole or outer sole without hobnails, which occurs but is an uncommon shoe type. It was decided that the methodology would be useful in determining whether it was an insole or outer sole by the presence or lack thereof of identifiable footprint impression evidence. Unlike the other confirmed insoles in the dataset where only one surface needed to be scanned, both surfaces of this sole were scanned, labelled side A & side B, in order to analyze both for impression evidence. Using the same set of tools and
techniques in MeshLab as the rest of the insoles in the study, footprint impression
evidence could not be confidently identified on either side, and thus, based on the results
from this sole and the insoles in the dataset, it was determined that this was an example of
an outer sole not an insole (fig. 4.15). Despite not being relevant for answering the
primary research questions presented in this thesis research, this outer sole is valuable for
providing a good example of what a lack of impression evidence looks like, acting as a
comparison.

Figure 4.14. Photograph of outer sole L-1986-368. (Above) Side A (Below) Side B.
I was able to identify faint traces of footprint impression evidence, particularly 3D impression depths (indentations), on this insole using the changing virtual light source tool without any additional rendering tools or shaders. I have characterized the footprint impression evidence for this insole as ‘ok’ because it was not possible to visualize a complete footprint impression, only the impressions in the areas where the deepest pressure points were placed. However, I believed that including an example of impression evidence characterized as ‘ok’ would provide a good comparison between what is characterized as ‘good’ and ‘ok.’ I found that visualizing the 3D model of the enhanced insole from oblique angles was best for visualizing and analyzing the footprint.
impression evidence on the insole (fig. 4.17). From this angle the depth of the
impression/indentation left on the heel/tread of the insole from wear is immediately
apparent, roughly outlining the position of the heel pad of the foot on the seat/heel of the
insole. The impression on the heel of this insole is more centered than some of the
previous insoles. Impression evidence on the waist is rather indistinct, with only traces of
very faint impressions, and thus, cannot be confidently identified or re-constructed.

Impression evidence on the tread of the insole was easier to identify. The depth of the
impression left on the tread by plantar pressure from the MPJs (‘ball’ of the foot) is
visible, and some 2D impression wear is also visible on the lower tread area correlating
with the metatarsal arch below the MPJs and the upper midfoot. When the rendering tool
“Shadow mapping” was applied to the 3D model of the insole, the impression outline of
the tread area is clearly visible, highlighting the depth of the indentations formed from
plantar pressure by the IPJ and MPJs (fig. 4.18). Finally, using oblique virtual light only,
the 3D impressions (indentations) of some of the toes can be roughly identified and
traced near the top of the insole, just below the narrow tip.

Figure 4.16. Photograph of insole L-1986-676.
Figure 4.17. Screenshot from MeshLab displaying impression evidence on Insole L-986-676, enhanced using a changing virtual light source. (Left) View of insole from oblique perspective. (Right) View of insole from angled top-down perspective.

Figure 4.18. Screenshot from MeshLab displaying impression evidence on the tread and toe of insole L-1986-676 with the “Shadow mapping” rendering tool enabled.

L-1986-679

Both 2D and 3D footprint impression evidence were identifiable on this insole using two different rendering tools combined with a changing light source in MeshLab: “Shadow mapping” and the shader “Reflexion_line.” I first attempted to identify 3D
impression evidence by viewing the insole surface topography from an oblique angle, but the changes in surface depths were too subtle to identify 3D impression evidence with confidence, so I instead opted to emphasize these more subtle depths using the “Shadow mapping” rendering tool from a direct overhead perspective (fig. 4.20, left). With this tool enabled I was able to identify 3D impression indentations on the tread and toe of the insole, correlating roughly with the plantar pressure points made by the MPJs (the ‘ball’ of the foot) and the IPJ (big toe) (fig. 4.20, left). I was not able to identify any substantial 3D impression evidence elsewhere on the insole. Several other rendering and shader tools were applied for enhanced visualization of 2D impression evidence, of which I found the shader “Reflexion_line” in combination with a changing virtual light source provided the best overall visualization of the 2D impression evidence on the insole from the heel to toe (fig. 4.20, right). The impression evidence on the heel/seat was relatively faint in comparison to that on the tread, with the darkest impression evidence located on along the medial border and upper lateral region of the heel. The impression continues up the waist of the insole on both the medial and lateral waist, but it appears to be more prominent towards the lateral waist. The 2D impression evidence on the tread and toe region of the insole is the darkest and validates much of the 3D impression evidence seen using “Shadow mapping.” The darkest impression evidence is concentrated on the lateral and medial borders of the tread, as well as the big and lesser toes, correlating roughly with the plantar pressure points made by MPJ1, the IPJ, lesser toes, and MPJ4 and MPJ5 during the gait cycle (fig. 4.20, right). Finally, the placement of the toes on the upper edge of the insole can be traced because of the prominence of their impressions,

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²⁸⁸ “Reflexion_line” shader technical specifications: ScaleFactor=nearly 0, Shading=max, Smoothing=roughly 5%. 
indicating that the individual’s big toe was placed unusually high up, squished in the narrow pointed toe cap of the insole, with their lesser toes also placed against the edge wall of the shoe (fig. 4.20, right). Overall, the footprint impression evidence for the tread higher up on the insole is much more visible and defined than that of the waist and heel, but a rough outline of the footprint can still be traced relatively easily. The footprint impression on the insole roughly correlates with an expected in-shoe footprint impression made by plantar pressure points during a normal gait cycle, with the greatest pressure placed on the MPJs and toes. However, it deviates slightly with less pressure placed on the heel/seat of the insole than expected, especially when compared with most of the other insoles presented in the study, which have prominent 3D and 2D impression evidence on the heel/seat made by the heel during the heel strike phase of the gait cycle. The lack of significant impression evidence on the heel/seat of this insole may indicate an irregular or asymmetrical gait, or simply a lack of impression evidence for an unrelated reason.
Figure 4.19. Photograph of insole L-1986-679.
Figure 4.20. Screenshot from MeshLab displaying impression evidence visible on insole L-1986-679. (Left) 3D impression indentations visible with “Shadow mapping” enabled. (Right) 2D impression evidence visible using the “Reflexion_line” shader tool and a changing virtual light source.

L-1986-686

A nearly complete 2D footprint impression was immediately identifiable on this insole with several different rendering tools combined with a changing virtual light source. I found that the “Lattice” shader tool offered the best visualization of the overall footprint impression because of the high contrast made between the dark greyscale
impression evidence and the light yellow colour of the insole surface (fig. 4.22). With this tool enabled it is possible to trace the footprint impression from the heel/seat to the toe of the insole. First, the impression evidence on the heel/seat is prominent and centralized, extending all the way back to the rear edge of the heel/seat. The impression evidence continues from the heel upwards across the lateral side of the waist as expected from typical plantar pressure points made during a normal walking gait cycle (refer to fig. 4.4-4.7). The impression evidence on the tread is also immediately evident and correlates almost exactly with plantar pressure points made by the 1st MPJ to 3rd MPJ of the ‘ball’ of the foot during a normal gait cycle (fig. 4.22). However, no impression evidence was identifiable on the lateral border of the tread, correlating with the 4th to 5th MPJ of the ‘ball’ of the foot, which could suggest an irregularity or asymmetry in gait, or merely the lack of impression evidence for an unrelated reason, such as preservation conditions. Finally, there is identifiable impression evidence on the toe area of the insole, which seems to be impressions made by the big toe (IPJ) and one or possibly two lesser toes adjacent to the big toe (fig. 4.22). Similar to the tread, the lateral toe region of the insole does not have any impression evidence, and thus, it is not possible to identify impressions for all the lesser toes. Overall, a nearly complete footprint impression can be traced on this insole, correlating almost exactly with the average in-shoe impression made from plantar pressure points during a normal walking gait cycle.\textsuperscript{290}

\textsuperscript{289} “Lattice” shader technical specifications: Eyeposition=0,0,4, Kd=0.8, LightPosition=400,4,4, Scale=10, Threshold=0.13.
\textsuperscript{290} See Wafai et al. 2015, figure 2 and 3.
Figure 4.21. Photograph of insole L-1986-686.
Figure 4.22. Screenshot from MeshLab displaying impression evidence visible on insole L-1986-686 with the “Lattice” shader enabled.

L-1992-3416

This insole is split into two separate pieces just underneath the tread. The top half of the insole consists of the tread and toe and the bottom half consists of the waist and heel/seat, but a portion of the upper waist, especially on the lateral waist, is missing (fig. 4.23). There is a large inscription on the tread that has been interpreted as “ITATI” in the assemblage database. Due to the insole being split into two halves, two separate 3D models were made for each piece, labelled “L-1992-3416-TopMesh” and “L-1992-3416-BottomMesh” respectively. Both pieces were digitally enhanced and analyzed
individually first, then together as one insole (fig. 4.24 and 4.25). It was not possible to visualize and identify a complete footprint impression on the insole because of the significant missing sections of the insole, but 2D or 3D footprint impression evidence was identified on all surfaces available to analyse, including the heel/seat, lower waist, tread, and toe. First, I attempted to identify any 3D impression indentations left by plantar pressure points during the gait cycle. I found that 3D impression evidence was only identifiable on the medial tread and toe using the “Shadow mapping” tool, correlating roughly with MPJ1, MPJ2, and the IPJ (big toe) of the sole of the foot (fig. 4.24). Next, I sought to identify 2D impression evidence corroborating the 3D impression evidence seen in figure 4.24. Similar to the results of previous analyses, the shader tool “Reflexion_line” offered the best greyscale contrast for visualization of the overall footprint impression evidence on the insole, highlighting the most prominent impression evidence in black (fig. 4.25). On the bottom half of the insole, the most prominent 2D impression evidence was situated on the central and lateral heel/seat, which as stated previously, is the first part of the foot to strike the ground during the gait cycle. There is identifiable impression evidence on the waist, but it is less prominent than the impressions on the heel/seat and more difficult to trace due to the missing sections of the insole (fig. 4.25). The 2D impression evidence on the tread is also prominent but masked slightly by the inscription and some small holes in the insole. It seems that the impression covers the entire visible area of the tread, but the darkest impression evidence is located on the lateral tread, particularly the lateral edge of the tread where some of the lesser toes must have been positioned against the wall of the upper shoe (fig. 4.25). Above the tread

291 “Reflexion_line” shader technical specifications: ScaleFactor=0, Shading=0, Smoothing=0.
at the top of the insole the 2D impressions made by the big toe (IPJ) and at least one, or possibly two, adjacent lesser toes are identifiable, validating the 3D impression evidence identified previously using “Shadow mapping.” It is evident from this footprint impression that the individual’s foot was positioned as close to the top of the insole as possible, with their lesser toes squished tightly up against the lateral edge (fig. 4.25). Considering the insole is split into two halves and missing a section at the waist, most of the footprint impression was identifiable, and arguably the most important parts of the impression, the tread, toes and heel, were visible.

Figure 4.23. Photograph of insole L-1992-3416.
Figure 4.24. Screenshot from MeshLab displaying 3D impression evidence visible on the top half of insole L-1992-3416 with the rendering tool “Shadow mapping” enabled.
Figure 4.25. Screenshot from MeshLab displaying impression evidence visible on the top and bottom halves of L-1994-3416 using the “Reflexion_line” shader.

L-2004-36-A

2D and 3D impression evidence was identifiable on this insole using a similar combination of digital tools and techniques as previous insoles, including a changing virtual light source, the “Shadow mapping” and “Screen space ambient occlusion” rendering tools, and the “dimple” shader tool. With “Shadow mapping” enabled, 3D impression evidence on the central tread and rear heel/seat of the insole was immediately evident, indicating that the heel of the individual most likely sat at the rear edge of the
insole directly against the attached heel stiffener piece (see fig. 4.26 & 4.27, left). 2D impression evidence was identifiable using a changing virtual light source and several different shaders, but similar to other insoles analyzed in this research, the high-contrast coloured visualization provided by the “Dimple” shader was best for identifying and tracing all footprint impression evidence (fig. 4.27, right). With this shader tool enabled, 2D impression evidence could be roughly traced from the heel to toe of the insole, with the most prominent, and thus, darkest impressions located on the lateral heel, medial waist, lateral and medial edges of the tread, and IPJ, correlating with plantar pressure points made by the heel, midfoot (possibly the medial arch), MPJ3, MPJ3 to MPJ5, and IPJ (fig. 4.27, right). The impression on the medial waist is rather irregular when compared to normal in-shoe plantar pressure distributions, in which the impression of the midfoot is typically located on the lateral waist, potentially indicating an irregular gait. In addition, it was not possible to identify impressions for the lesser toes, but their placement can be estimated based on the location of the tread impression and big toe impression (IPJ). Based on these visible impressions, it appears that the lesser toes would have been positioned right up against the edge of the insole (fig. 4.27, right).

293 “Dimple” shader technical specifications: Density=0, LightPosition=300,0,5, Scale=0, Size=0.
294 Wafai et al. 2015, 20393-20400.
Figure 4.26. Photograph of insole L-2004-36-A.

