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Human and Biomechanical Considerations in Hand Joint Disease

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by

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Abstract

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Faculty of Physical Sciences and Engineering
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While public involvement has become increasingly important in the development, delivery and improvement of healthcare research, there remains limited evidence of its integration in *biomechanical* engineering research, despite its interrelatedness with healthcare. This thesis adopted an experiential approach to explore the integration of long-term public involvement into a biomechanical engineering doctoral research project concerning the hand joints. Hands play a crucial role in human life, allowing people to grasp, touch and manipulate the world around them. These abilities are impacted by conditions such as osteoarthritis (OA) which can cause pain and limit mobility.

This doctoral research project was conceptualised to leverage an existing dataset of finger kinematics and imaging of ten consenting participants (free from hand or wrist disease or injury), using computational methods. Early-stage public involvement consultations with three public contributors, living with hand OA, highlighted key research considerations and encouraged the expansion of the public involvement efforts throughout the project. As a result, the project's efforts and the selected methodologies were informed by three contributor-recommended research priorities. These priorities included: (1) patient variability, (2) joint instability and (3) raising hand OA awareness.

This thesis provided a first-hand account of involving members of the public in biomechanical engineering research. Their involvement guided the utilization and processing of the pre-existing datasets and inspired broader impacts beyond the computational modelling efforts. As a result, this research produced a combination of biomechanical findings and public-centred outcomes, including open-source statistical shape models of the fingers, correlation markers between finger joint kinematics and shape information, and educational and dissemination materials for both public and academic audiences. While there remains a need for an improved infrastructure for integrating public involvement in quantitative-based research fields, where it is currently limited, this thesis acts as an in-depth case study, highlighting the associated successes and challenges while encouraging further exploration and integration.

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Research Thesis: Declaration of Authorship

Print name: Tinashe Alexa Munyebvu

Title of thesis: Human and Biomechanical Considerations in Hand Joint Disease

I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
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5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;

7. Parts of this work have been published as:

[1] T. A. Munyebvu, G. Lillywhite, N. May, C.B. Burson-Thomas, C. McGrath, C.D. Metcalf, M. Browne, & A. S. Dickinson. “How would you handle this?” The impact of embedding early patient and public involvement in a biomechanical computational engineering doctoral research project, Research Involvement and Engagement., doi: 10.1186/s40900-025-00694-3

[2] T. A. Munyebvu, C. D. Metcalf, M. Browne, M. O. W. Heller & A. S. Dickinson (2024, 5-6 September), Can potential indicators of finger joint instability be identified in statistical shape models and associated motion data? at BioMedEng24, Queen Mary University London, UK.

[3] T. A. Munyebvu, C. D. Metcalf, C. B. Burson-Thomas, D. Warwick, C. Everitt, L. King, A. Darekar, M. Browne, M. O. W. Heller & A. S. Dickinson, (Published: 03 July 2024), “OpenHands: An Open-Source Statistical Shape Model of the Finger Bones,” Ann. Biomed. Eng., pp. 1–12, Jul. 2024, doi: 10.1007/s10439-024-03560-7.

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[8] T. A. Munyebvu, G. Lillywhite, N. May, C.B. Burson-Thomas, C.D. Metcalf, M. Browne, & A. S. Dickinson (2022, 6-10 June). The value of involving members of the public in developing bioengineering technology for hand arthritis-related research. International Federation of Societies for Surgery of the Hand, International Federation of Societies for Hand Therapy & Federation of European Societies for Surgery of the Hand Combined Congress, London, UK.

Signature: Date:

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Definitions and Abbreviations

ADLs	Activities of Daily Living
BMJ	British Medical Journal
CED	Centre for Engagement and Dissemination
CMC	Carpometacarpal
CT	Computed Tomography
DIP	Distal Interphalangeal Joint
DP	Distal Phalanx
EPSRC	Engineering and Physical Sciences Research Council
FEA	Finite Element Analysis
GRIPP	Guidance for Reporting Involvement of Patients and the Public
HWYHT	How Would You Handle This
MP	Medial Phalanx
MS	Movement Smoothness
MSI	Movement Smoothness Indicator
MR	Magnetic Resonance
MRI	Magnetic Resonance Imaging
MSK	Musculoskeletal
NCCPE	National Co-ordinating Centre for Public Engagement
NHS	National Health Service
NIHR	National Institute of Health and Care Research
OA	Osteoarthritis
PCA	Principal Component Analysis
PC	Principal Component
PE	Public Engagement
PIP	Proximal Interphalangeal Joint
PP	Proximal Phalanx

PPI	Patient and Public Involvement
PPIE	Patient and Public Involvement and Engagement
PSD	Power Spectral Density
SSM	Statistical Shape Modelling
SSMs	Statistical Shape Models
TRL	Technology Readiness Level
UKRI	United Kingdom Research and Innovation
UoS	University of Southampton

Chapter 1 Introduction

1.1 Project Background and Motivation

1.1.1 Biomechanical Analysis of Hand Joints

Hands play a crucial role in human life, allowing people to grasp, touch and manipulate the world around them. These abilities are impacted by conditions such as osteoarthritis (OA) which can cause pain and limit mobility. In 2013, more than 1.5 million people in the UK sought treatment for hand and wrist OA, ranging from non-invasive (e.g. pharmaceutical) to invasive methods (e.g. arthrodesis or joint replacement) depending on the severity of symptoms [1]. On a global scale, incidence of hand OA is recorded to have increased from 371 million in 1990 to 676 million in 2019, highlighting its growing influence on the ageing population [2]. While hand joint conditions such as OA have a major impact on peoples' confidence, independence and quality of life, biomechanical analysis of the hand and wrist joints remains at an early level of understanding compared to lower-limb joints.

To improve clinical assessment and treatment design for musculoskeletal disorders such as OA, it is important to develop a better understanding of the hands. Various computational biomechanical engineering tools may be eligible, including musculoskeletal (MSK) modelling, finite element analysis (FEA) and statistical shape modelling (SSM) to study the condition and behaviour of biological structures under various conditions [3].

This project was conceptualised to leverage an existing dataset of finger kinematics, including computed tomography (CT) and magnetic resonance (MR) imaging of ten consenting participants, free from hand or wrist disease or injury [4]. Preliminary patient and public involvement (PPI) activities highlighted the limited incorporation of the public perspective throughout the biomechanical engineering research process, despite PPI becoming increasingly present in other research fields. To this end, this doctoral research project set off to understand how PPI may be incorporated in the biomechanical engineering research process of developing a computational model from the existing datasets described above.

1.1.2 The Social Responsibility of Engineers

According to the Engineering Council, engineering activity "*can have a significant societal impact and engineers must operate in a responsible and ethical manner, recognise the importance of diversity, and help ensure that the benefits of innovation and progress are shared equitably and do not compromise the natural environment or deplete natural resources to the detriment of future generations*." [5]. Engineering, as a culture rather than a practice, has sometimes been viewed as a field that is technology-focused, socially isolated, and with aims that do not always align with community objectives [6]–[8].

Cech [8] attributes a "culture of disengagement" in engineering education to be most evident in the process of defining the problem, where they directly state, "*engineers decide what considerations are integral to their design responsibilities for a particular technological puzzle and what concerns they can bracket*". According to Cech, this approach can lead to an exclusion of non-technical stakeholders and public welfare considerations. In the subsequent decade there has been a push in engineering education to encourage better community engagement and train engineers who possess and value a diverse range of technical and non-technical skills [9]–[11]. The term 'holistic engineer' has been widely adopted to represent engineers who possess knowledge and skills beyond technical expertise. These professionals have non-technical skills that come from an awareness of their ethical and professional responsibility and the societal impact of engineering. This is emphasised by Canney and Bielefeldt who state that "*recognizing the many non-technical dimensions of engineering projects is central to our view of social responsibility because it focuses on identifying the needs of others and working with all affected parties to find appropriate solutions*." [11].

The Professional Social Responsibility Development Model (PSRDM) [12] explores the attitudes of individual engineers toward professional responsibility and their role in addressing societal issues. To achieve this, engineers must develop personal social awareness, professional skills,

and an understanding of their combined strength. The National Institute for Health and Care Research (NIHR) defines Patient and Public Involvement (PPI) as research carried out *with* or *by* members of the public rather than *to*, *about* or *for* them [13]–[15]. It is also more collectively known as 'public involvement'. PPI and its associated democratic principles may be an enabler of a PSRDM development model as it advocates for a public-researcher partnership to identify and facilitate the user's needs [16], [17].

1.1.3 Public Involvement and Biomechanical Engineering

Biomechanical engineering is, at its best, an interdisciplinary field that benefits from collaboration with non-engineers such as but not limited to, clinicians, surgeons, and policymakers. However, it remains largely technology-led, and some researchers undertake biomechanical engineering without input from other stakeholders. In PPI, those involved in the research process are often referred to as 'public contributors' rather than 'participants' and can be involved in any and every stage of the research cycle [18], [19]. Their contributions can impact key research processes and lead to unique perspectives which can result in greater quality, clinical relevance, and impact on research [16], [17]. The democratic justification for PPI follows the notion that "*those affected by research are best placed to design and deliver it and have skills and knowledge of equal importance.*" [20].

Throughout this thesis, "engineering" being referred to as largely technology-led is used in a "research" context rather than a "design" context. Design engineers are relatively conscious of the needs of users and other stakeholders, and this is evidenced through the existence of the Design Council who advocate for frameworks such as the Double Diamond or IDEO, which have been practising human-centred design since their beginning in 1978 [21], [22]. Similarly, areas of research where the engineering is more linked to a kind of 'designed' product/device whose use is the person's choice are more likely to use public-centred approaches.

Engineering research heavily relies on quantitative methods. As discussed by Borrego *et al*. [23], much of engineering research investigates outcomes by simplifying complex systems into manageable and measurable variables. Quantitative methods facilitate deductive approaches due to their effectiveness in analysing numerical data, testing hypotheses and establishing objective conclusions. On the other hand, qualitative research is conducted with an emphasis on contextual analysis of textual data such as surveys, interviews, focus groups etc [23], [24]. Within engineering research and design, qualitative methods can be employed alongside quantitative methods (i.e. mixed methods approach) to explore experiences, opinions and contexts such as user feedback analysis and observational studies [24].

Similar to Borrego *et al.* [23], this thesis does not assume that one method is privileged over any other. Instead, it is strongly agreed that the choice of method should be driven by the research question. This thesis proposes the use of public involvement to inform the question. Public involvement is *not* a research method however the strong communication and analytical skills required to facilitate it are often associated with qualitative research. Therefore, the nature by which engineering research largely focuses on quantitative methods may serve as the following barriers for integrating public involvement approaches:

- an educational barrier; as researchers may not be aware of what public involvement requires, how it can benefit their work, how to support a diverse range of public members and the difference between public involvement and formal qualitative research; and
- a practical barrier; as quantitative methods tend to favour objectivity and replicability whereas public involvement in decision-making and research exhibits an evolutionary behaviour which cannot be predicted.

1.2 Research Aims

To address the educational and practical barriers associated with integrating public involvement in engineering research, this thesis adopts an experiential approach by embedding public involvement throughout the research process.

At the conception of the research project, it was not decided by those who collected the datasets how they would be used (i.e. type of model, user and accessibility). Suggestions such as evaluating treatment options and rehabilitation strategies were proposed by members of the interdisciplinary research team. However, a public perspective was absent. Therefore, as a result of preliminary PPI, it was crucial to include the expertise of those with OA lived-experience during the early-stages of this project to better understand its purpose, relevance and useability.

It was clear that use of existing data in this project presented potential confines to the extent of public influence as well as limitations on decisions made based on the OA lived-experience while leveraging non-OA datasets, however, it was equally important to not view this as a deterrent, but rather as an opportunity to understand how this project, which is largely quantitative in nature, could be more public-centred. To this end, this thesis aims *to explore the integration of long-term public involvement into a biomechanical engineering doctoral research project* (Table 1) with the research question guiding this thesis being: *can a quantitative-based*

research project be designed, conducted, and disseminated to address PPI-reported priorities for hand joint research?

Table 1 Outline of research stages and the associated PPI objectives.

Stage	**Associated Chapters**	**Description**	**PPI-orientated objectives**
Design	3	Outline research questions, aims and methodologies	Involve and engage members of the public to guide the research process of a biomechanical engineering project, leveraging an existing dataset
Development	4,5	Undertake the research efforts to address the priorities highlighted by public contributors.	Consult contributors to acquire context, guidance and feedback on the research efforts
Dissemination	6	Share research findings with relevant stakeholders and wider audiences	Collaborate with contributors to identify target audiences and produce appropriate material
Evaluation/Critical Reflection	7	Reflect on the overall research process to evaluate the PPI approach taken	Define practical learnings from this PPI approach for future biomechanical engineering research

1.3 Research Contributions

This project was conceptualised to leverage a unique dataset of finger kinematics and imaging of ten consenting participants, free from hand or wrist disease or injury. The data was collected between 2012 and 2016 at the University of Southampton/University Hospital Southampton (IRAS Ref: 14/LO/1059) [4] and ethical approval was granted for Secondary Data Analysis use during this project (ERGO Ref: 61718). During the duration of the project, a European Union Horizon 2020 programme 'APRICOT' project provided additional funding and resources to facilitate the PPIE activities undertaken. To this end, the public engagement work conducted in this thesis by the candidate contributed to the APRICOT's portfolio of PPI and dissemination efforts.

This thesis provides a first-hand account of embedding PPI in biomechanical engineering, a commonly known technology-led research field. The involvement of members of the public guided the utilization and processing of the pre-existing datasets and inspired broader impacts beyond the computational modelling efforts. As a result, this research produced a combination of biomechanical findings and public-centred outcomes, including open-source statistical shape models of the fingers, correlation markers between finger joint kinematics and shape information, and educational and dissemination materials for both public and academic audiences. Overall, these contributions highlight the scope for a more active public involvement approach to quantitative research fields like biomechanical engineering, where the research often directly impacts its end-users. While there is still much to learn about effectively incorporating PPI in quantitative-methodology-based fields – where it tends to be less prevalent compared to qualitative research –, this research serves as an in-depth case study with critical reflections on the successes and areas for improvement.

1.4 Thesis Structure

The project has a biomechanical engineering theme and has been led by an engineer, but PPI is central to its foundation and development. To this end, the thesis will mostly be written in the passive voice however a combination of 'I' and 'we' first-person voices will be used to denote the partnership of the researcher and public contributors or personal/critical reflection.