Figure 4.27. Screenshot from MeshLab displaying impression evidence visible on insole L-2004-26-A. (Left) 3D impression evidence visible with “Shadow mapping” tool enabled (Right) 2D impression evidence visible using “Dimple” shader.
Both 2D and 3D footprint impression evidence was identifiable on this insole using a changing virtual light source and the shader tools “Lattice” and “Reflexion_line.” First, the presence of 3D impression evidence, characterized by indentations in the insole surface, was immediately apparent with the use of oblique lighting and shifting the angle of view of the insole model. However, the addition of the shader “Reflexion_line” enhanced visualization of these depth impressions further and enabled visualization of the 2D impression evidence simultaneously (fig. 4.29, left). The 3D impression depths are most prominent in the heel/seat of the insole, where the individual’s heel would have put significant pressure on the surface of the insole while walking during a normal gait cycle. Once again, the impression appears to favour the lateral heel, correlating with the first touch of the heel strike made against the ground during a normal gait cycle (fig. 4.29). The 3D impression evidence on the heel/seat extends upwards along the lateral waist of the insole, tracing the lateral border of the footprint impression, and continues to the tread, roughly highlighting the indentation made by the MPJ pad on the insole (fig. 4.29, left). With the “Reflexion_line” shader enabled, the 2D impression evidence is darkest along the lateral border of the impression from the heel to tread, and especially on the medial border of the tread and the big toe and second and third toe regions, suggesting that the greatest pressure was placed on these areas. Based on placement of the footprint impression of the MPJs on the tread of the insole and what I consider to be the impressions of the big toe (IPJ) and second and third toes (lesser toes) just above it, it seems that the toes sat right up against the edge of the insole, potentially squished against

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295 “Reflexion_line shader” technical specifications: ScaleFactor=0, Shading=60%, Smoothing=0.
the wall of the shoe (see fig. 4.29, left). The “Lattice” shader enabled visualization of much of the same features as the “Reflexion_line” shader, but I found it was most effective at providing the best visualization of the overall rough outline of the footprint impression (fig. 4.29, right). Once again, similar to the results presented for previous insoles, the footprint impression evidence on the insole appears to correlate with typical plantar pressure points made during a normal gait cycle, namely the heel (lateral), the MPJ head (‘ball’ of the foot), and the IPJ (big toe) and lesser toes.

![Image of insole L-2005-27A](image)

Figure 4.28. Photograph of insole L-2005-27A.

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297 “Lattice” shader technical specifications: EyePosition=0,0,4, Kd=0.8, LightPosition=300,4,4, Scale=10, Threshold=0.13.
I was able to identify both 2D and 3D impression evidence on this insole using a combination of a changing virtual light source, oblique perspective, and several rendering and shader tools. Similar to the tools and techniques used on other insoles in this research, I found the best way to visualize the subtle changes in the surface topography of the insole and identify any 3D impression depths made by plantar pressure was by inspecting the 3D model from slanted, oblique angles and manipulating a virtual light source to mimic the oblique lighting techniques used in forensic examinations of impression evidence. For this insole, the addition of the “Dimple” shader without any
changes to its light position ranges helped visualize the subtle 3D impression indentations on the heel/seat and tread, which correlate with plantar pressure points made by the heel and entire MPJ pad, otherwise known as the ‘ball’ of the foot (fig. 4.31).298 Having identified 3D impression evidence, I successfully visualized 2D impression evidence using a variety of rendering and shader tools, but found that for this insole the “Reflexion_line” shader tool provided the best visualization of the overall footprint impression (fig. 4.32).299

First, I identified 2D impression evidence on both the rear and lateral border of the heel/seat. The impression evidence extends upwards to the lower waist, but cannot be accurately traced to the tread like on some other insoles in this research (fig. 4.32). However, from what impression evidence can be identified on the waist, it seems that the waist impression is fairly wide, correlating with the entire midfoot and possibly the medial arch of the sole. The 2D impression evidence on the tread is the most prominent and encompasses the entire area, validating much of the 3D impression depth identified previously (see fig. 4.31 and 4.32). It appears that the impressions made by the 1st and 5th MPJ pads are the darkest, and thus, most prominent, which aligns with plantar pressure distributions for the ‘ball’ of the foot. Based on the location of the impressions for the MPJ pads on the tread and visualization of the impression evidence just above it, it was possible to identify where the upper edges of the big and lesser toe impressions ended on the top of the insole, but identifying accurate impressions and their locations for each individual toe was not possible to achieve with confidence (fig. 4.32). However, based on the upper edges of the impression evidence for the toes, it is evident that the toes would have sat near the very tip of the narrow pointed toe region, and the

298 “Dimple” shader technical specifications: Density=0, LightPosition=0,0,5, Scale=0, Size=0.
299 “Reflexion_line” shader technical specifications: ScaleFactor=0, Shading=0, Smoothing=0.
lesser toes must have been squished up against the upper lateral edge of the insole. Overall, a semi-complete footprint impression was identifiable for this insole that matches with the results seen for the previous insoles in this case study.

Figure 4.30. Photograph of insole L-2007-84-A.

Figure 4.31. Screenshot from MeshLab displaying 3D impression evidence visible on insole L-2007-84-A using the “Dimple” shader with an oblique perspective.
Figure 4.32. Screenshot from MeshLab displaying 2D impression evidence visible on insole L-2007-84-A using the “Reflexion_line” shader in combination with a changing virtual light source.

L-2016-204

Using the “Shadow mapping” rendering tool, which emphasizes changes in the surface topography of the insole, I was able to identify 3D impression evidence for almost the entire footprint impression from the heel/seat to tread and big toe region of the insole (fig. 4.34). I was not able to visualize all 3D impression evidence on the tread at once with a single light direction, so I utilized two different light sources to capture all the impression depths on the tread, shown in figure 4.34, left and right. The 3D
impression evidence displayed with “Shadow mapping” tool starts at the rear heel and continues upwards along the central waist where it bends to the lateral waist, and then finally reaches the lateral tread (fig. 4.34, left). The 3D impression evidence on the tread encompasses a large portion of the tread, but it is clear that the ‘ball’ of the foot of this individual was placed close to the lateral border of the tread, leaving space between the impression and the medial border of the tread (fig. 4.34, left and right). In order to validate the results of the 3D impression evidence analysis, a series of shaders and rendering tools combined with a changing virtual light source were used to enhance and visualize 2D impression evidence. Once again, the “Reflexion_line” shader and a changing virtual light source proved the best for identifying and visualizing the 2D footprint impression on this insole in high contrast, which displayed a complete footprint impression from heel to toes (fig. 4.35).\[300\] The 2D impression revealed using this method matches exactly with the 3D impression evidence visible using “Shadow mapping” from the tread to upper waist, but the darkest impressions were positioned more towards the lateral side of the waist and heel than the 3D impression evidence, which was more central (compare fig. 4.34, left and fig. 4.35). There are identifiable 2D impressions on the areas emphasized by “Shadow mapping,” but they are not as dark. The slight discrepancy between the 3D and 2D impressions could be explained by slight differences in the locations of 2D stain and use-wear caused by consistent re-use and pressing of the foot against the lateral edge of the insole and upper wall of the shoe, and the physical indentations left on the insole surface from plantar pressure during the gait cycle. It may also be that the indentations on the heel and lower waist were a result of some other

300 “Reflexion_line” shader technical specifications: ScaleFactor=almost 0, Shading=max, Smoothing=10\%.
factor unrelated to footprint impressions. It was not possible to visualize any 3D impression evidence above the tread of the insole using “Shadow mapping,” but clear 2D impression evidence for all five toes were identifiable on at the top of the toe of the insole just above the tread using “Reflexion_line” (fig. 4.35). The impressions of the lesser toes are placed right up against the lateral edge of the insole and the impression of the big toe (IPJ) is placed right up at the top, just below the narrow toe cap of the insole (fig. 4.35). Overall, the entire footprint impression on this insole can be traced and does not deviate significantly from the average in-shoe footprint impression made by plantar pressure points during the gait cycle. However, it seems that overall impression heavily favours the lateral edge of the insole, especially on the heel and lower waist. This may indicate some form of irregularity in the gait of the individual or the way they wore these shoes, but the exact reason cannot be determined without further research and analysis outside scope of this thesis research.
Figure 4.33. Photograph of insole L-2016-204.
Figure 4.34. Screenshot from MeshLab displaying 3D impression indentations on insole L-2016-204 with “Shadow mapping” enabled. (Left) 3D impression indentations visible on central heel, waist and tread. (Right) 3D impression evidence visible on tread.
Figure 4.35. Screenshot from MeshLab displaying 2D impression evidence of footprint impression on insole L-2016-204 with “Reflexion_line” shader and a changing virtual light source.

L-2016-358

This insole yielded a nearly perfect 2D footprint impression, visible using several different rendering tools and shaders, confirming its validity. However, I found that the shaders “Dimple” and “Lambertian Radiance Scaling” combined with virtual light provided the two best visualizations of the overall footprint impression (fig. 4.37). The shader “Dimple,” as established previously, is valuable for the high contrast between the
greyscale colour of the impression evidence and the yellow colour of the surface of the insole, providing the best overall clarity, especially for areas with fainter impression evidence (fig. 4.37, left). “Lambertian radiance scaling” shows an almost identical visualization of the footprint impression evidence, but it is entirely in greyscale (fig. 4.37, right). In my opinion, “Lambertian” is slightly better in this case at reducing the distraction from some of the other surface features of the insole, such as shininess and wrinkles, allowing the viewer to have a less busy view of the surface. The footprint impression visible with both shaders extends from the heel/seat to the tread and toe of the insole, but is uncertain where exactly the toes of the individual were placed in the upper area. The heel impression is distinct, favouring the lateral heel, similar to many of the insoles presented above. The entire length of the midfoot impression is also completely identifiable along the waist, correlating with a typical footprint impression made by plantar pressure points during a regular gait cycle, as demonstrated by Wafai et al. 2015. The impression on the tread is also very distinct and easily identifiable, with the darkest impression area, and thus, the most pressure, concentrated on the lateral tread, roughly correlating with the 5th to 7th MPJs and possibly the lesser toes of the foot. It is hard to tell whether the two circular dark impressions on the upper lateral insole are lesser toe impressions or the top of the MPJs (‘ball’ of the foot), but if it was the top edge of the MPJs, then toes would have to had been incredibly squished into the side wall of the shoe. However, with this type of narrow pointed toe shoe, which would have originally

301 “Dimple” shader technical specifications: Density=almost 0, LightPosition=10,0,5, Scale=max, Size=max.
303 Wafai et al. 2015, 20393-20399, figure 1-3.
had uppers, I do not believe it is unreasonable to suggest that the foot would have fitted tightly inside the shoe with the toes squished against the edge wall.

Figure 4.36. Photograph of insole L-2016-358.
Figure 4.37. Screenshot from MeshLab displaying impression evidence on insole L-2016-358. (Left) Impression evidence visible with “Dimple” shader enabled. (Right) Impression evidence visible with “Lambertian Radiance Scaling” (1.00) enabled.

L-2016-415

3D impression indentations were identifiable on the tread and heel of this insole using only a partially oblique perspective and the “Dimple” shader. The impression indentation on the tread appears particularly deep, and the impression on the heel seems to be centralized (fig. 4.39). In order to confirm the 3D impression visualized with the “Dimple” shader, the “Shadow mapping” tool was applied to the insole and viewed from a direct top-down perspective. Using this technique, a large patch of 3D impression

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304 “Dimple” shader technical specifications: Density=0, LightPosition=1,0,5, Scale=0, Size=0.
evidence on the tread and some on the central heel were clearly visible, confirming the 3D impression indentations seen previously (fig. 4.40, left). Additionally, it appeared that there was also a more subtle impression indentation above the tread, on the top edge of the toe of the insole, which I correlate with the big toe (IPJ) (fig. 4.40, left). 2D impression evidence was also identifiable using both the “Reflexion_line” shader and the “Lambertian Radiance Scaling” (0.5) rendering tool combined with a changing virtual light source, but I found that “Lambertian” provided the clearest visualization of the entire 2D footprint impression evidence on this insole (fig. 4.40, right). With this tool, I identified 2D impression evidence on the heel, with the most prominent impression evidence on the rear and lateral heel. There is also identifiable impression evidence upwards along the waist, with the darkest impression evidence towards the central to medial waist. The 2D impression evidence on the tread is prominent, but only encompasses the lateral side of the tread, roughly correlating with the 4th and 5th MPJs. Similar to insole L-2007-84-A, the 3D impression evidence differed slightly with the 2D impression evidence. Here the 3D impression evidence covers a larger region of the tread than the 2D impression evidence, but the 2D impression evidence that is identifiable lies in the same area covered by the 3D impression evidence (compare fig. 4.40 left and right). Once again, this may be due to slight differences in impression evidence left by stains and use-wear over a long period of time and the physical indentations made during the gait cycle. The 2D impression on the lateral tread, correlating with the 4th and 5th MPJs only, could suggest an irregular gait pattern or the lack of impression evidence on the medial tread for another reason. Finally, the 2D impression evidence on the top

305 “Lambertian Radiance Scaling” technical specifications: Enhancement=0.5, Invert Effect=off, Double side=off.
medial edge of the toe of the insole appears to be made by the big toe (IPJ), validating the 3D impression evidence seen previously. The impression evidence up against the lateral border of the tread and upper region of the insole most likely belongs to the lesser toes based on the position of the impressions made by the tread and big toe, but it is impossible to make out each toe impression (fig. 4.40, right). If these are in fact the lesser toe impressions, they were situated right up against the edge of lateral edge of the tread and would have been squished into the uppers of the shoes. Similarly, the impression of the big toe lies very close to the top medial edge of the insole (fig. 4.40, right).

Figure 4.38. Photograph of insole L-2016-415.
Figure 4.39. Screenshot from MeshLab displaying 3D impression indentations visible on insole L-2016-415 using “Dimple” shader and an oblique perspective.

Figure 4.40. Screenshot from MeshLab displaying impression evidence visible on insole L-2016-415. (Left) 3D impression evidence emphasized using the “Shadow
mapping” tool. (Right) 2D impression evidence visible using “Lambertian Radiance Scaling” (0.5) and a changing virtual light source.

4.1.2 Case Study One Discussion

Case study one was the most successful case study in the research based on the amount and quality of ‘good’ and ‘ok’ 2D and 3D impression evidence identified on the insoles. A total of 40% (N=12) of the 30 insoles in this case study exhibited ‘good’ footprint impression evidence and 27.5% (N=11) of the insoles exhibited ‘ok’ footprint impression evidence. The insoles analyzed in this case study yielded the most well-defined and complete, or nearly complete, footprint impressions on their surfaces. The successful extraction of several complete or nearly complete footprint impressions from the dataset has offered invaluable insight into the size, shape, placement and plantar pressure distribution of different individual’s feet on the surface of the insoles, and potential regularities or irregularities in their gait as indicated by their foot impression evidence.

As stated previously, the primary objective of this case study was determining where the individuals feet sat on the insole of shoes in the assemblage with narrow, pointed toes. Without any identifiable footprint impression evidence, it is difficult to determine whether the individuals toes would have been squished near or at the very top of the narrow insole toe, or if the individuals wore shoes in a deliberately bigger size so their toes would have been placed further down from the narrow toe of the insole. The results of the impression evidence for this case study, presented above, show that Roman individuals of all age and sex categories wore shoes with narrow pointed toes in the first
manner rather than the latter. The majority of insoles had footprint impressions with identifiable and well-defined toe impressions demonstrating that the lesser toes were placed either very close to the edge or pressed directly against the edge of the narrow upper tread and toe region of the insoles where the upper leather would have joined the insole, and that the big toes were generally positioned high up within the narrow, pointed toe. Insoles L-1986-158, L-1986-686, L-1992-3416, L-2016-204, and L-2016-358 are particularly good examples illustrating how high up and close to the edge wall of the insole the placement of the toes often were in this style of shoe. It is evident by the deep and prominent impression evidence identified on the heelseat of these insoles, which sometimes also show significant pressure placed on the rear heel, that the feet of these individuals almost encompassed the entire length of the insole from heel to toe, indicating a small and tight fit.

Considering the construction of the shoes in this dataset, which have narrow toes and often also narrow waists, heels/seats and sometimes tread, and would have originally included upper leather pieces, it is not unexpected that the shoes would have fit much tighter than other styles, especially when compared to shoes with no full uppers, such as sandals. The tighter fit of the foot in these styles of shoes could be a plausible explanation for the successful results of this case study, especially when compared to the less successful results of the second case study. Typically, if a shoe fits tight on the foot, we tend to press down harder on the insole or interior surface from the feeling of pressure and discomfort, and thus, creating deeper and more prominent impressions on the insole than if wearing looser fitting shoes. Thus, I believe it is reasonable to assume that the tighter and smaller fit of many of the narrow pointed toe shoes from case study one, as
indicated by the footprint impression evidence, resulted in deeper and more prominent impression evidence, which was easier to capture and visualize than other insoles in the research. Perhaps unsurprisingly, the footprint impression evidence indicates that overall, the narrower the tread and pointed toe area of the insole is, the more the foot is tightly squeezed inside the shoe, as evident from the placement of the impressions and how much of the surface of the insole they encompass.

Although all insoles in this case study dataset displayed foot impressions indicating toe placement high up on the insole, the results seem to indicate a slight difference between the placement of toe impressions depending on the relative size category assigned to the insole. The results suggest that insoles in the larger size categories, ‘large’ (211-250 mm) and ‘extra-large’ (above 250mm), regardless of ownership category, yield toe impressions that are the closest to the top tip and the lateral or medial edges of the narrow pointed toe of the insoles, and have overall footprint impressions that are the tightest fitting (see in particular L-1986-158, L-1986-679, L-2004-36-A, L-2016-204, and L-2016-415). This is more apparent when comparing larger insoles with some of the insoles in the medium and small size categories, such as L-1986-676, L-2007-84-A, and L-2016-358.

The primary research question directing the first case study was satisfied by the results of the footprint impression visualization and analysis, which provided data on the sizes, shapes, and placement of individual feet within different narrow pointed toe shoes. Thus, the amount and quality of footprint impression evidence that was able to be identified on the insoles and the fulfillment of the primary research objective of the case study have both contributed to the success of the methodology employed in this thesis.
research. Furthermore, the results have contributed significant data and insight that enhances the podiatric and thereby local demographic information that can and will be extracted in the future from the leather footwear assemblage at Vindolanda. Additionally, these impression results are extremely useful for researchers and archaeologists with similar shoes in their collections but don’t have the resources to conduct 3D scanning and digital analyses. Generally, based on the impression results and analyses conducted in the case study, I would recommend taking 1 to 1.5 cm from the tip of smaller size insoles (small and medium) and 0.5 to 1 cm from larger size insoles (large, extra-large) when conducting measurements for more accurate foot length estimates for these styles of narrow pointed shoes.

4.2 Case Study Two: Sandal Insoles

4.2.1 Results

A total of 35 insoles were scanned using 3D SLS and digitally enhanced and visualized using a set of various rendering and shader tools available in the 3D processing software MeshLab. Each insole model was carefully and meticulously visually analysed to identify any traces of 2D or 3D footprint impression evidence on the surface of the insole, including sweat stains, surface wear and indentations from re-use. Out of 35 insoles in this case study, 24 insoles (N=24, 68.57%) revealed some form of identifiable footprint impression evidence, ranging from vague and faint to prominent and clear, and varying in location, size, and shape. Eleven insoles (N=11, 31.43%) did not exhibit any identifiable footprint impression evidence that could be confidently attributed to footprint
impressions. Out of the 24 insoles with identifiable footprint impression evidence, 8 insoles (N=8, 33.33%) were characterized as exhibiting ‘good’ footprint impression evidence, and 16 insoles (N=16, 66.67%) were characterized as exhibiting ‘ok’ footprint impression evidence (Table 5). The results for the insoles characterized as ‘good’ will be presented in the order they appear in the case study dataset (see Table 5 and Appendix D).

**Table 5: Case Study Two: Footprint Impression Results.**

<table>
<thead>
<tr>
<th>Insole #</th>
<th>Impression Quality</th>
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<tbody>
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<td>L-1985-120</td>
<td>Ok</td>
</tr>
<tr>
<td>L-1986-319</td>
<td>Good</td>
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<td>L-1986-459</td>
<td>Ok</td>
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<tr>
<td>L-1986-551</td>
<td>Good</td>
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<tr>
<td>L-1987-1334</td>
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<td>L-1988-2023</td>
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</tr>
<tr>
<td>L-1988-2148-B</td>
<td>Good</td>
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<tr>
<td>L-1988-2382</td>
<td>Good</td>
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<td>L-1989-2617-A</td>
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</tbody>
</table>
The first insole in the second case study yielded both 3D and 2D impression evidence with a variety of shaders, rendering tools, and changing virtual light sources. 3D impression evidence was immediately evident on the heel/seat and tread of the insole using the “Dimple” shader without any changes in light position or perspective (fig. 4.42, left).\textsuperscript{306} The impression indentation made on the central heel/seat is noticeably deep and the most prominent 3D impression evidence on the entire insole, suggesting a significant amount of pressure was placed on the central heel during the heel strike phase of the gait cycle. The impression indentation on the tread is not as prominent but is emphasized by the surrounding 2D impression evidence on the lateral and medial borders of the tread, as well as the big toe impression above it (fig. 4.42, left). The “Shadow mapping” tool was applied to validate the 3D impression evidence visualized using the “Dimple” shader and to emphasize any subtle impression indentations not visible with the previous method (fig. 4.42, right). With this tool enabled, 3D impression evidence running from the upper heel to the toe region was visible, correlating roughly with plantar pressure points made by the upper heel, lateral waist, the MPJ pads (the ‘ball’ of the foot) and the IPJ (big toe). Finally, a variety of shaders were successful at visualizing 2D impression evidence on the insole, but a combination of oblique virtual lighting and the shader “Minneart” provided

\textsuperscript{306} “Dimple” shader technical specifications: Density=60%, LightPosition=0,0,5, Scale=max, Size=50%.
the best overall visualization of the footprint impression identifiable on the insole.\textsuperscript{307} Using these tools, 2D impression evidence was identifiable on the rear, central and medial heel/seat, the lateral waist, tread, and toe regions of the insole (fig. 4.43). The darkest and most prominent impression evidence is located on the rear and central heel, the lateral and medial borders of the tread, and the lateral and medial borders of the toe, which seem to correlate with the lateral heel, 5\textsuperscript{th} and 1\textsuperscript{st} MPJs, the IPJ and lesser toes. The locations of the impressions correlating with the individual’s toes imply that the lesser toes were situated right on the lateral edge of the upper insole where the cut out toe patterns are situated and most likely hung off the edge at least partially, especially given the narrowness of the tread and toe of this insole and its large sized adult male ownership. Using the locations of the 3D and 2D impressions, it is possible to roughly trace an outline of the footprint impression on the insole, which compares well with expected in-shoe plantar pressure distributions made during the gait cycle (see fig. 4.4-4.7).

\textsuperscript{307} “Minneart” shader technical specifications: M=max.
Figure 4.41. Photograph of insole L-1986-319.

Figure 4.42. Screenshot from MeshLab displaying 3D impression evidence on insole L-1986-319. (Left) With “dimple” shader enabled. (Right) With the “Shadow mapping” rendering tool enabled.
Figure 4.43. Screenshot from MeshLab displaying impression evidence visible on insole L-1986-319 with the “Minneart” shader tool applied.

L-1986-551

I was able to successfully identify both 3D and 2D impression evidence on this insole using the “Shadow mapping” tool, the shader “Reflexion_line,” and an oblique light source. First, a 3D impression indentation was immediately visible on the central heel/seat of the insole on the un-enhanced model, but “Shadow mapping” was used to visualize more subtle impression indentations. With “Shadow mapping” enabled, I identified 3D impression indentations on the central heel, as expected, and a large impression extending from the upper waist to the upper toe region of the insole where the thong of the sandal is located (fig. 4.45, left). The placement of the 3D impression
evidence on the heel and upper waist correlates almost exactly with average in-shoe plantar pressure points made by the heel and midfoot during the gait cycle. However, it was difficult to determine with certainty whether the impression evidence on the tread and upper region of the insole correlated only with the MPJs (‘ball’ of the foot) or the MPJs and the big and lesser toes as well, as it seemed to be located abnormally high up on the insole and individual impression outlines made by the toes could not be identified. The 2D impression evidence identified using the “Reflexion_line” shader and oblique lighting confirmed the 3D impression evidence identified, with the darkest and most prominent 2D impression evidence on the rear and lateral heel, lateral waist, and tread/upper region of the insole (fig. 4.45, right). However, the 2D impression evidence on the tread and upper region did not provide much clarity regarding where the exact placement of the big and lesser toes would have been on the insole. There is 2D impression evidence on either side of the visible thong, right at the upper edge of the insole, which would only make sense if the big toe was placed on the right side of the thong and the lesser toes were placed on the left side of the thong, as one might expect (fig. 4.45, right). The location of the toe impressions on the lateral edge of the insole and the fact that they aren’t well-defined, as seen on insoles in the first case study, coupled with the location of the thong, may suggest that the lesser toes were partially hung off the edge of the sandal.

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308 “Reflexion_line” shader technical specifications: ScaleFactor=almost 0, Shading=max, Smoothing=10%.
Figure 4.44. Photograph of insole L-1986-551.
Figure 4.45. Screenshot from MeshLab displaying impression evidence visible on insole L-1986-551. (Left) 3D impression evidence visible with the “Shadow mapping” tool enabled. (Right) 2D impression evidence visible with “Reflexion_line” shader and an oblique virtual light source.

L-1986-678

This insole is missing its heel/seat, so it was not possible to extract a complete footprint impression, but the 3D and 2D impression evidence that was extracted and visualized is significant for providing additional data with which to analyse the placement of feet on Roman sandals with thongs. 3D impression evidence was identified using both the “Dimple” shader without any changes in light position and the “Shadow mapping”
tool with a changing virtual light direction (fig. 4.47, left and right). First, using the “Dimple” shader with a direct, top-down perspective, I identified impression indentations on the upper portion of the insole. Similar to L-1986-551, which had a similar shape, it is difficult to tell where exactly the tread begins and ends, and the toe area begins. I believe that the impression indentations seen using the “Dimple” shader belong to the upper tread and toes, correlating roughly with the pressure points made by the upper MPJs (the upper edge of the ‘ball’ of the foot), the big toe (IPJ) and lesser toes (fig. 4.47, left). The 3D impression evidence visible using the “Shadow mapping” tool confirms much of this impression evidence, and I also identified some impression evidence running vertically down the lateral waist (fig. 4.47, right).