Chapter 1: Introduction

Chapter 1 presents an overview of this doctoral project. The background outlines the motivations behind the study and presents the existing scope for the approach taken. The research aims are defined in this chapter while the contributions and structure of the thesis are also detailed.

Chapter 2: Literature Review

Chapter 2 provides a background in the biomechanical context of this project – including hand anatomy and the conventional computational tools used to study hand biomechanics – and a narrative review of the patient and public involvement literature, highlighting the scope for more active PPI approaches to quantitative-methodology-based fields of study where it is currently limited, such as computational biomechanical analysis research.

Chapter 3: Embedding Patient and Public Involvement in the Biomechanical Engineering Research Process

Chapter 3 describes the early-stage PPI activities and how these activities informed the project's structure (i.e. use of existing datasets, methods adopted, extent of PPI during future stages of the project etc.). During the PPI meetings, several different factors relating to OA and this research project were identified. However, considering the project time and resource constraints, we decided to concentrate on addressing *patient variability*, *joint instability* and *raising OA awareness* as the key priorities for this project. Additionally, this chapter discusses the continued involvement of the public contributors and their influence on the research process. It also highlights the challenges associated with this collaborative approach, mainly in the context of managing bias, diversity and inclusion.

Chapter 4: Characterising Shape Variability within an Exemplar Training Dataset of Finger Bone Triangular Surface Meshes

Chapter 4 presents the development of statistical shape models of the four fingers of the hand to investigate the variability within the exemplar training dataset of computed tomography scans provided for secondary use. A multi-body SSM pipeline, capable of computing the main modes of variation or 'principal components', consisted of three main stages, including pose neutralisation to remove joint angle variation during imaging. A consultation PPI approach was adopted during this study, whereby public contributors provided context, justification and

feedback on research methods adopted (i.e. prioritising modelling techniques based on their ability to characterise dataset variability) and supported critical thinking, guiding technical workflow, data analysis interpretation and data useability.

Chapter 5: The Investigation of Potential Joint Instability Indicators from Shape and Motion Data

Chapter 5 presents the correlation analysis between the principal components ('shape' data) computed from statistical shape analysis and features detected from angle-time signals ('kinematic' data) of the same population, using a wavelet-based workflow. This chapter details the process of denoising and decomposing the velocity-time signals to compute and a variable denoted in this study as 'movement smoothness'. This variable aims to represent the degree to which the movement appears fluid and coordinated. A consultation PPI approach was adopted during this study, whereby public contributors provided context and justification of research methods adopted (i.e. highlighted that movements become clumsier and more unpredictable as a result of their OA, suggesting that this be addressed in this research project somehow) and supported critical thinking; guiding technical workflow and data analysis interpretation.

Chapter 6: Raising OA and PPIE Awareness amongst Public, Community and Academic Audiences

Public involvement consultations identified 'raising hand OA awareness' within both public and research communities as one of the three PPI-reported priorities for this doctoral research project. Chapter 6 presents the outputs from the public involvement and engagement (PPIE) approach taken to develop material to (1) raise hand OA awareness in public spaces, (2) disseminate project outcomes and (3) increase public involvement resources and awareness amongst biomechanical engineering academics and students. A collaborative PPI approach was taken during development and delivery of the material presented in this chapter. Similar to public involvement, evidence of conducting public engagement (PE) is not mandatory in engineering research fields outputs. As a result, this chapter also reflects on the successes and challenges of handling the competing demands of the conducting public engagement activities while developing the computational modelling outputs.

Chapter 7: A Critical Reflection of the Research Approach

Chapter 7 provides a critical refection of the overall research process with a focus on the influence of PPI using the long-form Guidance for Reporting Involvement of Patients and the

Public framework (GRIPP). The categories discussed included thesis aims, methods used, evidence of impact and theoretical underpinnings forming the additional PPI insights needed for the concluding discussion in Chapter 8. A collaborative approach was taken to define practical learnings from this PPI approach for future biomechanical engineering research.

Chapter 8: Discussion and Conclusion

Chapter 8 forms the concluding discussion of this thesis, highlighting the key contributions and limitations of this research study while providing key areas for future work.

Chapter 2 Literature Review

2.1 Overview

This chapter takes a narrative literature review approach which is principally used to summarize, interpret, and critically evaluate the current state of knowledge. This thesis aims to explore the integration of long-term public involvement into a biomechanical engineering doctoral research project with the research question guiding this thesis being: *can a quantitative-based research project be designed, conducted and disseminated to address PPI-reported priorities for hand joint research?* To this end, this chapter broaches two major topics to:

(1) provide background on hand anatomy, the musculoskeletal joint condition known as osteoarthritis (OA) which can affect the hands, and the computational tools employed for the study of hand biomechanics and;
(2) explore the scope for patient and public involvement (PPI) in quantitative-methodology-based fields of study, where it is currently limited, by discussing the rationale behind and the principles and values of involving members of the public in research, the barriers and facilitators associated with this approach and the existing guidelines used to ensure high-quality PPI.

2.2 The Hand and Osteoarthritis

2.2.1 Hand Anatomy

The hand is one of the most complex structures in the human body. It can perform countless actions and thus is a crucial part of our everyday lives. One of the most essential functions of the hand results from the thumb's ability to oppose the fingers, known as prehension [25]–[27]. Prehension is classified into two grips: power grip and precision grip. Biomechanically, the power grip is the ability to apply forces whilst resisting arbitrary forces that may be applied to the object and the precision grip is the ability to make small adjustments of position to control the direction and magnitude of the force applied. This indicates that the neuromuscular system enables a person to anticipate and apply the forces required to complete a task and maintain a stable grip. These generated forces also make it possible to manipulate or transport objects as well as gather sensory information on the interaction with the object during a task to maintain stability. [28]

The human hand consists of a broad palm with five digits (four fingers and the thumb) and is attached to the forearm by the wrist. There are 27 bones in the hand; 8 carpal bones in the wrist, 5 metacarpal bones in the palm and the remaining 14 phalanx bones are found in the fingers and the thumb. There are also numerous joints, muscles, ligaments, tendons, and additional connective soft tissue in the hand. This architectural complexity facilitates the complex articulation of the hand which is essential to its broad range of required movement, and precise dexterity. Arteries, veins and nerves are also found within the hand and provide blood flow and sensations of touch, pain and temperature [25], [26], [29].

All 27 joints found in the human hand are synovial. In synovial joints, the bones are covered by articular cartilage which facilitates load transmission to the underlying bone (or subchondral bone), withstands high cyclic loads and resists compression due to its high water content and low permeability [30]. Although synovial joints can freely move, the extent of movement is dependent on the ligaments attached.

There are six different types of synovial joints. These are hinge, condyloid, saddle, planar, pivot and ball-and-socket. The joints found between the carpal and metacarpal bones are known as the carpometacarpal (CMC) joints which are classified as condyloid joints. The metacarpophalangeal (MCP) joints refer to the joints found between the metacarpal bones and the proximal phalanx. These are also condyloid. The remaining joints are called interphalangeal (IP) joints which are hinge joints; the fingers have two IP joints which are referred to as the

proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints and the thumb has a single IP joint.[29]

IP joint: A hinge joint is an articulation between the convex end of one bone and the concave end of another [31]. This joint is uniaxial. This means it only allows movement along one axis (Figure 1). This one degree of freedom (DOF) movement is flexion-extension in the radio-ulnar plane. The range of flexion in the PIP joints is greater than 90°. PIP joint flexion range increases from the second to the fifth finger. The range of flexion in the DIP joint is slightly less than 90° where it also increases from the second to the fifth finger. Active extension at either IP joint is negligible. [25]

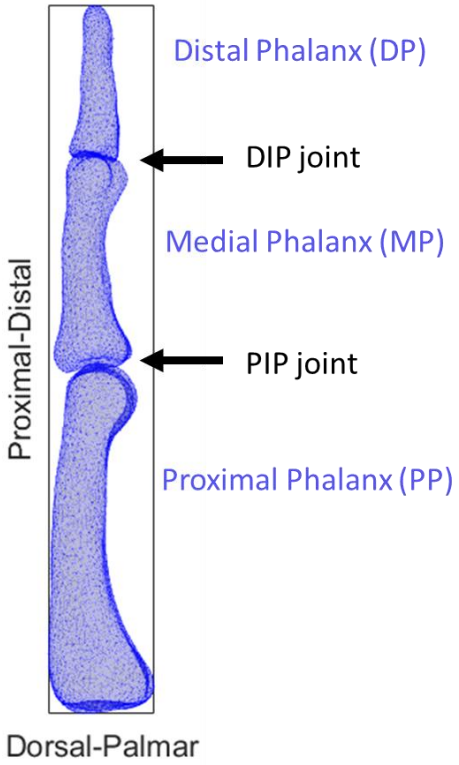

Figure 1 Index finger (right-hand) IP joints in radio-ulnar plane.

MCP joint: A condyloid joint allows movement with two degrees of freedom. It is an articulation between the shallow depression of one bone and the rounded structure of another bone [31]. This biaxial movement includes flexion/extension in the radio-ulnar plane and abduction/adduction in the palmar-dorsal plane. In the MCP joint, flexion has a range of motion of approximately 90°. It is slightly below 90° for the index finger and increases progressively across the other fingers. The active extension varies, reaching up to 30° or 40° whilst the MCP

joints of individuals with lax ligaments can reach up to 90° of passive extension. Of all the fingers, the index finger exhibits the greatest abduction/adduction range of motion. [25]

2.2.2 Hand Osteoarthritis

Osteoarthritis (OA) is the most common musculoskeletal (MSK) joint condition, affecting millions of people in the ageing population worldwide [32]–[36]. OA in the hands is highly prevalent [37], [38]. According to a study by Wan *et al.* [2] who used estimates from the 2019 Global Burden of Disease study to investigate the epidemiological trends of hand osteoarthritis from 1990 to 2019, the incident cases of hand OA increased globally from 1990 to 2019 whereby the global incident cases of hand OA in 2019 reached 6,760,000 (95% uncertainty interval (UI): 5.20×10^6-8.84×10^6) compared to 3,710,000 (UI: 2.86×10^6-4.84×10^6) in 1990.

2.2.2.1 Symptoms and Diagnosis

The pathological characterisation of OA in the hands includes the breakdown of articular cartilage, the remodelling of subchondral bone and the thickening of the joint capsule, all of which are eventually irreversible [30], [39]. OA is also characterised by the weakening of periarticular muscles, the formation of osteophytes (bony spurs) and ligament laxity [30], [35]. As well as causing chronic pain, hand OA can have a significant impact on hand function, limiting an individual's ability to perform everyday tasks. The link between joint instability and function is discussed in the literature where it is stated that the structural changes (resulting from injury or disease) of a joint can affect its function, causing limited flexibility and weakening [30]. In a review paper by Blalock *et al.* [30], directly attributes joint instability exhibited in post-traumatic OA to ligament damage however also describe the role each tissue (bone, cartilage, muscle, tendon etc.) plays in maintaining stability.

Hand OA symptoms most commonly include joint pain, joint stiffness, difficulty in moving fingers, weakened grip swelling and tenderness in the knuckles or around the wrist. In the late stages of hand OA, a reduction in the joint range of motion can also occur. There are three main clinical phenotypes of hand OA.

- *Nodal* hand OA involves the deformation of the DIP and the PIP joint. The deformity can appear as bony spurs known as Heberden (on DIP joints) or Bouchard nodes (on PIP joints).
- *First-CMC* hand OA of the thumb can co-exist with nodal hand OA.
- *Erosive* hand OA concerns the particularly aggressive and erosive damage of the PIP and DIP joints. [30], [39]

There are various ways to classify the diagnosis of OA. *Clinical OA* is based on a physical examination and requires an individual to have symptoms of which pain is the symptom most frequently reported. *Radiographic OA* involves the use of the Kellgren and Lawrence scale to grade radiographs based on the presence of osteophytes [40], [41]. *Symptomatic OA* considers both symptoms and radiographic evidence of structural changes in the joint. *Post-traumatic* OA develops after a joint injury such as a fracture, ligament sprain or cartilage damage [42].

2.2.2.2 Multi-factorial Causes and Implications

Biomechanical, genetic and environmental factors have been proposed as key factors assoicated with the development of OA, including joint injury, obesity, aging, and heredity [43]–[46]. According to Chen *et al* [35], at the cellular and molecular level*, "OA is characterized by the alteration of the healthy homeostatic state toward a catabolic state."*. *Primary* OA is considered complex and involves numerous factors with no known cause whereas, *secondary* OA develops as a result of an underlying condition, injury, or abnormality [47]. Genetics, ageing and hormonal issues have been suggested as contributing factors of primary hand OA [48], [49], however, Goislard de Monsabert *et al.* [50] highlight that no clear evidence has been provided of this. Secondary factors of OA have been identified as those that result in abnormal mechanical loading and the degeneration of articular cartilage. To improve the understanding of these loading conditions, Goislard de Monsabert *et al.* [50] used musculoskeletal modelling (MSK) to provide estimations of finger joint loadings. Their dataset highlighted the significant risk associated to pinch grip tasks and the high frequency of thumb-base OA, both which were not fully understood.

2.2.2.3 Epidemiology

A study by Wilder *et al.* [51] reported the prevalence (i.e. the frequency of the disease in the population at a given time) of joint-specific radiographic hand OA. The participants involved in the study were aged 40 years and over. Participants were not required to be living with radiographic hand OA. OA was examined in both hands and at three joints (the second DIP joint, third PIP joint and first CMC joint of the thumb) using the Kellgren and Lawrence scale. The DIP joint was found to have the highest OA prevalence, whilst the PIP joint demonstrated the lowest prevalence. The prevalence rates for the second DIP, first CMC and third PIP joints were 35%, 21% and 18% respectively. The prevalence of hand OA in all the joints increased with age which was expected and correlates with the findings from existing hand OA epidemiological studies [52], [53]. Although there were exceptions, Wilder *et al.* [51] found that overall women showed higher hand OA prevalence than men for the three inspected sites. The exceptions included men

aged 40-49 years who had a higher hand OA prevalence in the second DIP and the first CMC joint compared to women. From these findings, Wilder *et al.* [51] suggest that further investigation should be done to evaluate the sex-specific trends in the development of hand OA in younger populations (under 60 years old). To conclude, they recommend more epidemiological studies to address hand OA and bridge the gap between our current level of understanding about the hand and other joints such as the knee.