Next, the “Reflexion_line” shader tool with a changing virtual light source was successful at visualizing 2D impression evidence from the waist to tread and upper toe of the insole (fig. 4.48). I used two slightly different light directions to fully capture the 2D impression data on the tread and toe areas of the insole, which were the primary areas of focus (fig. 4.48, left and right). The 2D impression evidence on the waist confirmed the 3D impression evidence seen previously, but additional 2D impression evidence was identifiable on the medial edge of the waist, which deviates from normal plantar pressure distributions and suggests more pressure was placed on the medial arch of the foot. The 2D impression continues upwards to the tread, encompassing the entire width of the tread, and thus, all the MPJs, which correlates well with typical in-shoe plantar pressure distributions made during a normal gait cycle (fig. 4.48). Finally, using the 2D impression evidence visible with both light directions in figure 4.48, I was able to

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309 “Dimple” shader technical specifications: Density=0, LightPosition=0,0,5, Scale=max, Size=max.
310 “Reflexion_line” shader technical specifications: ScaleFactor=0, Shading=60%, Smoothing=0.
identify the impression made by the big toe (IPJ), which lies on the medial edge of the upper insole just to the left of the thong (fig. 4.48, right). Just like insole L-1986-551, it is difficult to identify the individual impressions of the lesser toes, but based on the 2D and 3D impression evidence identified, two of the lesser toes were placed on the top lateral edge of the insole, just to the right of the thong (see fig. 4.47, left and fig. 4.48, right). The other three lesser toes would have been placed just below these toes on the lateral edge of the insole and most likely at least partially hung off the edge based on the position of the other toes and the thong.

Figure 4.46. Photograph of insole L-1986-678.
Figure 4.47. Screenshot from MeshLab displaying 3D impression evidence visible on insole L-1986-678. (Left) Impression indentations visible with the “Dimple” shader. (Right) Impression indentations emphasized with “Shadow mapping” enabled.
Figure 4.48. Screenshot from MeshLab displaying impression evidence visible on insole L-1986-678. (Left) 2D impression evidence visible using “Reflexion_line” shader and a changing virtual light source. (Right) Close up of impression evidence visible on the tread and toe using “Reflexion_line” and a different virtual light direction.

L-1988-2148-B

I was not able to identify any 3D impression evidence on this decorative insole, but I was successful at identifying 2D impression evidence using the “Lattice” shader with a changing virtual light position (fig. 4.50).[^31] Impression evidence was immediately identifiable on the central heel/seat, tread and lateral toe of the insole. There is also some

[^31]: “Lattice” shader technical specifications: EyePosition=0,0,4, Kd=0.8, LightPosition=200,4,4, Scale=10, Threshold=0.13.
more faint impression evidence visible on both the lateral and medial borders of the waist, which makes sense considering how narrow the waist was of this particular insole. The impression on the tread encompasses the lateral and central tread, correlating with plantar pressure points made by the 5th to 2nd MPJs (fig. 4.50). Finally, there is impression evidence on the upper lateral edge of the insole, just left of the thong where the small cut out toe pattern lies (fig. 4.50). Based on the location of the impression of the MPJ pads, it appears that this impression was made by the 2nd and possibly 3rd lesser toes. The location of the impressions for the MPJs and lesser toes implies that some of individual’s lesser toes must have hung off the edge of the sandal at least partially. Additionally, there is no identifiable impression for the big toe (IPJ) and based on the location of the MPJs and the thong, it seems reasonable to assume that the individual’s big toe must have also hung off the edge of the insole in some manner. Overall, the footprint impression evidence visible on this insole matches with expected plantar pressure distributions made during a normal gait cycle.
Figure 4.49. Photograph of insole L-1988-2148-B.
I successfully visualized a nearly complete footprint impression on this insole using several different rendering and shader tools in combination with a changing virtual light direction, but found that “Reflexion_line” and “Lambertian Radiance Scaling” provided the two best high-contrast visualizations of the overall footprint impression (fig. 4.52).\textsuperscript{312} The 2D impression evidence visible on the insole using these tools includes the

\textsuperscript{312} “Reflexion_line” shader technical specifications: ScaleFactor=0, Shading=max, Smoothing=10%. “Lambertian Radiance Scaling” plugin tool technical specifications: Invert Effect=off, Double side=off, Enhancement=1.00.
heel, waist, a nearly complete tread and the big and lesser toes. The impression on the heel encompasses most of the heel, with the darkest impression evidence on the rear border and the upper medial border (fig. 4.52, left). The impression then continues upwards along the medial waist to the tread of the insole, favouring the medial side of the tread slightly. The impression made by the big toe (IPJ) is evident just above the impression of MPJ1 on the upper medial edge of the insole just left of the thong, and the impressions made by the lesser toes are fainter but still visible on the upper lateral edge of the insole just to the right of the thong (fig. 4.52, right). It is evident that the general footprint impression on this insole favours the medial side of the insole instead of the lateral side, which deviates from the average in-shoe plantar pressure distribution made during a normal gait cycle, especially for the midfoot impression on the waist (see fig. 4.4-4.7). Thus, the favouring of the medial insole may indicate an irregularity or asymmetrical gait. Furthermore, unlike the previous insoles presented from this case study, the individual impressions of the big and lesser toes can be identified and are placed on the upper edge of the insole, but not hanging off the edge. This may be explained by the larger width of the tread and toe regions of the insole in comparison to the insoles presented previously.
Figure 4.51. Photograph of insole L-1988-2382.
Figure 4.52. Screenshot from MeshLab displaying nearly complete footprint impression on insole L-1988-2382. (Left) Footprint impression visualized using the “Lambertian Radiance Scaling (1.00)” tool. (Right) Footprint impression visualized using the “Reflexion_line” shader and an oblique virtual light source.

L-2001-286

Only one shader tool, the “Lattice” shader, was successful at visualizing footprint impression evidence for this insole. The footprint impression evidence is clearly identifiable, and an almost complete footprint impression is visible from heel/seat to tread and upper insole, with some ambiguity in the toe area at the top of the insole (fig. 4.54).

Some of this ambiguity may be due to some damage and warping in the cut-out toe

313 “Lattice” shader technical specifications: EyePosition=0,0,4, Kd=0.8, LightPosition=50,4,4, Scale=10, 10, Threshold=0.13. A changing light source was also used in combination with the shader.
region, but regardless, it seems that based on the location of the MPJ pad impression visible on the tread, the toes must have been squished rather close to the edge of the insole. The footprint impression evidence visible on the insole correlates to a typical footprint impression made by a human with a normal gait walking cycle, as demonstrated by the study conducted by Wafai et al. 2015 (refer to fig. 4.4 to 4.7).\textsuperscript{314}

\textbf{Figure 4.53. Photograph of insole L-2001-286.}

\textsuperscript{314} Wafai et al. 2015, 20392-20408. See also forensic podiatric studies by Massey and Kennedy 2013; Nirenberg et al. 2020; and Larsen et al. 2021.
Figure 4.54. Screenshot from MeshLab displaying footprint impression evidence on insole L-2001-286 with “Lattice” shader in greyscale enabled.

L-2003-392-A

Both 3D and 2D impression evidence was identifiable on this incredibly narrow insole using “Shadow mapping,” and the “Dimple” shader tool combined with a changing virtual light source. First, I identified subtle 3D impression evidence on the upper lateral waist and parts of the tread using the “Shadow mapping” tool, which appear to correlate with the plantar pressure points made by the midfoot, the lower borders of the 2nd to 5th MPJs, the entire 5th MPJ, and the upper borders of the 3rd to 5th MPJ and possibly some of the lesser toes (fig. 4.56, left). I then visualized 2D impression evidence using the
“Dimple” shader and a changing virtual light position, and identified impression evidence on the heel, lateral waist and tread, and parts of the toe region of the insole (fig. 4.56, right). The 2D impression evidence on the heel is noticeably dark and encompasses almost the entire surface area, which makes sense considering how narrow the heel surface is for this insole. The impression continues upwards along the waist, with the darkest impression evidence located along the lateral edge of the waist, correlating exactly with the expected plantar pressure made by the lateral midfoot during a normal gait cycle (see fig. 4.4-4.7). The impression evidence continues to the tread, encompassing the entire surface area, but the darkest impression evidence is once again on the lateral border of the tread. Finally, there is impression evidence on the toe of the insole, which appears to belong to two toe impressions, the leftmost of which may belong to the big toe (IPJ), but unfortunately these impressions were not distinct enough to identify the specific toes with certainty (fig. 4.56, right). It is notable that a distinct impression made by the big toe (IPJ) is not clearly identifiable on this insole as on other insoles, and the lack of distinctive evidence for the big toe, the location of the MPJ impressions, and the narrowness of the tread and toe of this particular insole, may suggest that the big toe partially or entirely hung off the medial edge of the insole. It is also possible that there is simply a lack of evidence for this area of the insole for an unrelated reason. The footprint impression that is identifiable on this insole matches well with in-shoe plantar pressure distributions made during a normal gait cycle, except for the lack of prominent impression evidence made by the 1st and 2nd MPJs. On this insole, the most prominent impression evidence on the tread correlates with the 3rd to 5th MPJs, which

315 “Dimple” shader technical specifications: Density=0, LightPosition=20,0,5, Scale=max, Size=max.
may indicate an irregular or asymmetrical gait, possibly due to the narrowness of the insole surface itself.

Figure 4.55. Photograph of insole L-2003-392-A.
Figure 4.56. Screenshot from MeshLab displaying 3D and 2D impression evidence visible on insole L-2003-392-A. (Left) 3D impression evidence visible using the “Shadow mapping” tool. (Right) 2D impression evidence visible using the “Dimple” shader tool and a changing virtual light source.

L-2016-149

2D impression evidence was identifiable for this decorative insole using several different shader tools combined with a changing virtual light source, but “Reflexion_line” offered the best visualization of the most 2D impression evidence.\(^{316}\) 2D impression evidence was identifiable on the heel, central and lateral waist, tread, and parts of the upper toe of the insole (fig. 4.58). The impression evidence on the heel is much fainter than expected based on impression evidence found on other insoles and the expected

\(^{316}\) “Reflexion_line” shader technical specifications: ScaleFactor=0, Shading=60%, Smoothing=0.
pressure point from the heel during the heel strike phase of the gait cycle. The 2D impression evidence on the lower waist encompasses the entire width of the waist, correlating with the average plantar pressure distribution of the lower midfoot, especially considering the narrowness of the waist. The impression continues to the upper waist and lower tread area primarily following the lateral border and encompasses the entire width of the tread, correlating almost exactly with average plantar pressure distributions of the upper midfoot and MPJs of the ‘ball’ of the foot (see fig. 4.4-4.6). The medial border of the tread is particularly dark, correlating with the 1st and 2nd MPJs, again matching with the average pressure distributions for the ‘ball’ of the foot. Unfortunately, the impression evidence on the upper insole correlating with the big and lesser toes is not as well defined, but impression evidence is identifiable at the very top, just to the left and right of the thong on the large cut out toe pattern. Based on the location of the impressions correlating with the 1st and 2nd MPJs of the ‘ball’ of the foot, the impression on the left side of the thong must have been made by the big toe (IPJ) (fig. 4.58). The extreme narrowness of the space between the thong and the medial border of the insole implies that the big toe would have partially hung off the medial edge of the sandal. The impression on the right side of the thong almost certainly belongs to the first lesser toe, and based on this evidence the adjacent lesser toe would have been placed on the lateral edge of the upper insole on the second, smaller cut out toe pattern, and most likely would have partially hung off the edge. The last two lesser toes would have certainly hung off the lateral edge of the insole based on the impressions made by the ‘ball’ of the foot, big toe, and first lesser toe. Overall, a relatively complete footprint impression is visible on
this insole, providing valuable insight into the placement of the foot on Roman decorative sandals.

Figure 4.57. Photograph of insole L-2016-149.
Figure 4.58. Screenshot from MeshLab displaying impression evidence visible on insole L-2016-149 using the “Reflexion_line” shader and a changing virtual light source.

4.2.2 Case Study Two Discussion

Case study two was the least successful case study in the research based on the amount and quality of ‘good’ and ‘ok’ 2D and 3D impression evidence that was extracted and identified on the insoles. A total of 22.86% (N=8) of the 35 insoles in the case study exhibited ‘good’ footprint impression evidence and 45.71% (N=16) of the insoles exhibited ‘ok’ footprint impression evidence. ‘Good’ footprint impression evidence was
extracted from all relative size and ownership categories, but the majority (5 of 8) were
assigned to adult males in the large and extra-large size ranges (see Appendix D for the
categories assigned to each insole presented in the results above). Compared to the ‘good’
footprint impression results of case study one, presented above, this case study yielded
relatively poorer results, which I propose is attributed to two factors: the difference in
shoe constructions and the number of decorative features on the surface of the insoles.
First, the shoes included in the first case study were originally closed shoes with leather
uppers, which as I have described above, restricted the individual’s feet and resulted in
deeper and more prominent impression evidence. In contrast, case study two consisted of
sandals, which are open-toed shoes. Open-toed shoes like sandals generally provide much
more freedom of the foot and toes than closed shoes, allowing the toes in particular to
move around more. Thus, it is reasonable to assume that the freedom and movement of
the foot and toes would result in less overall pressure being placed on the insole than
closed shoes. Furthermore, the pressure that is placed on the insole would most likely be
distributed over a wider area than with closed and tight-fitting shoes, which tend to have
deeper impressions on certain points (heel and tread). Thus, it makes sense that feet on
sandals would be less likely to make deeper or more prominent impressions, especially
compared to the closed and tighter fitting shoes seen in case study one.

Second, many of the sandal insoles in this case study are highly decorative, with
surface features such as inscriptions, stamps, incised patterns, cut-out toe patterns and
very narrow waists, treads, or toes. Only two highly decorative insoles in this case study
yielded ‘good’ footprint impressions (L-1986-319 and L-2016-149), and four had varying
degrees of impression evidence characterized as ‘ok’ (L-1985-120, L-2003-357-A, L-
I suspect that the highly decorative nature of many of the insoles in this case study contributed to its less successful footprint impression results, especially when compared to case study one, which only featured two highly decorative insoles and whose insoles were generally much plainer and basic. It seems reasonable to assume that these highly decorative shoes would not have been worn as often as the other more plain, undecorated shoes in the dataset, acting as a ‘special’ pair of shoes separate from the owner’s ‘everyday’ shoes. Thus, it may be the case that these shoes were not worn enough to produce deep enough 3D impressions and only faint 2D wear impressions that could not be captured successfully with 3D SLS. Additionally, some insoles with particularly busy surfaces occupied by several stamps, incised patterns, or other decorative features, may have obscured any faint impression evidence on the surface and either prevented the 3D structured light scanner from capturing it at all, or made it too difficult to digitally visualize and identify afterwards in the post-processing stages of the methodology.

Despite the relatively less successful impression results compared to case study one, the footprint impressions that were extracted and identified as ‘good’ from case study two provided crucial information regarding the research objective driving the case study. The primary research objective of case study two was determining where the individuals’ toes would have lain on sandals with thongs unusually high up on the insole. It has been difficult to determine whether the foot was deliberately placed further back on the insole so that the toes didn’t hang off the edges of the insole, or if the toes were firmly secured between the thong and hung off the edges partially or fully. The results of the footprint impression evidence, presented in detail above, uncovered several insoles
strongly indicating that some of the toes would have partially hung off the edges of the insole, and in some cases, some of the toes completely hung off the edge (see L-1986-319, L-1986-551, L-1986-678, L-1988-2148-B, L-2003-392-A, L-2016-149). Many of these insoles are decorative and have very narrow treads and toes or narrow cut-out toe patterns that leave no room for all of the toes to fit on the surface of the insole (See L-1986-319, L-1988-2148-B, L-2003-392-A, L-2016-149 in particular).

The footprint impression results of this case study have demonstrated that Roman sandals from the site were worn either with toes right up against the edge of the insole, with some of the toes partially hung off the edge, or with some of the toes completely hanging off the top edge of the insole. Thus, regardless of the smaller subset of insoles yielding ‘good’ impression evidence, the footprint impression data that was extracted and analysed from the dataset was incredibly valuable and provided significant evidence refining our understanding of how Roman sandals were worn. The toe impression evidence identified offers a convincing answer to the research question driving the case study, and therefore, I consider case study two to be successful overall. Similar to case study one, the footprint impression results are also extremely useful for researchers with similar shoes in their collections but don’t have the resources to conduct 3D scanning and digital analyses on their shoes. Generally, based on the impression results and analyses conducted in the case study, I would recommend adding 4-5 cm from the bottom edge of the thong (the start of the thong) on sandals to account for the length of the average big toe. Further research involving digital metric analysis will refine the precise

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317 A survey conducted by Soltani et al. (2016) found that the mean length of the first to fifth toes on the right foot was 4.99, 4.68, 5.96, 4.25 and 3.22 cm and the mean length of the first to fifth toes on the left foot was 4.99, 4.66, 5.12, 4.21 and 3.23 cm, respectively.
measurement, but by including the extra length of the toes a more accurate foot length can be estimated.

4.3 Case Study Three: Children’s Insoles

4.3.1 Results

A total of 25 insoles were scanned using 3D SLS and digitally enhanced and visualized using a set of various rendering and shader tools available in the 3D processing software MeshLab. Each insole model was carefully and meticulously visually analysed to identify any traces of 2D or 3D footprint impression evidence on the surface of the insole, including sweat stains, surface wear and indentations from chronic re-use. Out of 25 insoles in this case study, 19 insoles (N=19, 76%) revealed some form of identifiable footprint impression evidence, ranging from vague and faint to prominent and clear, and varying in location, size, and shape. Six insoles (N=6, 24%) did not exhibit any identifiable evidence that could be confidently attributed to footprint impressions. Out of the 19 insoles with identifiable footprint impression evidence, 9 insoles (N=9, 47.37%) were characterized as exhibiting ‘good’ footprint impression evidence, and 10 insoles (N=10, 52.63%) were characterized as exhibiting ‘ok’ footprint impression evidence (Table 6). The results for the insoles characterized as ‘good,’ as well as the singular carbatina sample, will be presented in the order they appear in the case study dataset (see Table 6 and Appendix E). Four insoles that are duplicates with case study one and two will not be discussed again in this section.\textsuperscript{318}

\textsuperscript{318} Refer to the results presented for these insoles in case study one and two above. The four duplicate insoles are L-1985-19, L-2001-286, L-2005-27-A, L-2016-358.
Table 6: Case Study Three: Footprint Impression Results.

<table>
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<tr>
<th>Insole #</th>
<th>Impression Quality</th>
</tr>
</thead>
<tbody>
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<tr>
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</tr>
<tr>
<td>L-1987-1175</td>
<td>Ok</td>
</tr>
<tr>
<td>L-1994-4252</td>
<td>Good</td>
</tr>
<tr>
<td>L-2001-6</td>
<td>Ok</td>
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<td>Ok</td>
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<tr>
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<td>L-2002-84-B</td>
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<tr>
<td>L-2002-282-A*</td>
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<tr>
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<tr>
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<td>None</td>
</tr>
<tr>
<td>L-1111-8-LM</td>
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</tr>
</tbody>
</table>

L-1994-4252

The same footprint impression evidence was visible on this insole with two different expressive visualization shader tools, “Lattice” and “Reflexion_line,” combined with a manipulatable virtual light source. With the “Lattice” shader enabled, a nearly complete footprint impression was highly visible, extending from the heel to the toe of the insole (fig. 4.60, left). 319 Similarly, with the “Reflexion_line” shader tool enabled,

319 Lattice shader tool technical specifications: Eyeposition=0,0,4, Kd=0.8, Light Position=55,4,4, Scale=10,Threshold 0.13.
the same footprint impression was visible, but with a higher contrast between the impression evidence and non-impression areas of the insole, confirming the findings (fig. 4.60, right). Similar to the two insoles discussed previously, the darkest impression evidence representing the areas where the greatest plantar (sole) pressure was concentrated on the heel/seat, the tread, and the upper toe area on the insole. For the toe area, the impression depth made by the big toe and adjacent toe can be identified with reasonable clarity, and it appears that the remaining three toes were squished close to the lateral edge of the upper toe area as the impression of the MPJs (‘ball’ of the foot) is close to the edge. Regarding the impression evidence on the heel, the location of the impression towards the lateral side indicates that pressure was placed more on the lateral heel than medial heel. Thus, the impression evidence on the insole and its correlating distribution of plantar pressure aligns with the type of impression expected of a normal human gait cycle.

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320 “Reflexion_Line” shader tool technical specifications: Smoothing=almost 0, Shading=max, ScaleFactor=almost 0.
Figure 4.59. Photograph of insole L-1994-4252.
Figure 4.60. Screenshot from MeshLab displaying impression evidence on insole L-1994-4252. (Left) Impression evidence visible with “Lattice” shader (greyscale) enabled. (Right) Impression evidence visible with “Reflexion_line” shader enabled.

L-2001-99

Similar to insole L-1994-4252 above, the same partially incomplete footprint impression was identifiable with several different shader tools. I found that the best visualization of the impression was with the shader tools “Dimple” and “Reflexion_line,” combined with virtual oblique lighting. The footprint impression visible using both shaders extends primarily from upper heel/seat to the toe area of the upper insole (fig. 4.62). The heel/seat area of the insole has a small hole in the center and some wrinkling extending slightly upwards, which may have impacted the visibility of impressions in this area. The impression evidence that is visible on the heel is concentrated on the upper
lateral side of the heel extending upwards across the waist to the tread. The impression on
the tread is the most prominent and easily identifiable, and the impressions made of three,
possibly four, toes can be identified and traced above the tread. The darkest impression
areas are located vertically along the waist, correlating to the midfoot, and in a circular
area on the tread roughly correlating to MPJ5 or MPJ6 (refer to fig. 4.6). Both shader
tools used for the most successful enhancement demonstrated the same footprint
impression evidence but provided slightly different visualizations. The “Dimple” shader
illustrates the impression in greyscale against the insole surface in yellow, which provides
good contrast between the impression evidence and the rest of the insole (fig. 4.62,
left). The “Reflexion_line” shader in contrast, is completely shown in greyscale, but I
found it was better at eliminating the most additional surface textures and details that
distacted from the impression (fig. 4.62, right). Once again, the footprint impression
identifiable on the insole roughly correlates to the expected plantar pressure points placed
on the insole of a shoe during a normal gait cycle, with a slightly wider midfoot
impression than the impressions noted above.

321 “Dimple” shader technical specifications: LightPosition=11,0,5, Density=0, Scale=max.
322 “Reflexion_line” shader technical specifications: ScaleFactor=almost 0, Shading=max,
Smoothing=roughly 40%.
Figure 4.61. Photograph of insole L-2001-99.
Figure 4.62. Screenshot from MeshLab displaying impression evidence on insole L-2001-99. (Left) Impression evidence visible with “Dimple” shader enabled. (Right) Impression evidence visible with “Reflexion_line” shader enabled.

L-2002-282-A

Insole L-2002-282-A is the only carbatina examined in the research project and was chosen as a test sample to determine if 3D SLS and post-processing enhancement could successfully visualize foot impression evidence on this type of single-construction shoe. The test was partially successful, as I was able to visualize and identify a small section of a footprint impression on the tread and toe region of the inner shoe surface, but no other substantial impression evidence was evident, nor an outline of the entire footprint impression comparable to the insoles presented so far. Visualization of the
impression evidence was only successful using the “Reflexion_line” shader tool combined with a virtual light source (fig. 4.64). A small circular impression on the tread region is the darkest and thus, deepest impression on the surface, correlating with the results of the insoles presented above. It also appears that the impression extends more faintly into the toe region of the surface, close to the edge of the walking surface of the carbatina, which seems reasonable for this style of single-construction footwear. Unfortunately, due to the presence of upper leather pieces blocking much of the lateral side and heel section of the surface, it was not possible to determine whether there is impression evidence in those covered areas.

Figure 4.63. Photograph of carbatina L-2002-282-A.

323 “Reflexion_line” shader technical specifications: ScaleFactor=0, Shading=0, Smoothing=0.
Figure 4.64. Screenshot from MeshLab displaying impression evidence on the interior surface of carbatina L-2002-282-A with “Reflexion_line” shader enabled.

L-2007-73-A

Similar to the insole above, both 2D and 3D impression evidence was identifiable on this insole using oblique virtual lighting and perspectives, as well as the “Reflexion_line” shader tool (fig. 4.66). For this insole, similar to others with identifiable 3D footprint impression indentations, I found that viewing the insole model from an oblique or odd angle was most effective at visualizing the overall surface topography of the insole and identifying areas with greater depth impressions/indentations. For this insole, a view from the top of the insole at an oblique angle enhanced with oblique lighting provided the best visualization of depth impressions visible on the tread and heel, while also allowing me to visualize faint traces of 2D impression evidence from the tread to heel (fig. 4.66, left). Then, with this information in mind, I proceeded to apply the
shaders, of which I found the shader “Reflexion_line” best for visualization of the 2D footprint impression evidence on the insole (fig. 4.66, right). 2D impression evidence was identified on the bottom and lateral heel, extending upwards and widening on the upper waist, and concluding on the tread. It was not possible to identify toe impressions with certainty, because the impression evidence in this area was rather ambiguous, but it appears there may be faint impression traces of the big toe (IPJ) on the top of the medial toe area of the insole. Additionally, impression evidence near the top of the lateral toe area above the MPJ pad impressions on the tread may be impressions made by one or more of the lesser toes (fig. 4.66, right). Overall, based on the footprint impression evidence, the impression correlates with the expected footprint impression and plantar pressure points made during the gait cycle, but has a slightly wider impression on the upper waist area of the insole than previous insoles, potentially suggesting that the individual placed pressure on the medial arch and/or metatarsal arch of the midfoot during the gait cycle (see fig. 4.7). This could potentially indicate an irregular or asymmetric gait or merely the shifting of the foot placement on the insole over time and multiple steps.