2.2.2.4 The Physiological and Psychological Burden of Hand OA

Hand OA reduces grip strength, makes it difficult to perform everyday tasks, decreases work productivity and causes a loss of ability to perform manual tasks [54]. OA in the hands is common in the ageing population and can greatly interfere with hand function, significantly affecting an individual's ability to perform their normal activities of daily living (ADLs). In a review on the epidemiology and burden of OA by Litwic *et al.* [41], regarding hand OA, they state that *"even though the symptoms are often less disabling than when the knee or hip joints are involved, it can still significantly interfere with hand function."*

As well as impacting an individual's physical abilities, OA can have considerable psychological effects. Dziedzic *et al.* [36] undertook semi-structured interviews with participants aged 50 years and over with hand OA or hand pain, to talk about the experience and impact of hand OA on their daily lives. They found that amongst the participants, one of their key goals was to maintain independence, meaning they wanted to be self-reliant despite the limitations that hand OA presents. However, participants expressed that it was difficult to do that. Additionally, it was reported that hobbies and interests tended to be forgotten about to avoid the frustration associated with the inability to do them at the same pace or precision.

OA's psychological effects can also influence an individual's willingness to seek intervention. The main objective of any arthritic treatment (both invasive and non-invasive) is to preserve or restore function with complete or at least partial pain relief [55]. In a factorial trial to evaluate the effectiveness of joint protection and hand exercise in adults aged 50 years or older with hand OA, Dziedzic *et al.* [56] found that although hand OA is common and is significantly impactful on those affected, consultations with a General Practitioner (GP) are low. They suggest that this may be a result of the perception that nothing can be done, even when hand OA poses a major challenge on daily living.

2.2.2.5 Hand Osteoarthritis Treatment

Current finger OA treatments include both non-invasive techniques (medication and physiotherapy) and more invasive measures (arthrodesis - bone fusion and arthroplasty - total joint replacements). The primary objective of any arthritic treatment (non-invasive or invasive) is to restore joint mobility with complete or partial pain relief [57]. When more conservative methods are unsuccessful (i.e. non-invasive techniques), surgery is often recommended for severe cases of hand OA. Total joint replacements can range from metallic, cemented, silicone and pyrolytic carbon implants. Some implants are hard and secured within the bone, such as pyrolytic carbon implants, whereas others, such as silicone implants, are designed to be soft and flexible to allow some movement between the implant and bone interface. There are several reasons for a total joint replacement to fail over time such as aseptic loosening, infection or pain, all of which potentially indicate the need for revision surgery. [58].

The survival of an orthopaedic implant is measured by the risk of revision surgery. According to Aragon *et al.* [59], after the knee – which makes up a large portion of OA research, the trapeziometacarpal (TM) joint in the thumb is the second most OA-affected joint in the human body and yet the success rate of finger joint replacements does not match the performance of knee and hip joint replacements. For instance, according to the 11th Annual National Joint Registry Report and stated by Khan et al. [60], the risk of failure of a total knee arthroplasty (TKA) requiring revision surgery ten years post-operatively was less than 5% in the UK in 2014 [61]. Joyce and Unsworth [62] reviewed the failure modes of the Swanson finger prosthesis for the MCP joint, revealing a failure rate of up to 85 % after 5 years [63]. Despite its high failure rate, the silicone implant remains the gold standard for preserving PIP and MCP joints in the hand [55]. Adams *et al.* [64] systematically reviewed all published evidence for PIP joint replacements and found that, as of 2012, there was almost no information about the longer-term survival of any PIP and DIP implant. The authors also report high levels of complication rates of PIP joint replacements, highlighting that that level of risk would not be acceptable for a hip or knee replacement operation. Since 2012, the literature investigating the long-term outcomes of surgical options for PIP joint has been deemed limited, however, to combat this, Darwish *et al.* [65] recently published a systematic review comparing silicone, PyroCarbon and metal prostheses in PIP joint arthroplasty for primary degenerative OA between 1990 and 2021. Similarly, to expand the knowledge of the effectiveness of hand OA treatment, Selig *et al.* [66] published a study in 2020 to compare the short-, mid-, and long-term results of PyroCarbon PIP joint arthroplasty of study group who underwent surgery between 2002 and 2004. Out of 27 patients with 32 implants, long-term outcomes (average 9.8 years postoperative) were followed

up for 15 patients with 18 implants. An implant survival rate for PyroCarbon PIPJ arthroplasty of 87% after a minimum of 9 years follow-up was found. Other outcomes measures were recorded, including pain, implant migration, grip strength and patient satisfaction.

To improve clinical assessment and treatment design for musculoskeletal disorders such as OA, it is important to develop a better understanding of the hands. Various computational biomechanical engineering tools may be eligible, including musculoskeletal (MSK) modelling, finite element analysis (FEA) and statistical shape modelling (SSM) to study the condition and behaviour of biological structures under various conditions [3].

2.3 Computational Modelling Methods

2.3.1 Computational Biomechanical Engineering Tools

In-silico modelling is considered a logical extension, rather than replacement, of controlled in vitro experimentation, whereby it can aid in reducing costs (expenses and time) and overcoming resource limitations (i.e. access to specimens) [67]. For instance, simulating complex biological system can allow for measuring internal quantities non-invasively [68]. In a dentistry study , Yamaguchi *et al.* [69] combined *in-vitro* fatigue tests and *in-silico* FEA of various dental implant fixtures. This modelling technique aims to predict how structures will behave under various real-world conditions, such as stress and temperature. To evaluate the fatigue resistance of dental implants, Yamaguchi *et al*. used *in-vitro* step stress accelerated life tests along with *in-silico* FEA on computer-aided design models which allowed for the visualisation and quantification of mechanical stress/strain distribution of the marginal bone of dental implant fixtures and implant components. The authors suggested that the reported *in-silico* method can be used to investigate the geometrical implications of dental implants to reduce the complex interactions with bone that lead to fatigue failure.

MSK modelling is a powerful, computational simulation tool that facilitates biomechanical analysis of human movement [67]. MSK models have both clinical applications such as surgical planning, rehabilitation inventions and assistive device design and research applications for advancing biomechanical understanding of pathological and non-pathological movement [70]–[73]. A MSK model consists of rigid body segments (i.e. bones) connected by joints, which define articulation (i.e. location and orientation of joint axes) and the permitted DOFs and ranges of motion [74], [75]. Each rigid body is assigned geometry, mass and inertial properties. MSK models can non-invasively estimate muscle and joint contact forces during different

activities, such as walking or climbing stairs[76]–[78]. While extensive research has been done on modelling lower limb joints, this technique has also been applied to the biomechanical study of several upper limb joints [79]–[81].

Evaluating the variation in biological structures amongst a population can aid clinical decision-making processes such as diagnoses, treatment, and surgical planning [82]. Statistical shape modelling (SSM) is a powerful probabilistic tool for representing, characterising, and quantifying variations in shape and mechanical properties in a population [68]. For example, due to the complex progression of congenital heart disease and its unique structural effect on the anatomy, Bruse *et al*. [83] state that SSM has become an increasingly popular tool for processing and analysing large amounts of population data for cardiac studies.

2.3.2 Computational Modelling and OA

According to Erdemir *et al*. [84], there are three main inputs required to develop a full computational model of a human joint. These are (1) the anatomical properties of the joint, (2) the mechanical properties of the involved tissues, and (3) loading parameters. The basis of this strategy was discussed in relation to a knee-joint model however, it appears to apply to any joint and has been cited by other literature [3] as the basis of computational model generation. There exist numerous types of state-of-the-art models used to understand how OA affects the different parts of the joint. Some models focus on a single tissue and others on the entire joint, requiring multiple inputs [84]. It is important to assess the suitability of the modelling method employed and input data used as well as report the assumptions made during the process to enhance useability and impact.

In their review, Mukherjee *et al*. [3] discuss the benefits and the limitations associated with using computational modelling to study different aspects of joint degeneration, focusing mostly on the knee joint. For MSK models, they state that such models can estimate joint loading properties, but they cannot be used to identify areas of damage initiation or to categorise disease progression because they do not quantify tissue-specific stresses and strain. In the context of studying joint degeneration, MSK modelling is mainly used to estimate the presence and effect of excessive loading and therefore the risk of damage initiation and progression. This shows that whilst biomechanical analysis tools may not always consider the overall picture, they can further our understanding of how OA manifests and can impact different variables.

MSK and FEA studies are commonly informed by parameters obtained from a single or a variety of different sources. The literature rarely reports how these features compare against the rest of

the population. For instance, in the development of their MSK model of the hand and wrist, Mirakhorlo *et al*. [85] state that whilst using one single cadaveric dataset facilitated consistency, it limited generalizability. To broaden the interpretation of MSK models' outputs, the potential of a population-based approach to MSK modelling continues to be explored. For instance, in their editorial paper, Saxby *et al*. [86] suggest the tissue (i.e. bones, muscles and articular soft tissue) constructed using statistical models generated by population-based machine learning methods can be incorporated into subject-specific MSK models. By using a population-based approach to generate subject-specific models, the tissue geometries can be varied systemically along the principal modes of population variance, and the model outputs can be interpreted relative to the trends observed in the wider population. This has been studied by Clouthier *et al*. [87] who characterised the knee joint geometry using SSM and then investigated the effect of geometry on the joint biomechanics assessed using MSK simulation. By combining the two methods, they found that the articular geometry affected the joint kinematics, contact mechanics, and ligament loading.

2.3.3 Statistical Shape Modelling

2.3.3.1 Process

A statistical shape model uses dimensionality reduction techniques to provide information on shape variability within a training set, around an average shape. Statistical shape models can be descriptive or predictive. Descriptive models facilitate the study of shape characteristics and enable the investigation of any trends, clusters, or outliers within the dataset. Predictive models, which in some cases are an extension of a descriptive model, can be used to study the relationships between shape and continuous or discrete parameters and to create complete subject-specific geometries from incomplete data which is useful for informing other types of models [75], [83].

SSM can be applied to 3D data of soft and hard tissue [68]. These 3D objects are created from the segmentation of medical images (i.e. CT or MRI) representing the surfaces as point clouds or meshes (Figure 2). Each node of the mesh is described by x-, y-, and z-coordinates in Cartesian space. Before extracting shape information, registration ensures each geometry in the training dataset can be directly compared. Most registration techniques aim to morph a template geometry to each subject's shape to establish nodal correspondence. Dimensionality reduction algorithms are then applied to the registered data. This step is crucial for extracting information on shape variation. Principal component analysis (PCA) is a well-established and widely used technique to reduce the number of dimensions of the training data and decompose it into a set

of new variables or principal components (PCs), all whilst retaining most of the variability contained in the original variables [88]. While PCA is a common technique, it assumes normally distributed variation in the training datasets (i.e. Gaussian distribution) [89]. SSM aims to represent the training data with the fewest PCs or 'modes' possible. A 'mode' represents a shape variation observed in the population, for example, size, curvature, etc. The relative weight of each mode represents the amount of variability in the training data that is captured in that mode. Visualization of these modes of variation is done by converting the PCs back to a cartesian space and perturbing the mean geometry by some quantity of variance, one at a time [68]. Using SSM results, individuals within the training dataset can be categorised by inspecting clusters in mode scores, and virtual feasible individuals can be generated by selecting desired characteristics across selected modes.

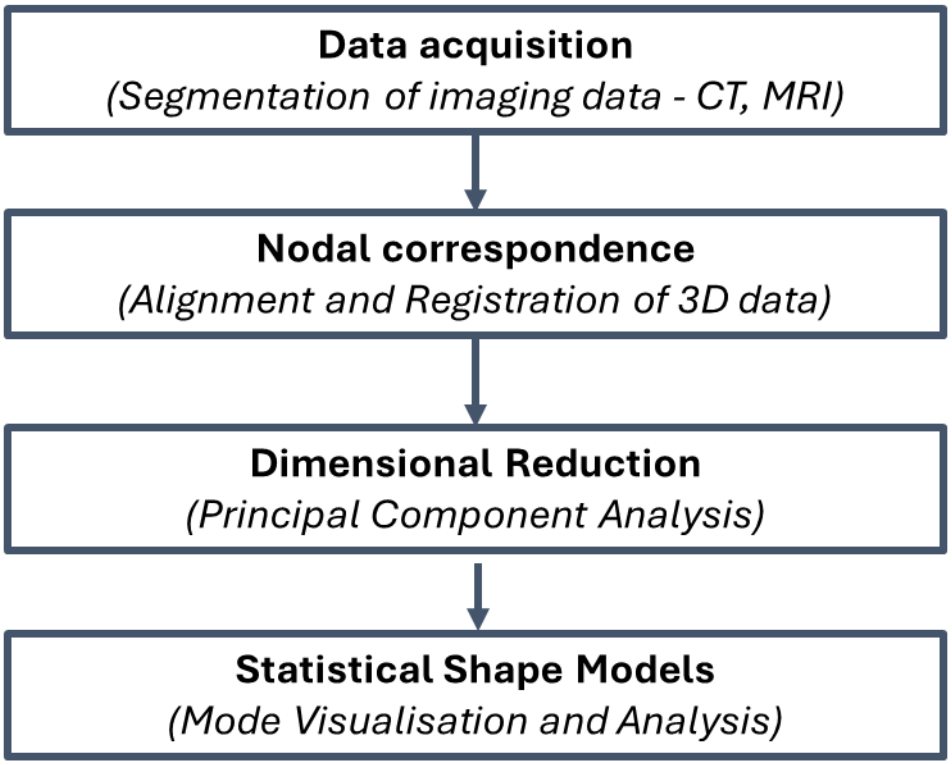

Figure 2 Typical workflow for generating a statistical model from population data for tissue morphology analysis

The potential to combine orthopaedic biomechanical studies with a population-based approach continues to be explored in literature [90]. This echoes Saxby *et al.'s* [86] suggestion for the tissue models to be constructed from statistical datasets using population-based machine learning methods. By using a population-based approach to generate subject-specific models, the tissue geometries can be varied systemically along with the principal modes of population variance, and the model outputs can be interpreted relative to the trends observed in the wider

population. Extracting the distinguishing characteristics of the individuals used to train a population model allows for the characterisation of sub-groups, such as done in archaeology [91] or for prosthetic socket design [92].