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324 “Reflexion_line” shader technical specifications: ScaleFactor= 0, Shading 70%, Smoothing=0.  
326 The wider impression on the waist of the insole, correlating with the medial arch or metatarsal arch regions of the midfoot is similar to the overall in-shoe plantar pressure distribution of a human with subtalar joint and heel pain during the gait cycle, shown in Wafai et al. 2015, 20400, figure 5. Determining whether these asymmetrical gait issues have any relevance to the footprint impression results of this insole would require further research and analysis.
Figure 4.65. Photograph of insole L-2007-73-A.

Figure 4.66. Screenshot from MeshLab displaying impression evidence on insole L-2007-73-A. (Left) Impression evidence visible with a changing light source from an oblique perspective. (Right) Impression evidence visible with “Reflexion_line” shader enabled from an angular, top down perspective.
Using a variety of different shader tools and both oblique perspective and virtual lighting I was able to identify 2D and 3D footprint impression evidence on a large portion of the surface of the insole. Similar to the methodology I conducted on L-2007-73-A, I began by visualizing the insole model from an oblique angle with an oblique virtual light source, but in this case, with the “Gooch” shader tool enabled for further enhancement. This combination of tools and perspective offered good visualization of the surface topology of the entire insole, allowing me to identify changes in surface depths, and thus, areas with 3D impression evidence left by plantar pressure points (fig. 4.68). It also provided good visualization of the 2D impression evidence as well. 3D Impression on the heel/seat and the tread was immediately evident. However, a large portion of the tread area of the insole is physically warped, so it was not possible to visualize the entirety of the impression evidence of the tread, only the lower tread and medial and lateral borders of the tread. In terms of 2D impression evidence, I was able to confidently identify impression evidence on the heel/seat, waist, parts of the tread, and potentially some traces of faint impressions of the toes, but this was made more difficult by areas of warping (fig. 4.68). Next, I applied the “Dimple” shader tool and visualized the insole model from a direct over-the-top perspective, which was successful at enhancing high contrast visibility of most of the 2D footprint impression evidence from the bottom of the heel up to the tread (fig. 4.69, left). The impression on the heel was fairly centered and extended right to the bottom edge of the heel. The impression evidence on the waist was particularly prominent on this insole and relatively wide in comparison to most of the impressions.

327 “Gooch” shader technical specifications: Shininess=max.
328 “Dimple” shader technical specifications: Density=60%, LightPosition=10,0,5, Scale=max, Size=50%.
seen thus far, comparable to insole L-2007-73-A above. As previously mentioned, visualizing the entire tread impression and identifying it with certainty was not possible due to warping, but it is possible to approximate a rough outline based on the impression evidence on the lower end and medial and lateral sides of the tread, and based on other comparable footprint impression evidence. Finally, the “Lattice” shader revealed much of the same 2D footprint impression evidence as the “Gooch” and “Dimple” shader, but was the best visualization of tread and toe area of the insole (fig. 4.69, right). With this shader it was possible to visualize the impression evidence on the upper lateral area of the tread not visible with the other shaders, and it appears that four toe impressions are visible on the lateral edge and top edge of the upper insole, representing the big toe (IPJ) and three lesser toes (fig. 4.69, right). Assuming that these are in fact the toe impressions, then the lesser toes of this individual were placed right up against the edge of the insole, and the big toe was placed close to the top of the insole, but not quite up against the edge, similar to the results seen on other insoles in the case study.

329 “Lattice” shader technical specifications: EyePosition=0,0,4, Kd=0.8, LightPosition=15,4,4, Scale=10, Threshold=0.13.
Figure 4.67. Photograph of insole L-2016-239.

Figure 4.68. Screenshot from MeshLab displaying impression evidence on insole L-2016-239 with “Gooch” shader enabled, viewed from an oblique angle.
Figure 4.69 Screenshot from MeshLab displaying impression evidence on insole L-2016-239. (Left) Impression evidence visible with “Dimple” shader enabled. (Right) Impression evidence visible with “Lattice” Shader enabled, viewed from an angular top down perspective.

L-2016-361

The final insole in case study three with identifiable footprint impressions characterized as ‘good’ is insole L-2016-361. Several different rendering tools and shaders in combination with a virtual light source were successful at visualizing 3D and 2D impression evidence, but I found that overall, the shader “Reflexion_line” offered the best overall visualization of the impressions (fig. 4.71).\textsuperscript{330} Once again, I utilized an

\textsuperscript{330} “Reflexion_line” shader technical specifications: ScaleFactor=almost 0, Shading=max, Smoothing=almost 0.
oblique perspective and changing light source to visualize the surface topography of the insole in order to check for impression indentations representing plantar pressure points, but enhanced view of the 2D impression evidence simultaneously using the “Reflexion_line” shader (fig. 4.71, left). I identified a subtle 3D impression indentation on the rear of the heel, and another subtle impression on the upper waist and tread. Additionally, 2D impression evidence from the rear heel to the tread and toe area is visible. From this angle, it is unclear whether the 2D impression evidence on the tread extends to the toes as well, or if it is only the tread. Using the “Reflexion_line” shader again, but with an overhead angle and different light direction, I was able to get a better view of the 2D impression evidence identified from the previous angle. Using this angle and light direction the 2D impression evidence had a greater contrast, providing better visualization of the entire footprint impression (fig. 4.71, right). Once again, it is clear that the darkest impressions were on the rear heel, the upper waist, and the tread and toe regions of the insole. From this angle, it seems that the impression on the tread ends and includes the impressions of the toes as well, and thus, the footprint impression is nearly complete (fig. 4.71, right). The footprint impression on this insole, however, generally appears to favour the medial side of the insole, and the impression on the heel favours the bottom edge of the heel, which may be the result of an irregular or asymmetric gait.
Figure 4.70. Photograph of insole L-2016-361.
Figure 4.71 Screenshot from MeshLab displaying impression evidence on insole L-2016-361. (Left) Impression evidence visible with “Reflexion_line shader” enabled, viewed from an angular top down perspective. (Right) Impression evidence visible with “Reflexion_line” shader enabled, viewed from a direct angle with a different light direction.

4.3.2 Case Study Three Discussion

Case study three was much more successful than originally anticipated based on the amount and quality of ‘good’ and ‘ok’ 2D and 3D impression evidence that could be identified on the children’s insoles. Overall, a total of 36% (N=9) of the 25 insoles in the case study exhibited ‘good’ footprint impression evidence and 40% (N=10) of the insoles exhibited ‘ok’ footprint impression evidence. Originally, I hypothesized that case study
three would be the least successful case study in the research. I presumed that it would be more difficult to extract footprint impressions from children’s insoles because of their much lighter weight and the fact that children’s feet grow very quickly and thus, might not wear the same pair of shoes for as long as adults, which may generally result in less deep and permanent impressions than adult individuals. However, using the research’s methodology I was able to identify a significant amount of impression evidence on the children’s insoles in this dataset regardless of these potential issues.

As mentioned previously in chapter 3, the shoes included in this dataset were not restricted to certain styles or constructions, so the insoles yielding ‘good’ footprint impression evidence included pointed toe insoles, sandals, and other various styles. In my analysis of the impression evidence, I attempted to identify any patterns, notable features, or differences in footprint impression evidence between different styles and constructions of insoles. Overall, the impression evidence indicates that children’s feet encompassed most of the insole surface with their toes placed high up and against the edges of the insoles regardless of shoe style or construction. These results also went against my original hypothesis regarding the placement of feet in children’s insoles that the size, particularly the length of the insoles, would be bigger/longer than the foot to allow room for growth. Additionally, the footprint impressions identified on the children’s insoles generally encompassed most of the surface area of the insole, which may suggest a tight fit. Thus, the close proximity of the toes to the top edges of the insoles and the size ratio between the foot and insole surface might indicate that Roman children at the site often wore the same pair of shoes for as long as possible, even when their feet grew and were pressed against the edges of the shoe for closed shoes or spilled over the edges in the case
of open sandals. However, this developed hypothesis cannot be proven until more data is collected on the children’s insoles using digital metric analysis and further podiatric and anthropological analyses can be conducted.

The primary research objective driving the case study on children’s insoles, as explained in chapter 3, was determining whether some insoles currently assigned to ownership by a young child might have actually belonged to small-footed adolescent males or females. The results for the case study provided a significant amount of footprint impression data for which to conduct further podiatric analyses for refining age categories, but due to the limitations in the scope of a master’s thesis, I was not able to conduct any additional digital metric or podiatric analysis on the insoles. As a result, the primary research objective for this case study is yet to be satisfied, but the crucial impression data needed to fulfill this objective has been successfully extracted for future research.

4.4 General Discussion

Overall, the newly proposed methodology in this thesis research was successful and the impression results presented above have aptly confirmed the viability of this methodology for capturing and enhancing both 2D and 3D footprint impressions on the surface of Roman leather insoles for augmented visualization and podiatric analysis. 2D and 3D footprint impression evidence was identifiable on almost all of the insoles from all three distinct case studies conducted in the research, with variable results for characteristically ‘good’ and ‘ok’ impression evidence visible on the surfaces of the individual insoles in each case study. Complete or nearly complete footprint impressions
were visualized and analysed on several insoles in each case study dataset, presented above in the results section.

The sizes, shapes, and placement of the footprint impression evidence identified in this research generally followed the average in-shoe footprint impressions created by plantar pressure distributions during a normal walking gait cycle, confirming the validity of the results. Overall, the deepest and most prominent impressions on the insoles in the research were concentrated on the heel/seat, tread, and toe regions of the insoles, corresponding with the prominent plantar pressure points made by the heel, ‘ball’ of the foot (MPJ pads), and toes of the foot during the different phase of the normal gait cycle. There were eleven insoles in the whole dataset, however, that showed footprint impression evidence deviating from average in-shoe plantar pressure distributions, which indicate potential irregularities or asymmetries in the gait of those individuals or potentially other physical health problems (see Table 5 for all identified irregularities). These irregularities were not limited to a single size range or ownership group, and at least two cases of irregular impressions were identified on insoles from each category, indicating that these irregularities are not age or sex specific. However, it is notable that seven of the eleven impression irregularities occurred on insoles from case study one, and thus, on pointed toe shoes. Perhaps the high number of irregularities on pointed toe insoles suggests that individuals are more likely to experience gait issues wearing these very narrow, most likely uncomfortable or at least tightly fitting insole shapes, but this hypothesis cannot be substantiated without further analysis and additional samples. Finally, I found that many of the irregular impressions identified in this research were remarkably similar to the asymmetrical plantar pressure distributions noted by Wafai et
al. for individuals with irregular gaits and physical disabilities affecting the feet, substantiating the presence of a statistically significant number of irregularities in the walking gait cycles of various Roman individuals at Vindolanda. Once again, another dataset of insoles and more complex podiatric and anthropological analyses are necessary to confirm these irregularities, identify patterns and specific gait or physical health issues for individual shoes. Further investigation into irregularities of gait and foot health will be a significant focus of future research.

During the process of conducting the methodology I recognised a few notable areas of difficulty that may be useful for researchers attempting to apply a similar methodology on their assemblage of archaeological shoes. First, as I anticipated in chapter 3 when discussing the conservation processes conducted on the leather footwear from the assemblage at Vindolanda, it was much more difficult to visualize footprint impression evidence, particularly complete impressions, on the insoles in the dataset conserved using the early 1970s form of PEG. Only two of the four 1970s insoles in the dataset yielded any identifiable impression evidence, of which these were only characterized as ‘ok’ because it was not possible to trace a potential footprint outline as on the insoles with impression evidence characterized as ‘good.’ Thus, researchers interested in applying a similar methodology with shoes in their collections that have been conserved with early forms of PEG should focus their resources on any shoes that have been conserved with other chemical treatments. Additionally, I found that the methodology employed in the research was generally less successful on the insoles with highly decorative surface features (stamps, inscriptions, incised patterns) than on the more plain or basic insoles without these features. Footprint impression evidence was
identified on seven of thirteen decorative insoles, but only three decorative insoles yielded ‘good’ impression evidence significant enough to warrant further analysis. Thus, if limited in resources or time, researchers may find it most efficient and fruitful to apply a similar methodology on footwear with less or no decorative surface features. Finally, I found that certain surface features such as warping, damage and holes, depending on their location and size, could completely or partially obscure the visualization impression evidence or result in a busier surface that would make identification of impression evidence more difficult. Researchers attempting to conduct a similar methodology should be mindful of these difficulties, especially if the footwear is generally less well preserved.

The successful results of the methodology employed in this thesis research for visualizing footprint impression on Roman leather insoles is significant on its own, even without the data collected for individual case studies, because it has proven the feasibility of the methodology, providing researchers with less access to resources such as 3D SLS with the necessary information to inform their own projects. Researchers can use the methodology, results and analyses offered in this thesis to inform their own research and determine whether or not a similar methodology would be applicable and fruitful for their own footwear collections. Furthermore, as discussed above for case study one and two, the results of the analysis conducted here has provided valuable podiatric data from which we can refine current podiatric measurement practices for certain shoe styles and constructions. Researchers with Roman footwear collections with similar styles of footwear as those in this research’s dataset, but lacking access to 3D SLS and digital resources can use the data results and recommendations provided above in chapter 4 to obtain more accurate foot length estimates than previously and enhance their own
podiatric analyses. Additionally, based on the results I believe that a similar methodology to the one conducted in this research could be successfully applied to non-Roman leather shoes, such as medieval leather shoes or ‘bog’ shoes from the Netherlands, as long as the footwear has sufficient preservation and conservation conditions and no significant upper leather pieces that could impede the 3D scanning process.

In addition to capturing and enhancing the visualization of footprint impressions on the surface of Roman leather insoles, the methodology employed in this research also revealed a second unintended application; the enhancement of small, faint and sometimes indistinct surface features on the insoles, such as stamps, inscriptions, incisions, and manufacturing marks. As noted previously, several of the insoles in the dataset had highly decorative surface features, and during the process of digitally enhancing and visualizing these insoles I noticed that the methodology significantly improved the visualization of incredibly small and faint details of decorative features that are incredibly difficult or impossible to see with the naked eye due to surface wear.\textsuperscript{331} Additionally, there were several insoles on which I discovered new inscriptions, inscription letters or patterns, stamps, or other decorative features that were not detected previously using traditional analytical techniques.\textsuperscript{332} Moreover, on several insoles I discovered incredibly fine tool marks and tracing patterns on the surfaces that weren’t previously visible, which are significant for illuminating aspects of the leather footwear manufacturing process.\textsuperscript{333} The advanced visualization of the decorative and manufacturing features on the insoles has

\textsuperscript{331} The best examples were L-1111-8-LM, L-2001-49, L-1111-7, L-2001-231, L-1994-4242, L-1987-1281, but others were discovered as well. However, a full examination of each individual insole is outside the scope of this thesis research and will the subject of future research.


not only proved the additional feasibility of the methodology employed in this research for this type of application, but the information gained will also aid scholars in augmenting their understanding of how Romans expressed their status and tastes through the styles and placement of the various decorative features on their insoles. A full examination and analysis of all the decorative features and manufacturing marks discovered or enhanced for each insole is currently outside of the scope of this thesis, but it will certainly be a fruitful avenue for future research.

Table 5: Insoles with identifiable footprint impression irregularities in the thesis dataset.

<table>
<thead>
<tr>
<th>Insole # &amp; Ownership</th>
<th>Description of Impression Irregularity</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-1985-19 (Child)</td>
<td>Heel impression on the seat is not as pronounced as expected based on in-shoe plantar pressure points made during the walking gait cycle</td>
<td>On most insoles in the dataset the heel impression is one of the deepest and most prominent impression, correlating with the heel strike phase of the gait cycle</td>
</tr>
<tr>
<td>L-1986-158 (Adult Male)</td>
<td>Impression evidence on the waist indicates that the individual placed significant pressure on their medial midfoot (medial arch), deviating from expected in-shoe plantar pressure distributions made during the gait cycle</td>
<td>Most insoles in the dataset have significant impression evidence on the lateral waist, correlating with plantar pressure made by the lateral midfoot during a normal gait cycle</td>
</tr>
<tr>
<td>L-1986-679 (Adult Female)</td>
<td>Heel impression on the seat is not as pronounced as expected based on in-shoe plantar pressure points made during the walking gait cycle</td>
<td>On most insoles in the dataset the heel impression is one of the deepest and most prominent impression, correlating with the heel strike phase of the gait cycle</td>
</tr>
<tr>
<td>L-1986-686 (Adult Female)</td>
<td>Lack of impression evidence on the lateral side of the tread of the insole, where plantar pressure made during the gait cycle</td>
<td>Most insoles in the dataset have significant impression evidence across the entire width of the insole.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footprint impression favours the medial side of the insole instead of the lateral side, deviating from average in-shoe plantar pressure distributions made during a normal gait cycle.</td>
<td>Generally, footprint impressions in the dataset favour the lateral side overall, correlating with the lateral heel, midfoot, and MPJS of the foot.</td>
</tr>
<tr>
<td>Lack of impression evidence on the medial tread made by the 1st and 2nd MPJs and prominent impressions correlating with the 3rd to 5th MPJs, deviating from expected average plantar pressure distributions.</td>
<td>The 1st and 2nd MPJs of the ball of the foot typically produce the most prominent impressions on the tread of the insole during a normal gait cycle.</td>
</tr>
<tr>
<td>Impression evidence on the waist correlating with the midfoot is located on the medial waist, deviating from expected plantar pressure distributions demonstrating impression evidence favouring the lateral waist/midfoot.</td>
<td>Most insoles in the dataset have impressions correlating with the average plantar pressure distributions favouring the lateral waist/midfoot.</td>
</tr>
<tr>
<td>Abnormally wide impression on the upper waist correlating with the upper portion of the midfoot, deviating from expected plantar pressure distributions during a normal gait cycle.</td>
<td>Possibly suggests that this individual placed abnormal amounts of pressure on their upper medial arch and metatarsal arch of the midfoot.</td>
</tr>
<tr>
<td>The footprint impression seems to favour the lateral edge/border of the insole more than normal, especially on the heel and waist.</td>
<td>This may suggest that the person walked asymmetrically, favouring their lateral foot during the gait cycle.</td>
</tr>
<tr>
<td>The footprint impression generally favours the medial side of the insole more than normal and the heel impression on the seat is abnormally located against the rear edge.</td>
<td>The heel impression centered against the rear edge of the seat may suggest a tight fitting shoe or an abnormal walking gait.</td>
</tr>
<tr>
<td>Lack of impression evidence on the medial tread made by the 1st, 2nd and 3rd MPJs and prominent impressions on the lateral tread.</td>
<td>The 1st and 2nd MPJs of the ball of the foot typically produce the most prominent impressions on</td>
</tr>
</tbody>
</table>
correlating with the 4th to 5th MPJs, deviating from expected average plantar pressure distributions the tread of the insole during a normal gait cycle.

4.5 Conclusion

The research conducted in this thesis has proven to be successful and significant for enhancing the podiatric analytical tools and techniques available within the discipline of Roman archaeology for similar future applications, despite the limited scope of the analyses that could be conducted in a master’s thesis. The results of the enhanced visualization and analyses that was conducted has not only confirmed the feasibility of the methodology for future use by researchers with similar leather footwear collections but has also revealed additional avenues of research for which the methodology could be applied in the future. The podiatric data collected in the three case studies of the research is also particularly significant, refining and expanding our knowledge of the sizes, shapes, placement, and gait irregularities of feet from the Roman populations at the site, and allowing researchers to conduct more accurate foot length measurements on Roman footwear. The results from all three case studies have also provided valuable insight into certain aspects of Roman footwear practices, including the placement of the foot and toes on open-toe sandals, within closed pointed toe shoes, and in children’s footwear. Thus, all three case studies outlined in chapter 1 have been sufficiently satisfied by the results of the methodology, and the thesis research as a whole has, in many respects, filled some of the gaps in Roman archaeology research using 3D SLS by advancing both the tools and
knowledge available within the discipline. In the future, I plan to continue the research presented here by conducting more precise digital metric analyses and digital comparative analyses on the footprint impressions identified in order to further enhance the accuracy of the podiatric data and the insights it can offer. Furthermore, I also plan to continue my initial analyses with further comprehensive podiatric and anthropological analyses concerning the irregularities seen in the gait cycle on some of the insoles in the dataset (Table 5), thereby extracting more accurate data expanding our current knowledge of the health of the populations at Vindolanda.
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Appendix A

The Conservation Process for Archaeological leather from Vindolanda from 1985 to 1993.\(^{334}\)

1. Initial on-site treatment:
   
   1.1 Incoming objects placed without washing in suitably sized perforated polythene bags with 'Tyvac'* identification label inscribed with waterproof marker pen.
   
   1.2 Bags placed in storage tank containing tap water
   
   1.3 Bags withdrawn from tanks as needed and leather given a quick preliminary wash in tap water, dipped in 0.03% aqueous solution of Busan 30L ** in tap water.
   
   1.4 Rubber gloves to be worn when handling objects in this solution
   
   1.5 After this preliminary treatment, items placed in labeled perforated plastic bags and stored in 0.03% aqueous solution of Busan 30L in tap water, to await laboratory treatment.

2. Laboratory Process Part 1: Chemical treatment:
   
   2.1 Items thoroughly brush washed with aqueous solution of 1% Lissapol NDB ***
   
   2.2 Items placed in 4% solution EDTA di-sodium salt in tap water for 1 hr. (pH 5.5), with occasional gentle agitation of vessel. (See note 1)
   
   2.3 Items drained 3 mins. & transferred to 2% acetic acid bath for 1 hour. With occasional gentle agitation of vessel. (See note 1)
   
   2.4 Items rinsed in running tap water in vessel with controlled overflow for 30 mins. Or until leather within pH range 5-6. (See Note 2 & 3).

3. Laboratory Process Part 2: Dehydration & Lubrication:
   
   3.1 Items placed in acetone Bath No.1 for 30 mins
   
   3.2 Items transferred to fresh acetone, bath No.2 for 30 mins. (See note 4)
   
   3.3 Leather specimens bench dried in ventilated area until all acetone has evaporated.
   
   3.4 Leather Dressing preparation:
      
      - 0.3g Busan 30L., 50 g anhyd. Lanolin, 20g Bavon ASAK ABP **** in solution with 1 ltr. 1, 1, 1,-trichloroethane (Genclean).

   3.5 Dressing applied by brush & specimens allowed to bench-dry at room temperature in a well ventilated chamber for 24 hrs.
   
   3.6 Specimens placed in perforated polythene storage bags.

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\(^{334}\) Taken directly from Jackman 1989. I have not made any edits to his appendix.
Note 1. Times should be taken as minimal and extended as appropriate to size & complexity of object

Note 2. The pH is checked by pressing a short-range pH indicator paper (cf. Lyphan) where possible onto both grain and flesh surfaces for 1 min.

Note 4. Removing the last traces of acidity from composite objects such as shoes, to bring them to an equilibrium pH 5 to 6 throughout, is difficult to achieve using water alone. Under these circumstances, after the prescribed washing procedure, it is recommended that they be immersed in a 0.2N sodium acetate solution for at least 1 hr. before going forward for the acetone treatment.

* 'Tyvac' labels supplied by Frank Joel.
** Busan 30L, (Buckman Chemicals) TCMBT.
*** Lissapol NDB (ICI) Non-ionic detergent.
**** Bavon ASA KABP, (Hodgeson Chemicals) Leather lubricant based on alkenyl succinic acid derivative.
Appendix B

The Conservation Process for Archaeological Leather at Vindolanda from 1993 to present.335

1. Initial on-site treatment:

   1.1 Incoming objects placed without washing in suitably sized perforated polythene bags with identification labels inscribed with waterproof marker pen.
   1.2 Bags placed in storage tank containing tap water
   1.3 Bags withdrawn from tanks and leather given a careful preliminary wash in tap water to remove surface dirt

2. Laboratory Process Part 1: Chemical treatment:

   2.1 Items placed in 5% solution EDTA di-sodium salt in tap water for 1 hr. (pH 5.5), with occasional gentle agitation of vessel.
   2.2 Items rinsed in running tap water in vessel with controlled overflow for 1 hour.
   2.3 Items drained 3 mins. & transferred to 1% acetic acid bath for 1 hour, with occasional gentle agitation of vessel.
   2.4 Items rinsed in running tap water in vessel with controlled overflow for 1 hour.

3. Laboratory Process Part 2: Dehydration & Lubrication:

   3.1 Items placed in acetone bath no.1 for 30 mins
   3.2 Items transferred to acetone bath no.2 for 30 mins.
   3.3 Leather specimens air dried in ventilated area until all acetone has evaporated. Leather can be kept flat under glass plates or padded with tissue paper if needed.
   3.4 Leather Dressing preparation (optional step):
      ▪ 0.3g Busan 30L., 50g anhyd. Lanolin, 20g Bavon ASAK ABP **** in solution with 1 ltr. 1,1,1,-trichloroethane (Genclean)?
   3.5 Leather lightly brushed; leather dressing is applied with brush & item allowed to air-dry at room temperature in a well-ventilated chamber for 24 hrs (optional step).
   3.6 Specimens wrapped in tissue paper and placed in perforated polythene storage bags for long-term storage.