2.3.3.2 Existing Hand SSMs

SSM has been widely employed to characterise the morphology of biological structures [93], including the ventricles, mandible, residual limbs following amputation, and joints in the foot, knee and hip [83], [94]–[98]. In their review paper, Sarkalkan *et al.* [99] explore the application of SSM on femur data. They highlight how SSM describes the mean shape and mean density distribution of bones within a certain population as well as the main modes of variation of shape and density distribution from their mean values. This type of analysis on bone lends itself well to the opportunity for diagnosis, evaluation, and treatment of skeletal diseases. In a review paper, Bischoff *et al.* [90] present the ways SSM has been used in orthopaedic biomechanical analysis including preprocessing of shape models, morphological evaluation, material properties, kinetics and kinematics. Considering the joints of the hand, statistical models have focused so far on the thumb, demonstrating morphological variation in the CMC joint. Rusli and Kedgley [100] present the impact of morphology variation on joint instability across their study population, highlighting the significance of these findings in future CMC OA studies. Schneider *et al.* [101] focused on characterising the morphological sex and age patterns amongst their study population of CMC joint bones. For example, they found that a female cohort had similarly shaped trapezium and first metacarpal bones as men. Although statistical models of the full hand's external anatomy have been reported [102], there is no current SSM report on the interphalangeal joints found in the thumb or those found across the fingers, despite the prevalence of their degeneration [103] and scope to improve surgical outcomes [64].

2.3.3.3 Model Generation

2.3.3.3.1 Dependence on training population

It is important to consider the statistical significance of the population used to construct a statistical shape model. In a thesis on SSM of the shoulder, Sintini [68] states that a model's ability to effectively capture inter-subject variability is strictly related to the size and quality of the training set. Sintini attributes the terms "size and quality" to how accurately the target population being modelled is represented. In their archaeological research study, Woods *et al.* [91] discuss the statistical model's dependence on the training datasets, stating that a larger dataset would have made it possible to construct independent statistical shape models for

each sample group and thus compare the major differences in the samples by comparing the difference in the principal components. Additionally, the effectiveness of dimensional reduction is highly dependent on the training data because, unless it is explicitly present in the training data, even the simplest invariance cannot be captured by the PCA [104].

2.3.3.3.2 Dimensional Reduction Algorithms

Although similar dimensional reduction algorithms exist, such as partial least squares regression (PLSR), kernel-PCA (KPCA) and independent component analysis (ICA), most SSM studies use PCA [91], [105]–[108]. PCA is popular because of its low noise sensitivity, its ability to decrease data redundancy and its low computational cost on large datasets [109]. However, PCA assumes that a linear transformation can capture most of the variation of the data (i.e. Gaussian distribution of variation) and thus, it is not effective on non-linear datasets [110]. For instance, despite PCA's effectiveness where linearity exists, the shape of many biological does not follow a simple Gaussian distribution such as highlighted by Kirschner *et al.* [111] who generated a mean shape of vertebrae generated using linear SSM techniques but discovered it was not representative of existing vertebra. In addition, data corruption such as artefacts and noise, influences the training data quality and impacts the resultant PCs. In another study, Yang *et al.* [107] evaluated the compactness, generality, and specificity of three different dimensional reduction algorithms (PCA, KPCA and ICA) methods in their research on posture-invariant 3D human hand statistical shape models. They found that PCA had the lowest generality error and needed the fewest components, as a result, they proceeded with PCA-based SSM. It is unknown which dimensional reduction algorithm is most suitable for SSM of the hand. However, whilst PCA is the popular technique, these studies suggest that researchers should evaluate the condition of their training data (i.e. linearity, normality, representativeness etc.) when selecting a dimensionality reduction algorithm.

2.3.3.3.3 Useability of computational modelling outputs

The use of computational models of the MSK system has become increasingly popular in many fields of clinically-driven research, including for surgical planning [112], [113], implant design [114], [115] and rehabilitation purposes [75], [116]. In their efforts to decipher the art of modelling and simulation of the knee joint, Erdemir *et al.* [84] discuss the four-phase life cycle of computational models in biomechanics research and innovation. They state that a large number of models exist with varying levels of fidelity in anatomical and mechanical representation. This cited example once again concerns the knee joint but will be used as a guide in the absence of an appropriate example for hand-specific models.

The model phases of computational models in biomechanics discussed by Erdemir *et al.* [84] include:

1. Model Development – to create the initial working models
2. Model Calibration – to adjust model parameters
3. Model Benchmarking – to assess model performance
4. Model Reuse – to examine the useability of the model/simulation for scientific and clinical decision-making

Modelling can be a subjective practice. The decision of the researcher/modeller likely impacts the results found and thus the conclusions made from a model/simulation. This makes establishing a strategy and maintaining a workflow important for ensuring the model's reproducibility [117][118].

An example of the plausibility of computational modelling and simulations in clinical practice is presented in an article by Killen *et al.* [75]. They provide examples of the role MSK modelling plays in disease prevention, patient stratification, pre-surgical planning and implant/assistive device design. One example includes the use of MSK modelling on patients who have undergone knee ligament reconstructions and were thus at an elevated risk of developing OA. Initially, this was thought to be due to high joint contact forces post-surgery but MSK modelling outcomes showed that those patients exhibited lower joint contact forces; dismissing the previous assumption that higher joint contact forces contribute to OA development. Overall, this modelling study was used to identify key biomarkers (i.e. joint contact forces) that play an important role in OA development and which cannot be measured *in vivo* [119]. Although it was thought higher joint contact forces were associated with the development of OA, the MSK modelling techniques used in the study showed that OA was still developed in the knee joint post-reconstructive surgery despite lower joint contact forces. This study shows that for clinical use; it is crucial that computational models can accurately simulate both pathological and non-pathological datasets. However, this is a major challenge, especially as building subject-specific models can be costly and time-consuming. This is where using alternative modelling techniques such as SSM alongside MSK modelling can be useful for population-level analysis or reconstructing subject-specific geometries from the referenced population.

The development of tools (both *in-silico* and *in-vitro*) is largely dependent on the resources available. (i.e. input data, software capabilities). Few researchers have access to the anatomic data required for biomechanical analysis of the joints, and there is cost, inconvenience, and risk associated with CT or MRI scanning volunteers. The method of combining SSM and MSK

modelling efforts allows existing models to be applied to new individuals with relatively low expense, which may support clinical translation [120]. However, as encouraged by Saxby *et al*. [86], this approach relies on the research community to share models and technologies. In a review paper, Bischoff *et al*. [90] discuss the scope for incorporating population-level variability in orthopaedic biomechanical analysis using statistical methods. They state that PCA provides the necessary information to effectively and efficiently integrate variability into mechanistic models of joint function. With this, biomechanical engineers can study the effects of variability on biomechanics, in a way that may be predictive of a larger patient population rather than at a solely patient-specific level.

Whilst developing these computational methods for biomechanical analysis is beneficial for clinical application, they tend to be designed by the modelling experts themselves rather than alongside service users. Therefore, to understand the suitability of modelling techniques applied it is additionally crucial for modelling experts to collaborate with those who will be impacted by the model's outcomes. However, as discussed in Chapter 1, there is limited evidence of public involvement in quantitative-based research fields, such as computational biomechanics.

2.4 Public Involvement

2.4.1 Terminology

The National Institute for Health and Care Research (NIHR) defines Patient and Public Involvement (PPI) as research carried out *with* or *by* members of the public rather than *to*, *about* or *for* them [13]–[15]. It is also more collectively known as 'public involvement'. The democratic justification for PPI follows the notion that "*those affected by research are best placed to design and deliver it and have skills and knowledge of equal importance.*" [20]. Members of the public involved in research are commonly referred to as 'public contributors' and can be involved in any and every stage of the research cycle [18], [19]. Their contributions have been shown to influence key research processes, resulting in greater quality, clinical relevance, and impact [16], [17].

The many ways that the public can interact with research tend to fall into three main categories: *participation*, *engagement*, and i*nvolvement*. Participation describes activities where the public, referred to as 'subjects' or 'participants' take part in a research study; for example, when people are recruited to take part in a clinical trial. Engagement is defined as the process of sharing

information about research and research findings with the public as well as promoting participation in research. Involvement, on the other hand, is the active partnership between researchers and the public throughout the research cycle, influencing and shaping research decisions [121], [122]. While these categories differ in strategy, they are often linked and can complement each other. It may explain why the terms are used synonymously, despite their distinct attributes. The growing use of the term Patient and Public Involvement and Engagement (PPIE) is an example of making the important distinction while incorporating the principles of both methods [123]. For instance, Holmes *et al*. [124] propose a continuous cycle of engagement and involvement in research. They note that although their proposed cycle depends on the circumstances, research area, and people involved, it revolves around inclusive research (i.e. Research-Led PPIE), co-creating high-quality engagement outputs, and amplifying those outputs to engage people (i.e. Demand-Led PPIE) and establish public-centred policy [124].

There is no universal definition of or agreed term for the involvement of members of the public in research. For instance, Han *et al*. [125] use the term ‘community-engaged research’ to describe what is, under the NIHR’s definition, public involvement. They even cite publications that utilise the term ‘public involvement’ to enhance their arguments. Similarly, Forsythe *et al*. [126] use the term 'stakeholder engagement’ to depict the involvement of patients and healthcare stakeholders in the planning and execution of biomedical research. This shows the breadth of terminology used to portray similar public-centred activity. However, as highlighted by Palm et al. [127], when they undertook a review of involvement literature to explore the principles and standards for public involvement, this lack of cohesiveness may impact how the quality of involvement occurring in research is assessed. As the NIHR is one of the UK’s leading research bodies in advocating for a PPI research approach, the terms ‘PPI’ and ‘public involvement’ will be used throughout this thesis to describe the involvement of members of the public in research. Literature utilising alternate PPI terminology (i.e. community/stakeholder involvement or engagement) may be cited in this thesis as long as the definition to depict their efforts resembles the NIHR’s description of involvement.

2.4.2 The History and Emergence of Public Involvement in the United Kingdom

Public involvement first became of interest within the UK National Health Service (NHS) in the 1990s. Healthcare professionals such as Marian Barnes [128] advocated for citizen involvement in decision-making rather than a return to “paternalism” whereby service users are offered limited autonomy by their healthcare provider. Barnes criticized this system of paternalism,

stating that it is the responsibility of the NHS to provide education and training to develop a model that ensures clinicians and other professionals steer away from the assumption of superiority of expert knowledge. As stated by Gibson *et al*. [129], these changes in attitudes may have resulted in public demand for a larger voice in deciding on their services as well as governmental demands to improve the efficiency and quality of these services [130]. Examples of increasing pressure from the public for greater involvement include the 1989 *'Working for patients'* white paper, which called for an NHS reform to give patients better choices in their healthcare, generate greater satisfaction and reward NHS workers who effectively respond to local needs and preferences [131].

The 1991 NHS Research and Development Strategy was the first government document to highlight the relevance of public involvement [132]. Then, in 1996, England's Department of Health established the Standing Advisory Group on Consumer Involvement in the NHS Research and Development Programme [133]. This body known to advise and promote public involvement in England was later rebranded as Consumers in NHS Research before settling on INVOLVE in 2003 [134]. When the NIHR was established in 2006, INVOLVE, became part of its portfolio and within the same year, the Department of Health stated that *"patients and public must be involved in all stages of* the research process" [133], [134] In 2020, the NIHR Centre for Engagement and Dissemination (CED), launched and subsumed the remit of INVOLVE, alongside responsibilities related to participant recruitment and evidence dissemination [134].

There has also been a real global push for the involvement of non-researchers such as patients, caregivers, advocacy groups, clinicians, and policymakers in health care research [135]. For instance, institutions such as the Patient-Centred Outcomes Research Institute (United States of America) and Strategy for Patient-Oriented Research (Canada) are highly committed to funding and promoting public involvement in healthcare research [136]–[138]. A review by Boote *et al*. [139] highlighted this increased interest in public involvement in healthcare research, stating that more researchers are "walking the walk" and committing to incorporating PPI into their studies. Of the 683 papers identified in the bibliometric review of the public involvement literature in healthcare research published between 1995 and 2009 [139], majority of the papers originated from the USA (297) and the UK (223). In more recently published literature, the UK has been deemed the leader in publishing PPI work with less literature originating from mainland Europe (excluding the UK) [140]. A systematic review by Biddle *et al*. [140] aimed to identify the attitudes and approaches to PPI across Europe in both public and private health services and research institutions. They found an uneven distribution of PPI implemented across Europe and attributed this to access to guidance and support as well as existing or favourable PPI

infrastructure. However, despite the lower volume of PPI publications, Europe's attitude to PPI was identified as similar to that within the UK. In their systematic review which aims to explore the presence of PPI in health research in low and middle-income countries, Cook *et al.* [141] also highlight the well-established nature of PPI in the UK, notably attributing that to two-decade long existence of the INVOLVE framework. They note that whilst this is true, the UK still faces obstacles, with concerns of "tokenistic involvement" becoming the result of involving members of the public as an obligation to funders. They suggest this is also an issue, if not more acute, for research done in low and middle-income countries, where PPI is done but strategies used are often not published. To improve the execution and documentation of PPI in these countries, Cook *et al.* recommend that funders and journal publishers make PPI an explicit requirement and pre-existing PPI guidance and tools are adapted and encouraged for use [141].

2.4.3 Rationale of Public Involvement

The democratic justification for PPI follows the notion that *"those affected by research are best placed to design and deliver it and have skills and knowledge of equal importance."* [20]. According to the NIHR, involving members of the public ensures that the research both addresses their needs and is measured against the outcomes that are important to them [142]. This links closely to the mantra, "*Nothing about me, without me"* – a core person-centred decision-making principle insisting that the public should have as much a say in the research about them as the researcher. As well as improving study design, contributors can improve the wider public's access to research. For example, if research requires participants for clinical trials, working with members of the public can help to shape the study design in such a way that considers and well-communicates the participant's needs and capabilities, thus enhancing recruitment and retention.

To build a better understanding of the role of public involvement in research, Marjanovic *et al.* [143] published a learning report which included a rapid review of academic and grey literature published between 2000 and 2018. The report was complemented by a series of interviews from researchers and organisations dedicated to working with the public and providing guidance for others to do so effectively. They found that the public's reasons for being involved in research are heavily influenced by their diverse life experience, interests and prior involvement in healthcare research. These included [143]–[145] :

- wanting to help others in similar positions
- contributing to an improved healthcare system

- wanting the patient's views to be reflected where they otherwise would not and influence research and healthcare.
- having a general interest research and in contributing to creating scientific knowledge
- having an interest in the research topic, often due to personal experience

The learning report also addressed the rationale of public involvement from a researcher's perspective, revealing that many of the reasons why researchers involve the public coincide with the public's reasonings. However, Marjanovic *et al.* also highlighted that researchers that incorporate PPI in their work believe that it is the *"right thing to do"* and that it will improve research outcomes [143].

2.4.4 Values and Principles of Involvement

INVOLVE (recently subsumed by CED) defines and presents six values and principles of public involvement in research in a framework informed by reviewed literature, publications and reports [146]. The framework (Table 2) was designed for researchers, organisations, public contributors and others to support and manage public involvement in research [147].

Table 2 Summary of INVOLVE's values and principles for public involvement in research [148]

Value	Summary	Principles in practice
1. Respect	Researchers, research organisations and the public respect one another's roles and perspectives	1a. Public members' skills, knowledge and experience are respected. 1b. The knowledge and experience of researchers and others involved in administering or managing research skills are respected. 1c. Public members are included as key partners of research. 1d. Public members are involved from the outset. 1e. Public members' contributions to the research are recognised
2. Support	Researchers, research organisations and the public have access to practical and organisational support to involve and be involved	2a. Public members have access to learning and development to support their involvement in research. 2b. Researchers and others have access to learning and development to support public involvement in research. 2c. There is flexibility to support public involvement. 2d. Public members' expenses are covered, and they are informed in advance if payment will be offered for their time. 2e. Infrastructure within research organisations enables and supports public involvement in research.
3. Transparency	Researchers, research organisations and the public are clear and open about the aims and scope of involvement in the research	3a. Researchers and others involved in the research openly discuss with public members the purpose, scope and expectations in advance of their involvement in the research. 3b. Researchers provide clear information to public members about their role and their input. 3c. Public members are open about their ability to contribute.

4. Responsiveness	Researchers and research organisations actively respond to the input of public members involved in research	4a. Public members, researchers and others contribute to collaborative decision-making. 4b. Researchers and research organisations are committed to public involvement and are willing to act on the input of the public. 4c. Public members commit to their involvement in research and are willing to contribute to the research.
5. Fairness of opportunity	Researchers and research organisations ensure that public involvement in research is open to individuals and communities without discrimination	5a. Public members, researchers and others understand and sign up to the principles of equality, diversity and inclusion as defined in the Equalities Act 2010 5b Researchers and research organisations ensure that public involvement opportunities are accessible to all. 5c. Information is presented in accessible and alternative formats and written in plain English.
6. Accountability	Researchers, research organisations and the public are accountable for their involvement in research and to people affected by the research	6a. Researchers and research organisations have policies in place for the governance of public involvement in research and public accountability. 6b. Researchers and research organisations are accountable to public members involved in the research. 6c. Public members are accountable to researchers, research organisations and others for their involvement. 6d. Researchers, research organisations and public members assess the impact of public involvement in the research.

2.4.5 Theoretical Models of Involvement

Different approaches to involvement exist, whereby the levels of power sharing vary [146]. In their paper, Boote, Telford and Cooper [149] outline conceptualization of consumer involvement, highlighting how the empowerment of the 'consumer' within the research process increases with each 'level'. They define 'consumer' as individuals, groups and organisations which fall into the category in relation to health research (i.e. service users, support groups and charities). Their 'levels of involvement' model ranges between consultation, collaboration and 'consumer' control and can be considered as drawing on Arnstein's 'ladder of citizen

participation' (Figure 3) which describes how power is distributed between citizens and institutions [149].

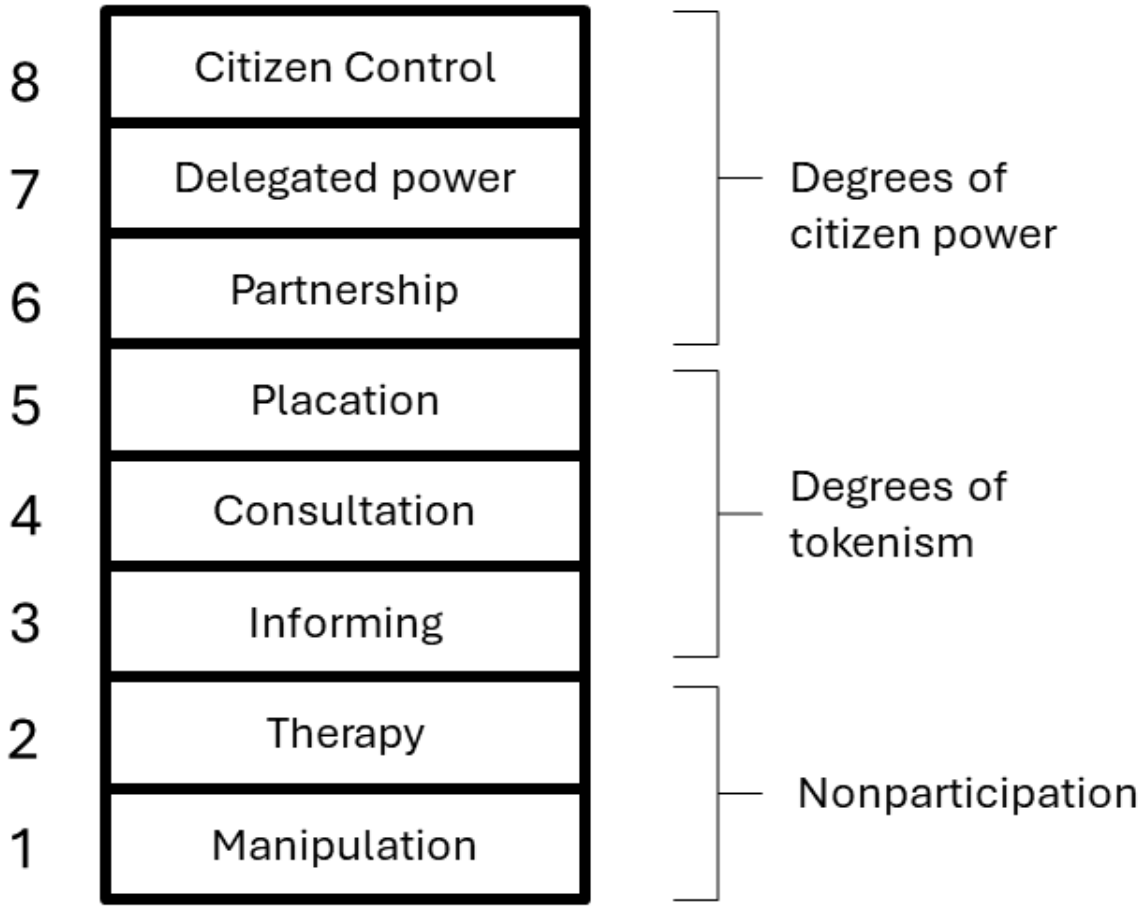

Figure 3 Arnstein's ladder of citizen engagement

In Arnstein's model, each rung on the ladder represents increasing degrees of citizen participation [150]. The first two rungs describe levels of non-participation in which the 'powerholders' aim to 'educate' those involved rather than having them take a design-making seat. Further up the ladder, the rungs represent degrees of tokenism, by which citizens have a voice, but their impact is limited. The remaining rungs present the degrees of citizen power, of which we enter a stage by which citizens have the majority of the seats at the decision-making table. Arnstein describes this ladder as a simplification of reality however, it has since been interpreted and built upon in different contexts. Most PPI interpretations commonly include a 'hierarchal structure' that suggests the ideal approach to public involvement is the 'sharing of power' which is found at the top of the ladder [146]. For instance, a modified version by Mayes [151] propose a six-rung ladder and uses similar terminology as the NIHR framework to describe each level of involvement (Table 3)

Table 3 Six-rung ladder describing levels of involvement by Mayes [151]

Rung	**Description**
Co-design	Patient/public are partners in the design of the project from the beginning, and they influence the decision-making process
Meaningful Involvement	Patients/the public are involved with clear evidence of influence however the staff make the final decisions.
Peripheral Involvement	Patients/the public are involved in the project but with limited influence (for instance, they have been involved too late to enact real change)
Consulting	Patient/public views are actively sought; however, plans have more or less been cemented.
Tokenism	Patient/public views are sought and heard but not acted upon and therefore there is no clear scope for influence.
Informing	one-way communication where information is shared via websites, leaflets, posters and presentations and the patient/public views are not sought.

Rather than 'levels', the NIHR's *Briefing Notes for researchers - public involvement in NHS, health and social care research* define 'approaches' to public involvement (Figure 4). These include consultation, collaboration, co-production, and user-controlled research [14]. Similar to the definition of public involvement, there is no unanimous agreement across Europe on terminology used to describe these approaches [140]. Using the NIHR definitions, a systematic review of the attitude toward PPI across Europe by Biddle *et al.* [140] demonstrated that 87.5% of the cited studies directly or indirectly stated their PPI 'approach'. In their paper, they note that most studies used more 'active' approaches to PPI however, they also state that the choice of approach depends on the specific context and nature of the study. Overall, this links to the emphasis placed on power-sharing in PPI, whereby power imbalances and hierarchy have been recognised as barriers to achieving collaborative work in practice [152].

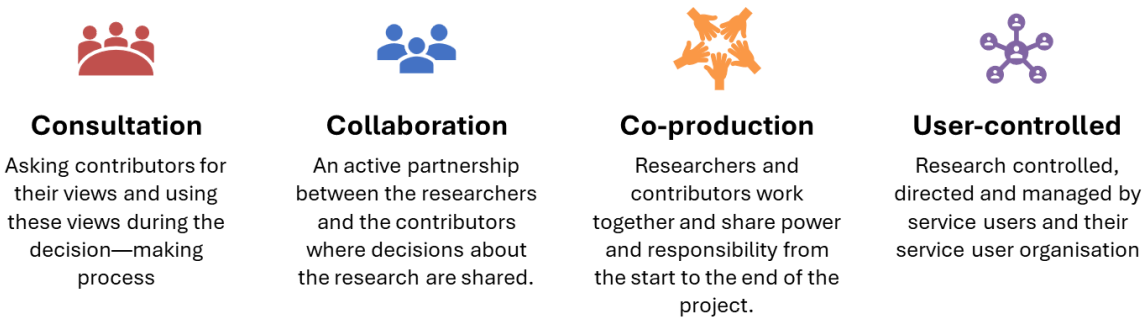

Figure 4 Definitions of the main PPI approaches [14]

2.4.6 The Role and Duration of Involvement

Public contributors can be involved in and enhance a project at any and ideally, every stage of the research cycle (Figure 5). However, it is recommended that they become involved in the research at the earliest stage possible [142].

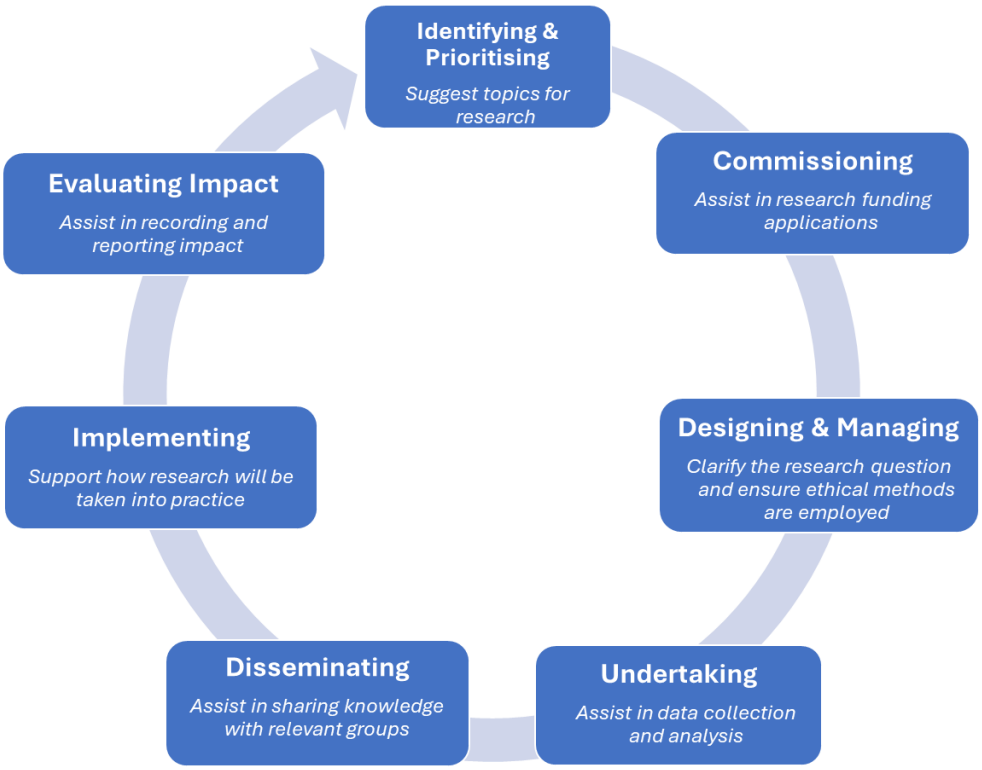

Figure 5 Research cycle with examples of PPI contribution

A case study by Filippo Bianchi [153] from the Collaboration for Leadership in Applied Health Research and Care Oxford illustrates how much of a difference public involvement can make in the early stages of research. In the form of an educational booklet, this project aimed to develop a behavioural intervention to help people eat less meat. Involving members of the public in the

early stages of intervention planning resulted in several modifications; including the booklet's graphics to make it more engaging, the expansion of the range of meat substitutes listed to ensure participants do not grow bored of the products and the emphasis on positive consequences of eating less meat for educational purposes.