---

335 I created this appendix based on information given by Jackman 1989, van Driel-Murray 1993, and Barbara Birley (Curator at the Vindolanda Trust).
** Busan 30L, TCMBT.
*** Lissapol NDB, non-ionic detergent.
**** Bavon ASAK ABP, leather lubricant based on alkenyl succinic acid derivative.
# Appendix C: Case study one dataset

<table>
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<th>Painted Min. Width (mm)</th>
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### Appendix D: Case study two dataset

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<td>Excellent</td>
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<td>L.VIII B10-VII, probably ditch context</td>
<td>4</td>
<td>Excellent</td>
<td>215</td>
<td>N/A</td>
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<td>37</td>
<td>41</td>
<td>Large 211.250</td>
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<td>L.1995.4100</td>
<td>Sandal, swapped and sewn</td>
<td>L.VIII B10-VII, probably ditch context</td>
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<td>Excellent</td>
<td>200</td>
<td>N/A</td>
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<td>Medium 190-210</td>
<td>Adult female</td>
</tr>
<tr>
<td>L.1995.4225</td>
<td>Sandal, swapped and sewn</td>
<td>L.VII B10-VII, probably ditch context</td>
<td>4</td>
<td>Excellent</td>
<td>250</td>
<td>N/A</td>
<td>84</td>
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<td>L.1995.4242</td>
<td>Sandal, swapped and sewn</td>
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<td>4</td>
<td>Excellent</td>
<td>250</td>
<td>N/A</td>
<td>86</td>
<td>56</td>
<td>65</td>
<td>Large 211.250</td>
<td>Adult male</td>
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<td>L.1995.4285</td>
<td>Sandal, swapped and sewn</td>
<td>L.XII B10-VII, western ditch, ca. 190-180</td>
<td>6A</td>
<td>Excellent</td>
<td>246</td>
<td>N/A</td>
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<td>L.2001.41</td>
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<td>1</td>
<td>Good</td>
<td>230</td>
<td>N/A</td>
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<td>Adult male</td>
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<td>L.2001.298</td>
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<td>Good</td>
<td>145</td>
<td>N/A</td>
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</tr>
<tr>
<td>L.2002.664</td>
<td>Child’s Sandal</td>
<td>L.XII B10-VII, western ditch, ca. 190-180</td>
<td>2/3</td>
<td>Good</td>
<td>136</td>
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<td>Child</td>
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<td>L.2003.335-1A</td>
<td>Sandal, swapped and sewn</td>
<td>L.XII B10-VII, western ditch, ca. 190-180</td>
<td>4</td>
<td>Good</td>
<td>219</td>
<td>N/A</td>
<td>66</td>
<td>42</td>
<td>52</td>
<td>Medium 190-210</td>
<td>Child</td>
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<td>L.2003.362</td>
<td>Sandal, swapped and sewn</td>
<td>L.XII B10-VII, western ditch, ca. 190-180</td>
<td>4</td>
<td>Excellent</td>
<td>205</td>
<td>N/A</td>
<td>56</td>
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<td>35</td>
<td>Medium 190-210</td>
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<td>Excellent</td>
<td>210</td>
<td>N/A</td>
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<td>Adult male</td>
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<td>L.2004.332-A</td>
<td>Sandal, swapped and sewn</td>
<td>L.XII B10-VII, western ditch, ca. 190-180</td>
<td>4</td>
<td>Excellent</td>
<td>252</td>
<td>N/A</td>
<td>85</td>
<td>53</td>
<td>58</td>
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<td>L.2004.60-A</td>
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<td>4</td>
<td>Excellent</td>
<td>233</td>
<td>N/A</td>
<td>77</td>
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<td>56</td>
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<td>Adult male</td>
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<td>L.2015.136</td>
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<td>L.XII B10-VII, western ditch, ca. 190-180</td>
<td>4</td>
<td>Good</td>
<td>195</td>
<td>178</td>
<td>66</td>
<td>44</td>
<td>44</td>
<td>Medium 190-210</td>
<td>Caucasian/Adolescent</td>
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<td>L.2016.149</td>
<td>Sandal, swapped and sewn</td>
<td>L.XII B10-VII, western ditch, ca. 190-180</td>
<td>4</td>
<td>Excellent</td>
<td>241</td>
<td>210</td>
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<td>Adult female</td>
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<td>L.2017.23</td>
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<td>L.XII B10-VII, western ditch, ca. 190-180</td>
<td>4</td>
<td>Excellent</td>
<td>241</td>
<td>215</td>
<td>79</td>
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<td>Large 211.250</td>
<td>Adult male</td>
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<td>Sandal, swapped and sewn</td>
<td>L.XII B10-VII, western ditch, ca. 190-180</td>
<td>4</td>
<td>Excellent</td>
<td>215</td>
<td>N/A</td>
<td>56</td>
<td>34</td>
<td>35</td>
<td>Medium 190-210</td>
<td>Caucasian/Adolescent</td>
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<td>L.XII B10-VII, western ditch, ca. 190-180</td>
<td>4</td>
<td>Excellent</td>
<td>205</td>
<td>N/A</td>
<td>56</td>
<td>34</td>
<td>35</td>
<td>Medium 190-210</td>
<td>Caucasian/Adolescent</td>
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<td>L.XII B10-VII, western ditch, ca. 190-180</td>
<td>4</td>
<td>Excellent</td>
<td>205</td>
<td>N/A</td>
<td>56</td>
<td>34</td>
<td>35</td>
<td>Medium 190-210</td>
<td>Caucasian/Adolescent</td>
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# Appendix E: Case study three dataset

<table>
<thead>
<tr>
<th>Object #</th>
<th>Object Name</th>
<th>Context #</th>
<th>Period</th>
<th>Insuse Preservation</th>
<th>Inside Length (mm)</th>
<th>Foot length estimate (mm)</th>
<th>Tread Width (mm)</th>
<th>Wand Min. Width (mm)</th>
<th>Seat Max. Width (mm)</th>
<th>Relative Size (mm)</th>
<th>Possible Owner</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-1995-19</td>
<td>Child nailed and sewn &amp; pointed</td>
<td>UXKIV in 2nd Antorine ditch</td>
<td>6</td>
<td>Excellent</td>
<td>100</td>
<td>N/A</td>
<td>52</td>
<td>40</td>
<td>45</td>
<td>Small</td>
<td>120-189</td>
</tr>
<tr>
<td>L-1990-876</td>
<td>Child nailed w/ thong</td>
<td>UXKIV E C2 (above V trench) Antorine ditch bottoms - II</td>
<td>6</td>
<td>Excellent</td>
<td>160</td>
<td>145</td>
<td>50</td>
<td>31</td>
<td>31</td>
<td>Small</td>
<td>120-189</td>
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<tr>
<td>L-1997-1175</td>
<td>Child’s Sandal</td>
<td>UXKIV west Vlll. ditch</td>
<td>4th century</td>
<td>Excellent</td>
<td>165</td>
<td>N/A</td>
<td>63</td>
<td>37</td>
<td>36</td>
<td>Small</td>
<td>120-189</td>
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<tr>
<td>L-1994-4252</td>
<td>Sasand, nailed</td>
<td>UXKIV (V) in Ill inside chain</td>
<td>3</td>
<td>Excellent</td>
<td>104</td>
<td>N/A</td>
<td>68</td>
<td>43</td>
<td>42</td>
<td>Medium</td>
<td>190-210</td>
</tr>
<tr>
<td>L-2001-6</td>
<td>Child nailed pointed</td>
<td>V2001-3A-collaps/destroyitn. beneath north end of searan workshop inside feat</td>
<td>5</td>
<td>Good</td>
<td>160</td>
<td>170</td>
<td>54</td>
<td>34</td>
<td>35</td>
<td>Small</td>
<td>120-189</td>
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<td>L-2001-90</td>
<td>Child nailed</td>
<td>V2001-3A-collaps/destroyitn of period 2/3 structure</td>
<td>3</td>
<td>Ok</td>
<td>165</td>
<td>N/A</td>
<td>58</td>
<td>40</td>
<td>41</td>
<td>Small</td>
<td>120-189</td>
</tr>
<tr>
<td>L-2001-127</td>
<td>Child nailed</td>
<td>V2001-3A- period 5 contains deep inside feat</td>
<td>5</td>
<td>Ok</td>
<td>140</td>
<td>N/A</td>
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<td>30</td>
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<tr>
<td>L-2001-296</td>
<td>Child sandal</td>
<td>V2001-3A- period 1 foot ditch, number 4. Below room 4 in period 4 above</td>
<td>1</td>
<td>Excellent</td>
<td>165</td>
<td>N/A</td>
<td>47</td>
<td>32</td>
<td>30</td>
<td>Small</td>
<td>120-189</td>
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<tr>
<td>L-2002-668</td>
<td>Child’s Sandal</td>
<td>V2002-106- lower part of searan east ditch</td>
<td>48</td>
<td>Good</td>
<td>136</td>
<td>N/A</td>
<td>47</td>
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<td>34</td>
<td>Small</td>
<td>120-189</td>
</tr>
<tr>
<td>L-2002-84B</td>
<td>Child nailed</td>
<td>V2002-20E- early timber period, building 1, floor of room 1</td>
<td>2-4</td>
<td>Excellent</td>
<td>190</td>
<td>N/A</td>
<td>66</td>
<td>41</td>
<td>41</td>
<td>Medium</td>
<td>190-210</td>
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<tr>
<td>L-2002-292A</td>
<td>Child carinated</td>
<td>V2002-40A-ditch 18 derron/longline</td>
<td>6A</td>
<td>Excellent</td>
<td>130</td>
<td>N/A</td>
<td>45</td>
<td>35</td>
<td>35</td>
<td>Small</td>
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<tr>
<td>L-2016-65</td>
<td>Child nailed, thong, pointed</td>
<td>V2016-85B-active fill layer top</td>
<td>6B</td>
<td>Good</td>
<td>160</td>
<td>150</td>
<td>54</td>
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<td>36</td>
<td>Small</td>
<td>120-189</td>
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<td>L-2016-239</td>
<td>Child nailed, thong, pointed</td>
<td>V2016-88B-active fill layer top</td>
<td>6D</td>
<td>Good</td>
<td>175</td>
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<td>L-2016-306</td>
<td>Child nailed &amp; thong</td>
<td>V2016-81B-above primary ditch fill of the top of the Saxonian ditch</td>
<td>6B</td>
<td>Excellent</td>
<td>183</td>
<td>170</td>
<td>65</td>
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<td>L-2016-358</td>
<td>Child nailed &amp; thong</td>
<td>V2016-81B-above primary ditch fill of the top of the Saxonian ditch</td>
<td>6B</td>
<td>Excellent</td>
<td>158</td>
<td>145</td>
<td>59</td>
<td>31</td>
<td>35</td>
<td>Small</td>
<td>120-189</td>
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<td>L-2016-361</td>
<td>Child nailed &amp; thong</td>
<td>V2016-81B-above primary ditch fill of the top of the Saxonian ditch</td>
<td>6B</td>
<td>Excellent</td>
<td>145</td>
<td>130</td>
<td>45</td>
<td>30</td>
<td>30</td>
<td>Small</td>
<td>120-189</td>
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<td>L-2016-404</td>
<td>Child nailed</td>
<td>V2016-81B-above primary ditch fill of the top of the Saxonian ditch</td>
<td>6D</td>
<td>Ok</td>
<td>180 (incomplete) 190 est.</td>
<td>185</td>
<td>62</td>
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<td>L-2016-441</td>
<td>Child thong &amp; thong</td>
<td>V2016-81B-above primary ditch fill of the top of the Saxonian ditch</td>
<td>6B</td>
<td>Good</td>
<td>181</td>
<td>170</td>
<td>64</td>
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<td>L-2016-451</td>
<td>Child thong &amp; thong</td>
<td>V2016-81B-above primary ditch fill of the top of the Saxonian ditch</td>
<td>6D</td>
<td>Good</td>
<td>183</td>
<td>170</td>
<td>60</td>
<td>40</td>
<td>40</td>
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<td>L-1111-8 LM</td>
<td>Child’s Sandal</td>
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<td>161</td>
<td>N/A</td>
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<td>37</td>
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<td>120-189</td>
<td>Child</td>
</tr>
</tbody>
</table>
# Curriculum Vitae

**Name:** Glanfield, Maria

**Post-Secondary Education and Degrees:**
- University of Western Ontario
  - London, Ontario, Canada
  - 2016-2020 B.A
- University of Western Ontario
  - London, Ontario, Canada
  - 2021-2023 M.A

**Honours and Awards:**
- Graham & Gale Wright Ontario Graduate Scholarship (OGS)
  - 2022-2023
- Social Science and Humanities Research Council (SSHRC)
  - Canada Graduate Scholarship – Master’s
  - 2021-2022
- Faculty of Arts & Humanities Deans Entrance Scholarship, University of Western Ontario
  - 2021
- Deans Honour List, The University of Western Ontario
  - 2016-2020

**Related Work Experience:**
- Graduate Research Assistant
  - Imaging the Vindolanda Stylus Tablets
  - The University of Western Ontario
  - 2022-2023
- Graduate Teaching Assistant
  - The University of Western Ontario
  - 2021-2023
- Graduate Research Assistant
  - Vindolanda Archaeological Leather Project
  - The University of Western Ontario
  - 2021-2023

**Conferences:**
- “Applying 3D Structured Light Scanning to Roman Leather Insoles from Vindolanda” (Poster)
  - The Classical Association of Canada Annual General Meeting
  - Halifax, Canada, May 10-12, 2023
“Applying 3D Structured Light Scanning to Roman Leather Insoles from Vindolanda” (Poster, Award winner)
Archaeological Institute of America Annual Conference
New Orleans, USA, January 5-8, 2023

“Applying 3D Structured Light Scanning to Roman Archaeology: The Vindolanda Archaeological Leather Project” (Poster)
The Classical Association of Canada Annual General Meeting