In another example, Andrews *et al.* [154] highlight how public involvement improved the research design and funding application for a project evaluating the effectiveness of a cycling intervention for hip OA. Public contributors involved in this project helped to identify and prioritise key research areas by providing feedback on the relevance of the research, the study design, the programme itself and the project's dissemination plans. These insights fed into the funding application and led to key changes in the study's methodology. For example, contributors revealed that the cycling programme duration should be increased from six to eight weeks where the two extra weeks could be spent on the practical aspects of the programme (i.e. consolidating the cycling technique). Contributors also suggested that all participants should keep an exercise diary as this could help them stick to the schedule and motivate them to exercise. Andrew *et al.* conclude their paper by praising the public involvement outcomes and encouraging more researchers to collaborate with public contributors from the conception of a research question. [154]

Though recommended, public involvement is not always included in all stages of the research cycle. Contributors' involvement may be short-term (occurring in intervals) or long-term (spanning the entire duration of the project). For this reason, the commitment (i.e. duration, frequency and regularity) of PPI varies across research projects [143], [146]. A recent study by Dawson *et al.* [17] is a practical example of conducting long-term PPI in doctoral research. In their research project, public contributors were involved in the planning of the systematic review where they added extra terms to the search strategy and questioned the existing definition of various terms in the literature. As a result, Dawson *et al.* provide key recommendations for facilitating long-term public involvement and demonstrate extensive opportunities to involve people in research. Their reflections were based on personal accounts and a retrospective examination of email correspondence, documents with tracked changes and meeting notes. From this evaluation, they conclude that public involvement contributed to the recruitment of study participants, data analysis and dissemination. [17]

As well as helping with research design, public contributors can be involved in data collection, and dissemination, and assist in recording impact. They also attend management, planning and task meetings, review documentation and co-deliver content to other stakeholders. However, as stated by Evans *et al.* [155], descriptions of these activities that take place throughout the

research process are commonly under-documented and thus their effects on research conduct are poorly understood.

In a longitudinal case study with three projects involving public contributors, Barker *et al.* [156] aimed to identify how the public contributors establish their 'internal' legitimacy alongside the 'external' legitimacy they receive from the government body or research institution. According to Barker *et al.* establishing internal legitimacy means finding a "valuable" role. Using interviews, observations and documentary data collection, their study found that public contributors established their legitimacy by nine distinct roles (Table 4). It was noted that individuals who took part in the study occupied multiple roles but not all nine. As a result, Barker *et al.* emphasised that public contribution is not *"confined to lived experience"* with the typology showing how public contributors can also be involved "*strategic decision-making, research unconnected to particular conditions, or acute service delivery*" [156].

Table 4 Example of contributor roles as described by Barker *et al.* [156]

Expertise	**Description**
Lived Experience	Providing expertise gained from having first-hand experience
Occupational Knowledge	Providing job-related expertise
Occupational Skills	Offering aptitude developed through employment
Patient Advocate	Promoting the interests of patients
Keeper of the Public Purse	Encouraging wise spending
Intuitive Public	Piloting materials suitable for the public
Fresh-Eyed Reviewer	Critiquing materials
Critical Friend	Critiquing progress and proposing new initiatives
Boundary Spanner	Urging professionals to work across the organisation

2.4.7 Guidance and Frameworks

2.4.7.1 UK Standards for Public Involvement

The UK Standards for Public Involvement [15] developed by INVOLVE (Table 5), aims to help researchers and organisations develop high-quality and consistent public involvement in

healthcare research. Published in 2019, these standards are a framework for what "good" public involvement in research looks like and can be adapted to different research environments. These standards are designed to be used by researchers with varying PPI expertise, from those who are new to public involvement in research to experts with established PPI groups.

Table 5 UK Standards for Public Involvement in Research [15].

Standard	Definition
Inclusive Opportunities	Offer public involvement opportunities that are accessible and that reach people and groups according to research needs.
Working Together	Work together in a way that values all contributions, and that builds and sustains mutually respectful and productive relationships.
Support and Learning	Offer and promote support and learning opportunities that build confidence and skills for public involvement in research.
Communication	Use plain language for well-timed and relevant communications, as part of involvement plans and activities.
Impact	Seek improvement by identifying and sharing the difference that public involvement makes in research.
Governance	Involve the public in research management, regulation, leadership and decision-making.

2.4.7.2 Briefing Notes for researchers - public involvement in NHS, health and social care research

The NIHR's *Briefing Notes for researchers - public involvement in NHS, health and social care research,* first published in 2012 [142], is also a guidance document for researchers new to public involvement in research (Table 6). It explains the various ways that members of the public can be involved in research while providing information on how to plan, assign resources and support their PPI efforts. Whilst designed for those starting to consider involving members of the public in their work, this guidance can also be helpful to those with experience in public involvement as a means of reviewing their practice and refreshing their skills.

Table 6 Summary of Briefing notes for researchers - public involvement in NHS, health and social care research [142]

Briefing Note	Contents
1. Introduction	• The purpose of the guidance
2. What is public involvement in research?	• Definitions of involvement, engagement and participation

3. Why involve members of the public in research?	• Democratic principles • Providing a different perspective • Improving the quality of the research • Making the research more relevant • Interests of research funders and research organisations • Ethics
4. Why members of the public get involved in research	• Reasons for public involvement from a public perspective
5. How to involve members of the public in research	• UK Standards for Public Involvement • Resource public involvement in research • Do I need ethical approval for public involvement? • Clarify your organisational responsibilities
6. Who should I involve and how do I find people to involve?	• Who should I involve? • Involve more than one person • How do I find people to involve?
7. Approaches to public involvement in research	• Consultation • Collaboration • Co-production • User controlled research • Organising and hosting meetings • Planning for meetings: face-to-face • Planning for meetings: online • Conducting the meetings (face-to-face and online) • After the meeting (face-to-face and online)
8. Ways that people can be involved in the different stages of the research cycle	• Identifying and prioritising research • Commissioning research • Designing and managing research • Undertaking the research • Disseminating research • Implementing research • Evaluating impact

9. What to do when things go wrong	• Considerations for solving potential issues that arise
10. Where to go for further information	• Resources from NIHR and associated advisory bodies on where to find more information

2.4.7.3 Guidance for Reporting Involvement of Patients and the Public (GRIPP)

The first version of the Guidance for Reporting the Involvement of Patients and the Public (GRIPP) was published in 2011 [157]. It was developed from a thematic analysis of the Patient and Public Involvement in Research: Impact, Conceptualisation, Outcomes and Measurements (PIRICOM) [158] and Patient And Public Involvement Review on the Impact on healthcare Services (PAPIRIS) [159] systematic reviews. The development of the GRIPP checklist [160] aimed to address:

- poor quality of methods reporting
- unclear content validity of studies
- poor reporting of context and process
- enormous variability in the way impact is reported
- little formal evaluation of the quality of involvement
- limited focus on negative impacts

GRIPP is considered to be the first international attempt to enhance the quality of PPI reporting. The second version, GRIPP2, was revised in 2017 and developed collaboratively with patients and the public [161]. GRIPP2 exists in two forms: a Long Form (LF) and a Short Form (SF). The long-form (GRIPP2-LF - including 34 items) is aimed at studies where PPI is the main focus, and the short-form (GRIPP2-SF – including 5 items) is designed for studies that include PPI [161].

Since its development, there has been widespread use of this reporting checklist in research incorporating PPI such as for guiding reporting strategy [162]–[164] and reviewing existing publications [165], [166]. Researchers new to PPI are often encouraged to review the GRIPP2 checklist during the conception of studies [167]. In addition, the GRIPP2 checklist has been requested as supporting documentation for the submission of an article to the Research Involvement and Engagement Journal [168].

While GRIPP2 is a useful method of planning and reporting PPI, and the first internationally recognised framework, users report facing difficulties. For instance, a descriptive study of research publications (1st January 2014 to 31st October 2017) of NIHR CLAHRC by Jones *et al.* [166]. This study involved lay co-researchers (i.e. public contributors) using both forms of the

GRIPP2 checklist during the review process. When asked about their experiences of using the GRIPP2 forms, they described the LF as *'too complicated'*, *'needlessly repetitive'* and *'a lot of duplication'* whereas the SF was discussed more favourably being deemed as *'quite useful and straightforward'* and *'particularly easy for a lay member'*. Overall, it was suggested by Jones *et al.* that both forms would benefit from *'clear instructions'* of use, especially for public reviewers. Based on the experience of the reviewing process from the co-researcher perspective, recommendations for new sections to be added to the GRIPP2-SF were made. These included sections to record whether (1) PPI contributors are acknowledged for their involvement, (2) PPI is reported in the abstract (which is included in the LF) and (3) there are PPI co-authors [166]. The evaluation of the appropriateness of repetition within the GRIPP2-LF may also be useful for dissemination purposes. For instance, journal articles often have word-limits and therefore, adhering every single item on the GRIPP-LF may impact the fluidity and conciseness of a publication's overall narrative.

2.4.7.4 Additional Frameworks

In a review of practical resources for young investigators, Arumugam *et al.* [167] advocate for a PPI approach to research, collating several different recommendations and checklists for embedding PPI in various stages of research projects. As well as mentioning the GRIPP2 checklist, they discuss PPI in rheumatic and musculoskeletal research, citing the European Alliance of Associations for Rheumatology's (EULAR) recommendations for the inclusion of patient representatives. Within this framework, contributors are referred to as 'patient research partners'. They are partners *"with a relevant disease who operate as active research team members on an equal basis with professional researchers, adding the benefit of their experiential knowledge to any phase of the project"*. This exemplary work by EULAR is highlighted in their efforts to develop patient-reported outcome measures (PROs) with patients [169]. The Outcome Measures in Rheumatology conferences are also mentioned by Arumugam *et al.* [167] to have proposed guidelines for public contributors to actively participate in conferences so that their perspectives are effectively included.

Other guidance resources exist, such as the Facilitate, Identity, Respect, Support and Training (FIRST) tool proposed by Hewlett *et al.* [170] which aims to help contributors consider their involvement as a partner in research. This model was created based on the experiences of researchers and partners collaborating in rheumatology research and intends to be used as a practical guide. Arumugam *et al.* conclude their review with seven practical ways to get started with PPI. These include [167]:

- Making your research patient and public-friendly.
- Reviewing and implementing recommendations for PPI in rheumatic and musculoskeletal research.
- Referring to tools which have been developed to facilitate participation, communication and co-creation.
- Including qualitative approaches to explore patients' experiences of PPI and involve patients in research.
- Ensuring and facilitating continuous learning and quality improvement of PPI research experience.
- Acknowledging patient research partners and/or include them as coauthors on publications.
- Paying patient partners for research contribution.

2.4.8 Challenges of Involvement

Despite the recent push and established benefits of public involvement, there also exists numerous challenges [146]. In their report on enabling meaningful PPI contributions, Ball *et al*. [171] summarise these challenges into four main categories (Table 7).

Table 7 Challenges to involving patients and the public in research as summarized by Ball et al. [171]

Type of Challenge	**Examples**
Systemic challenges in the research system, related to the governance of PPI in research and to knowledge management	• Inappropriate financial resourcing of PPI activities • Poor reporting on PPI processes and limited monitoring and evaluation, • Insufficient coordination and shared learning between different PPI bodies • Limited patient and public awareness about engagement needs and opportunities
Challenges related to the capacity of individuals to engage	• Limited experience, knowledge, skills or confidence • Lack of access to training • Health and wellbeing related challenges such as inability to travel to research meetings
Administrative and management challenges.	• Limited administrative support for implementing PPI processes such as organising meetings and timely payment of contributors

	• Lack of in-built mechanisms for giving feedback to PPI contributors
Challenges related to culture, values and attitudes	• Tokenism • Dismissive attitudes of some researchers • Challenges to managing expectations of PPI contributors about the nature and scale of engagement • Managing power dynamics in teams

Alongside these list of challenges, Ball *et al.* provide a list of recommendations for facilitating effective PPI. These include [171]:

- Thinking carefully about who to involve and why
- Ensuring roles of PPI contributors are clear and well communicated
- Ensuring that PPI contributors are well informed and supported to effectively engage
- Thinking about ethical considerations
- Build in monitoring and evaluation mechanisms
- Reporting on the methods used to engage patients and the public and on involvement outcomes
- Designing efforts to recruit and retain patient and public contributors in a way that reflects the diverse factors which motivate them
- Considering the mix of approaches that will allow for effective awareness raising and recruitment
- Enabling engagement through a mix of levers

2.4.8.1 Systemic challenges

In their call for more citizen involvement in healthcare decision-making in the 1990s, Marian Barnes [128] stated that substantial time and resources would be required to develop more effective models that enable users to engage in dialogue and deliberation about service and policy issues. This is an observation that stands the test of time. For instance, whilst Andrews *et al.* [154] made public-recommended changes to their cycling intervention for a hip OA study, they could not implement all suggestions, particularly those restricted by time and resource constraints outside of the research team's control. In response to this limitation, they recommend that intensive planning is required to maximise the benefits of including public involvement in the research design process.

The established convention states that public involvement does not require ethical approval because working 'with' the public assumes an equal partnership [172]. In contrast, public participation concerns the public 'taking part in' research studies, a practice that does require

ethics. The confusion between the two methods means that public involvement can sometimes be unintentionally unethical. This is addressed in the commentary by Pandya-Wood *et al.* [172] which proposes an ethically-conscious framework for public involvement at the design stage of NHS health and social care research. This commentary highlights that whilst public involvement can be a prerequisite for ethics review boards to approve studies in health and social care, the ethical review does not consider how researchers work with the public in the design of their studies. Therefore, they have put forward a list of standards that address the potential ethical issues. This includes [172]:

1. Allocating sufficient time for public involvement
2. Avoiding tokenism
3. Registering research design stage public involvement work with NHS Research & Development Trust Office at the earliest opportunity
4. Communicating clearly from the outset
5. Entitling public contributors to stop their involvement for any unstated reasons
6. Operating fairness of opportunity
7. Differentiating qualitative research methods and public involvement activities
8. Working sensitively
9. Being conscious of confidentiality
10. Valuing, acknowledging and rewarding public involvement

These standards are a useful guide for conducting meaningful public involvement. This is a draft framework, meaning it has not been endorsed by national UK bodies however, Pandya-Wood *et al*. have stated that they aim to refine this list with the input of members of the public before seeking this endorsement.

Nollett *et al.* [173] has also aimed to provide some clarity on this issue of PPI and ethics. Fuelled by conflicting guidelines, Nollett *et al.* explore case studies from their own institution to come to their own conclusions. In their publication, they suggest that the ongoing uncertainty about whether or not one should apply for ethics comes down to the understanding of the difference between conducting research on people (i.e. participation) and facilitating two-way learning (i.e. involvement and engagement) [173]. As a result, they developed a guidance for academic staff on whether ethical approval is and is not required.

2.4.8.2 Administrative and management

A well-established PPI infrastructure facilitates the organisation of meetings, reimbursement of public contributors and the delivery of feedback [171]. In their paper on using qualitative health

research methods to improve patient and public involvement and engagement in research, Rolfe *et al.* [174] comment that whilst several publications exist to guide researchers who are new to PPI, few address how to evaluate the effectiveness of their involvement. This lack of evaluation is mirrored by the lack of feedback given to patients/public members involved. Similarly, Mathie *et al.* [175] highlight that many PPI contributors have reported a lack of feedback from researchers regarding the usefulness or impact of their input. This feedback is crucial as it reinforces the concept of an equal partnership and eliminates the transactional nature of research. Feedback from researchers and contributors also creates motivation for further involvement and aids learning and development. To improve the feedback experience, Mathie *et al.* [175] co-produced feedback processes to improve current feedback practices in six PPI groups in England. This study showed that effective PPI feedback processes can be done if they are embedded throughout the research process and are facilitated by sufficient support and resources. Overall, public involvement is easier to manage when there is a shared understanding of the researchers' and contributors' motivations, experience, and expectations.

2.4.8.3 Culture, values and attitudes

Tokenism and the lack of inclusivity remain widely recognised challenges within public involvement. Ocloo and Matthews [176] discuss the uncertainty surrounding the purpose of PPI, how to involve and support a diversity of patients and the public and how to evaluate its impact. This links to the key findings of the public involvement learning report by Marjanovic *et al.* [143], which states that despite an increase in public involvement in healthcare research, there is also a limited agreement about how, when, and why it should be done. Similar to Buck *et al.* [177] who identified the main challenges associated with how researchers integrated public involvement within clinical trials, Ocloo and Matthews [176] suggest that researchers need to be trained and supported when undertaking public involvement studies to avoid devaluing it. They state that by developing models of healthcare that are more co-designed and co-produced between all stakeholders, it is possible to move beyond tokenism, share power, and create more equitably in the decision-making process. Jackson *et al.* [178] also attribute the conceptual and practical barriers of PPI in research to a lack of understanding from researchers regarding what PPI involves, how to support a diverse range of lay members and the difference between PPI and qualitative research methods. These studies highlight the importance of sufficient training and awareness of the commitment required.

Rolfe *et al.* [174] highlight the potential risks when PPI is done poorly, despite good intentions. Some of these risks included: (1) tokenistic involvement (i.e. patients' suggestions may have little influence on how research is conducted), (2) engaged patients do not represent the

diversity of people affected by the research and (3) research outcomes may not be relevant to the patients' lived experiences. They discuss that whilst training and tools for patient engagement are being developed, 'how to get started guides' omit rigorous methods and evidence-based approaches. This supports Gamble *et al's*. [179] position whereby they regard PPI as a field where policy has tended to outpace evidence. As an evolving space, they recommend that prospective research evaluate how changes to policy influence the interpretation and implementation of PPI. The researchers interviewed in Gamble *et al*'s study who had undergone training also raised doubts regarding the validity of PPI's objectives and supporting evidence. This suggests that while training is useful, its effectiveness in producing high-quality PPI is still at risk in the presence of dismissive attitudes.

With an increasing number of funding bodies and ethics boards requiring researchers to adopt public involvement standards [167], [180], there is a potential risk that public involvement becomes a tickbox exercise to acquire funding rather than a vehicle for change. PPI is present in most of the trials that are financed by the HTA programme, but there is still some doubt about how it is evaluated and appreciated. Russell *et al*. [181] agree that public involvement has become an expected norm and a well-established way of democratising science however they criticise the way the research community conceptualise its benefits through their hyper-fixation on impact. They further this criticism by stating that rather than being empowering or emancipatory, there exists the danger of public involvement in health research being designed and directed towards researchers' productive aims rather than integrating the contributor's suggestions. For instance, the inherent managerial and academic expectations such as meeting structures, journal paper generation and the acquisition of funding can lead to the risk of tokenism and superficial PPI endorsement [182].

2.4.9 Evaluation and recording impact

2.4.9.1 Recognizing learning as an outcome

In their commentary, Staley and Barron [183] criticise the research community's perception of public involvement's impact. They discuss the potentially harmful effects of conceptualising public involvement as an 'intervention' to be evaluated the same way treatment is and discuss why this thinking may be unhelpful and contribute to poor practice and misunderstanding. In other words, you cannot evaluate a project conducted with PPI against a "control" (i.e. the same project conducted without PPI influence). Instead, they suggest that involvement is understood as "conversations that support two-way learning". By exploring this idea of mutual learning, they define involvement as evolutionary, subjective and unpredictable. This, however, makes

measuring its impact difficult. To counteract this, they propose an emphasis be applied to the quality of interaction between researcher and contributors because, due to the absence of the researcher's reflections and learnings, objective reporting of the outcomes only provides a partial picture. Dawson *et al.* [17] also highlighted this in their reflections on long-term involvement in a doctoral project, stating that including the reflections from the researchers as well as the contributors allowed for a better understanding of the mutual benefit of sharing knowledge and working together for a common goal. In their research reflection section, Dawson *et al.* put forward the disillusionment that public involvement is a time-consuming and resource-intensive activity. Instead, they state that its success is highly dependent on the relationships cultivated with the contributors.

2.4.9.2 Exploring PPI Experience Using Qualitative Methods

Qualitative methods have been cited to complement PPIE activities as a means of exploring researchers' and patients' experiences with PPI [167]. Conversations with public contributors throughout the research process are often captured informally using meeting notes as proof of the discussion rather than for analysis. According to Arumugam *et al.* [167] qualitative research methods like in-depth interviews, focus group discussions, and contributor observations can be utilized to investigate contributor experiences with PPI. For instance, Gamble *et al.* [179] explore the risk of tokenism by conducting interviews with researchers and public contributors to observe whether the documented plans for PPI in randomised controlled trial grant applications were being implemented. Factors listed from interviews as examples of impact included early involvement, building a relationship between researchers and contributors, responsive or managerial roles, and having defined PPI goals. In their publication, they highlight the concept of a 'self-fulfilling prophecy' which is achieved when researchers take a tokenistic or minimalistic approach aimed at meeting funder requirements rather than meeting goals and objectives set by researchers for PPI. To avoid this prophecy, Gamble *et al.* recommend that funders remove PPI tick box sections from their forms and replace them with a PPI-specific protocol that details the goals, methods, and costs of PPI [179].

A narrative qualitative approach acknowledges human experiences and allows individuals to share their perspectives of an event without externally imposed constraints [184]. The purpose of such an approach is not necessarily to acquire truth or fact but instead, meaning. This approach also complements the motivations behind PPIE, which aims to record/present the meanings of individuals' experiences rather than be objective, decontextualised truths [185]. The effectiveness of capturing someone's PPI experience with qualitative methods in research is further evidenced by Hoven *et al.* [186] who used qualitative methods to investigate the

experiences of patient research partners and the research team in a co-creative long-term collaboration in cancer research. From the semi-structured telephone interview conducted with people involved, five overarching categories were identified through content analysis. These included *(1) reasons for investing in a long-term collaboration, (2) benefits of participating, (3) improving the research (4) elements of success and challenges and (5) ways to improve*. The authors demonstrated the complimentary nature of qualitative and reflective methods for evaluating PPIE, once again emphasizing the importance of understanding the differences between participation, engagement, and involvement to ensure they can be effectively and ethically integrated.

2.5 The Scope for Public Involvement in Biomechanical Engineering

2.5.1 Engineering Research Methods

As discussed by Borrego *et al*. [23], much of engineering research investigates outcomes by simplifying complex systems into manageable and measurable variables. To this end, engineering research heavily relies on quantitative methods. Quantitative methods facilitate deductive approaches due to their effectiveness in analysing numerical data, testing hypotheses and establishing objective conclusions. On the other hand, qualitative research is conducted with an emphasis on contextual analysis of textual data such as surveys, interviews, focus groups etc [23], [24]. Within engineering research and design, qualitative methods can be employed alongside quantitative methods (i.e. mixed methods approach) to explore experiences, opinions and contexts such as user feedback analysis and observational studies [24].

Public involvement in empirical research is often discussed in a qualitative research context. The limited evidence of the impact of PPI on quantitative data analysis was identified and discussed by Staley [187] in a report exploring the impact of PPI in the NHS. In this report, it was suggested that this gap in evidence may reflect a lack of involvement rather than a lack of evidence itself. Further regarding the proportion of studies including PPI, in their systematic review of published PPI literature in health research published between 1995 and 2009, Boote *et al*. [139] found that out of the 230 empirical papers where such classification could be made, more examples were found of PPI in qualitative (n=139) than quantitative (n=61) research. As their findings resonated with Staley [187], Boote et al. stated that it could be speculated that *"(i) researchers find it easier to involve the public in the design and conduct of qualitative compared with quantitative research; and (ii) the public is more comfortable with collecting and*

interpreting interview and focus group data compared with more statistical data arising from quantitative research designs such as clinical trials." [139]. While this suggests that the PPI infrastructure may be more robust for qualitative-based research environments, statisticians, Pfannkuch and Wild [188], state that context knowledge is needed to do even the most purely technical role effectively. This is further emphasised by Cobb and Moore who state in their 1997 article on mathematics, statistics and teaching that *"data are not just numbers, they are numbers with a context."* [189].

Despite its limited evidence and infrastructure, there remains scope for PPI in quantitative research studies. Similar to Borrego et al. [22], this thesis does not assume that one research method is privileged over any other. Instead, it is strongly agreed that the choice of method should be driven by the research question, to which in a biomechanical engineering research context, often resolves around a condition that the researcher does not have experience of. Therefore, working with the public can inform the research question and ensure subsequent research efforts reflect their contributions. However, the nature by which engineering research largely focuses on quantitative methods may serve as the following barriers for integrating public involvement approaches:

- an educational barrier; as researchers may not be aware of what public involvement requires, how it can benefit their work, how to support a diverse range of public members and the difference between public involvement and formal qualitative research; and
- a practical barrier; as quantitative methods tend to favour objectivity and replicability whereas public involvement in decision-making and research exhibits an evolutionary behaviour which cannot be predicted.

2.5.2 Preceived Engineering Culture and Social Responsibility

According to the Engineering Council, engineering activity "*can have a significant societal impact and engineers must operate in a responsible and ethical manner, recognise the importance of diversity, and help ensure that the benefits of innovation and progress are shared equitably and do not compromise the natural environment or deplete natural resources to the detriment of future generations."* [5]. However, engineering, as a culture rather than a practice, is frequently perceived as a field that is technology-focused, socially isolated, and with aims that are not always associated with community objectives [6]–[8].

Biomechanical engineering is, at its best, an interdisciplinary field that benefits from collaboration with non-engineers such as but not limited to, clinicians, surgeons, and policymakers. However, it remains largely technology-led, and some researchers undertake biomechanical engineering without input from other stakeholders. A wide range of health and clinical research studies have embedded PPI in their work, including but are not limited to cancer [190], [191], mental health [152] and HIV [192], [193] research. While PPI has been actively encouraged by engineering-specific research bodies in recent years [5], [194], [195], there remains limited evidence of its integration in *biomechanical* engineering research, despite its interrelatedness with healthcare.

Cech [8] attributes a "culture of disengagement" in engineering education to be most evident in the process of defining the problem, where they directly state, "*engineers decide what considerations are integral to their design responsibilities for a particular technological puzzle and what concerns they can bracket*". According to Cech, this disengagement can lead to an exclusion of non-technical stakeholders and public welfare considerations. Using longitudinal survey data of students at four universities in the United States, Cech explores (a) how students' public welfare beliefs change during their engineering education, (b) whether engineering programs emphasize engagement, and (c) whether these program emphases are related to students' public welfare beliefs. They found that the students engagement with public welfare concerns decreased over the course of their engineering education. In response, Cech recommends that if programs are able to dismantle the *"ideological pillars of disengagement"* they must foster more engaged engineers [8]. In another article, Cech [7] explores two ideologies that they suggest are social justice issues within the culture of engineering. The first is depoliticization, which is the belief that engineering is a purely "technical" field in which engineers design technological objects and systems stripped of political and cultural concerns. The second ideology is meritocracy which legitimates social injustices, undermining the drive to rectify such inequalities. Cech proposes that since these are built into the culture and are deeply embedded in the professional socialization of engineering students, more should be done than solely introducing these concepts into education; engineers must also directly confront these ideologies for change to happen [7]. Nevertheless, there has been a push in engineering education to encourage better community engagement and train engineers who possess and value a diverse range of technical and non-technical skills [9]–[11]. For instance, the term 'holistic engineer' has been widely adopted to represent engineers who possess knowledge and skills beyond technical expertise. These professionals have non-technical skills that come from an awareness of their ethical and professional responsibility and the societal impact of engineering. This is emphasised by Canney and Bielefeldt who state that "*recognizing*

the many non-technical dimensions of engineering projects is central to our view of social responsibility because it focuses on identifying the needs of others and working with all affected parties to find appropriate solutions." [11].

2.5.3 The Scope for Public Involvement in Engineering Research

Despite the reported lack of involvement of members of the public in quantitative research projects, recent years have seen engineering organisations become more aware of the benefits of PPI and thus have begun encouraging it in their research strategies. For instance, in 2019, the UK's Engineering and Physical Sciences Research Council (EPSRC) recognised the importance of inspiring, informing and interacting with the public [194]. Following this, PPIE was officially reported in the EPSRC's 2022 'Healthcare Technologies Strategy' as one of six enablers [195]. In addition, the need to foster more "*socially and environmentally responsible approaches to engineering"* was emphasised in the EPRSC's 2022 'Tomorrow's Engineering Research Challenges – Visions from the UK Research Community' report. The report defends the fact that engineers inherently consider numerous perspectives of the 'user' however it is also stated that an improved understanding of human behaviours and needs is required to become more conscious of the social and environmental factors associated with research efforts and outputs [196]. Besides research, the fourth edition of the Accreditation of Higher Education Programmes (AHEP) by the Engineering Council includes the additional focus on inclusive design and innovation, which highlights steps taken to strengthen their stance on the importance of societal needs in general and within the engineering profession [5]. There is no direct reference to public involvement however it could be a means to facilitate this goal. Therefore, while systematic and cultural limitations exist for embedding public involvement in engineering research spaces, the potential is significant.

Throughout this thesis, "engineering" being referred to as largely technology-led is used in a "research" context rather than a "design" context. Design engineers are relatively conscious of the needs of users and other stakeholders, and this is evidenced through the existence of the Design Council who advocate for frameworks such as the Double Diamond or IDEO, which have been practising human-centred design since their beginning in 1978 [21], [22]. Similarly, areas of research where the engineering is more linked to a kind of 'designed' product/device whose use is the person's choice are more likely to use public-centred approaches. For instance, when designing technology for mobile applications, it is a core part of the design process to seek the opinions of users to improve design [189]. In a more related context, prosthetics and orthotics is a branch of biomedical engineering research that often adopts public-centred principles.

Therefore, this thesis puts forward an argument for embedding long-term PPI in the biomechanical engineering research process, particularly in branches where it is less established, such as in a computational biomechanics.

2.6 Chapter Summary

The evidence-base of PPI in empirical research has been reported to mostly contains qualitative research studies. Without an existing PPI infrastructure, researchers in quantitative-based fields may be unfamiliar with what PPI entails and how to support public contributors. Therefore, as well as providing a background to the biomechanical elements of the project, this chapter also proposed the scope for the integration of PPI in engineering research where it has been encouraged but is currently limited. The quantitative and largely independent nature of computational modelling, especially when compared to clinical studies during which, engaging with the public is a fundamental part of the process, makes this doctoral research project an appropriate and novel case study for exploring the process of integrating long-term public involvement in a biomechanical engineering context.

Hand OA can have a significant impact on hand function, causing chronic pain and limiting an individual's ability to perform everyday tasks. Computational biomechanical analysis is a tool used to simulate and study complex biological tissue and systems. To contextualise the available datasets for process during this project, this chapter presented the types and useability of such tools and how they can aid in advancing our understanding of tissue structure, function and pathology. At the conception of the research project, it was not decided by those who collected the datasets how they would be used (i.e. type of model, user and accessibility). Suggestions such as evaluating treatment options and rehabilitation strategies were proposed by academic members of the interdisciplinary research team. However, a public perspective was absent. Therefore, as a result of preliminary PPI, it was crucial to include the expertise of those with OA lived-experience during the early project stages to better understand the research's purpose, relevance and useability. Chapter 3 describes how PPI was initially integrated and the influence it had on the project's governance and structure. Subsequent chapters (Chapter 4 - Chapter 6) present how the PPI outcomes were addressed throughout the project and Chapter 7 provides a critical reflection on the PPI approach adopted throughout the research process.

Chapter 3 Embedding Patient and Public Involvement in the Biomechanical Engineering Research Process

3.1 Overview

Engineering is often described as a technology-driven field. However, whilst frameworks exist to engage with stakeholders, patient and public involvement (PPI) is not often undertaken in projects that have a quantitative methodology. This can have an impact on research quality, relevance, accessibility and experience. This is especially significant in a biomechanical engineering context where the end-user is often a person with experience of a condition that the researcher does not have. This chapter describes the first steps taken to embed PPI into a biomechanical engineering doctoral research project, and the outcomes and learnings that came from this approach. Three members of the public living with hand osteoarthritis (OA) were involved in the early-stage PPI consultations. These sessions aimed to openly discuss the hand OA lived experience, current treatments and considerations for the project. Subsequently, a long-term partnership with public contributors was established and the project's focus shifted from purely developing a computational model to addressing three PPI-identified priorities

(patient variability, joint instability, and raising hand OA awareness) using the appropriate methods and resources available. Though the number of contributors was small, it allowed for meaningful and long-lasting partnerships to be developed.

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3.2 Introduction

Biomechanical engineering, at its best, is an interdisciplinary field that benefits from collaboration with non-engineers such as but not limited to, clinicians, surgeons, and policymakers. However, it remains largely technology-driven. PPI in research ensures that studies focus on outcomes important to the public. Literature shows that PPI in health research can enhance design, quality, relevance, accessibility, and experience [159], [197]–[199]. There exists a wide range of health research studies that have embedded PPI in their work, including but are not limited to cancer [190], [191], mental health [152] and HIV [192], [193] research. Although PPI has been actively encouraged by engineering research bodies in recent years [5], [194], [195], PPI is rarely implemented or reported in biomechanical engineering projects, particularly those using quantitative methodologies, which may discourage researchers with limited PPI experience from integrating it into their work.

The UK's National Health Service (NHS) reported limited evidence of PPI impact on quantitative data analysis and attributed this to a lack of involvement rather than evidence, highlighting the scope for more PPI in quantitative-based projects [187]. In addition, in their systematic review of published PPI literature in health research published between 1995 and 2009, Boote *et al*. [139] suggested that researchers may find it easier to involve the public in qualitative rather than quantitative research. However, statisticians, Pfannkuch and Wild, state that context knowledge is needed to do even the most purely technical role effectively [188]. PPI represents a means of addressing the democratic principles of research and recognises that patients/public *"have a personal experience of disease that is not available to most researchers, but that complements researchers' analytical skills and scientific perspective."*

[170]. This is particularly significant in a biomedical field where the public are often the direct end-users of research outcomes.

This doctoral research project was conceptualised to leverage an existing dataset of finger kinematics, including computed tomography (CT) and magnetic resonance (MR) imaging of ten consenting participants, free from hand or wrist disease or injury [4]. Preliminary PPI activities highlighted the limited incorporation of the public perspective throughout the biomechanical engineering research process, despite PPI becoming increasingly present in health and care research. To this end, this doctoral research project set off to help identify and prioritize the decisions made during the development of the computational hand models. The quantitative and largely independent nature of computational modelling (especially when compared to clinical studies during which, engaging with the public is a fundamental part of the process) made this particular project an appropriate case study for exploring the integration of PPI in a field where it is less established. With this aim in mind, this chapter describes:

(1) how PPI was first implemented in this biomechanical engineering doctoral research project;
(2) the outcomes of the early-stage PPI work and how they informed the project structure and methods; and
(3) reflections on the process and impact of PPI on the project.

3.3 Methods

This chapter was written following the short-form Guidance for Reporting Involvement of Patients and the Public (GRIPP2-SF) checklist [161]. A full checklist can be found in Appendix A.

3.3.1 Terminology Used

This first-hand account of PPIE in an engineering context calls for the use of a combination of ‘I’ and ‘we’ first-person voices to denote the partnership between the researcher and public contributors or personal/critical reflection. ‘Public contributor’ is used to describe the members of the public involved. Throughout this chapter, PPI is used represent involvement (e.g. working with the public to inform research design) whereas PPIE may be used to encompass the combined involvement and engagement efforts exhibited throughout the research process.

3.3.2 PPI Consultation Design

3.3.2.1 People involved

Three members of the public were involved within the first six months of the project. All three were female, over fifty years old, currently living with either clinically confirmed or suspected OA in their hands. The severity of symptoms varies between the contributors, ranging from mildly to severely impacting their quality of life. They all volunteered to be part of this project and had no previous experience of PPI to this degree. They were recruited through the Saints Foundation - a charitable organisation run by a local football club [200]. Saints Foundation are a 'social prescriber' for the NHS. They provide weekly exercise sessions that promote regular exercise and independence within the local community.

3.3.2.2 Stages and Nature of Involvement

The initial consultations during the project design stage were conducted in accordance with the GRIPP2 checklist [161], UK Standards for Involvement [15], and NIHR's briefing PPI notes for researchers [142]. Reimbursement was offered to all public contributors involved. Ethical approval was not required as persons were acting in an advisory role (Briefing Note 5). However, ethical approval (ERGO2720) was sought for dissemination purposes, allowing consent to capture the discussions and contributors' lived-experiences in the form of interactive and collaborative notes, and share them at conferences, in publications or on social media.

A 'terms of reference' (see Appendix A.2) document was created and distributed to everyone who would be present during the session. This document included information on the purpose, location and format of the meetings, how the meetings would be conducted and data protection considerations. It must be noted that this document was written based on the initial project aims and objectives (i.e. prior to PPI sessions). We recognised that there wasn't much guidance or case-study based evidence of how to integrate PPI in computational biomechanics and thus, we sought out shadowing opportunities from colleagues working in research fields (i.e. health science and medicine) where PPI is well-established to help gain knowledge in how to run meetings, capture impact and reimburse contributors.

Four one-hour sessions were held online via video conferencing software (Zoom, Zoom Communications, Inc., California, United States of America), due to transmission control rules during the COVID-19 pandemic. Each session was organised around discussion prompts (Table 8). These discussions were made as general as possible to ensure that the conversation remained open to all perspectives and to minimise the risk of researcher bias. This was also

done to reassure public contributors that there was no 'right answer' and allow both the researchers and public contributors to learn from each other in a spontaneous manner. As well as open conversations, discipline-specific language was avoided to ensure that the conversation was accessible to everyone, and feedback would be readily given.

Table 8 Discussion Prompts for each consultation session

Session no.	**Discussion Prompt**
1	• What are your opinions on currently available OA treatments? • What do you think of this research project?
2	• What movements/actions are most difficult to do living with hand OA? • What considerations should researchers have in mind when developing tools to investigate OA?
3	• What activities of daily living are mostly impacted by hand OA? • What techniques do you use to manage your symptoms?
4	• What is the public perception of hand OA? • What recommendations would you give to people developing treatment?

3.3.3 Capture or measurement of early-stage PPI impact

Points discussed verbally during the sessions were recorded in the form of hand-written and interactive electronic notes (Jamboard, Google Inc., California, United States of America). These notes acted as a written record of the session and were sent via email to attendees. This allowed everyone to access, edit, and delete any information they felt did not represent what was discussed. After the last session, the notes were collected, summarised and reviewed by all attendees. The process and impact of these PPI sessions on the doctoral project were evaluated using impact logs (see Appendix A.3), adapted from a People in Health West of England (PHWE) template [201].

Spaces for reflection were created to ensure the interpretation of the discussion was accurately documented. For instance, all attendees of the meeting (researchers and public contributors alike) were invited to write blog posts that would be published online to depict their experience

during this stage of the project [202]. These blog posts were prompted to answer one or all of the following questions:

- Why did you get involved in this project?
- Why do you think public involvement is important?
- How did you find the PPI sessions you attended?

3.4 Study Results and Discussion

The following sections present the outcomes from the early-stage PPI consultations and the impact they had on informing the project's structure including the aims, research methodology and the role of PPI.

3.4.1 Outcomes from Consultations

During the sessions, public contributors were keen to share their views and expertise relating to their lived experience of hand OA and researchers were enthused to hear their perspectives, especially those they had not come across in their literature searchers or education. From a researcher perspective, I felt that a productive and respectful environment was cultivated, whereby everyone seemed comfortable sharing their ideas and contributing to the discussion.

> "[The researchers] … who were running these sessions were quite surprised by some of the things that are affected by arthritis and what we have to do to overcome it. Simple things we take for granted like sewing, writing a letter, opening those childproof caps, or trying to. Even gripping a bread knife or picking something up, when we are in the throes of a flare-up can be nigh on impossible."
>
> – *Public contributor talking about the researchers* [202]

Interestingly, everyone was more engaged in the meetings when we switched from using closed-book notes to capture the outcomes from the meeting to interactive notes (Figure 6 and Figure 7). This form of communication allowed for the notes to be viewed on-screen by all participants and in real-time. It drove the conversation and allowed for a more collaborative and representative record of what was discussed during the meetings. At the end of every session, I would save the original Jamboard (Appendix D) and create a formatted version combining the real-time post it notes, and additional points recorded by members of the group. The final Jamboards were circulated, and attendees were invited to add, edit or delete details they believed did not represent the discussions had.

"PPI group was not only interesting but very informative, especially in the way that [the researcher] took notes and put them on the Jamboard. She was so very organised and her excellent technical skills with the computer meant that any points we made in our discussion were quickly put on the screen."

– Public contributor [202]

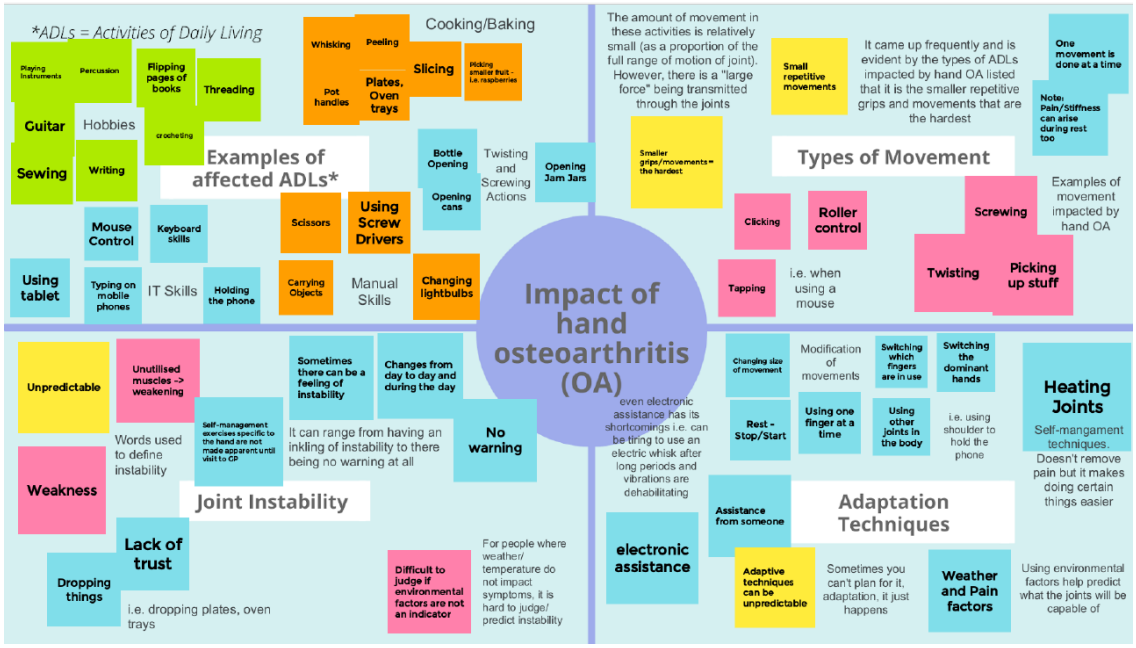

Figure 6 Interactive whiteboard created using Jamboard to depict our session 3 discussions

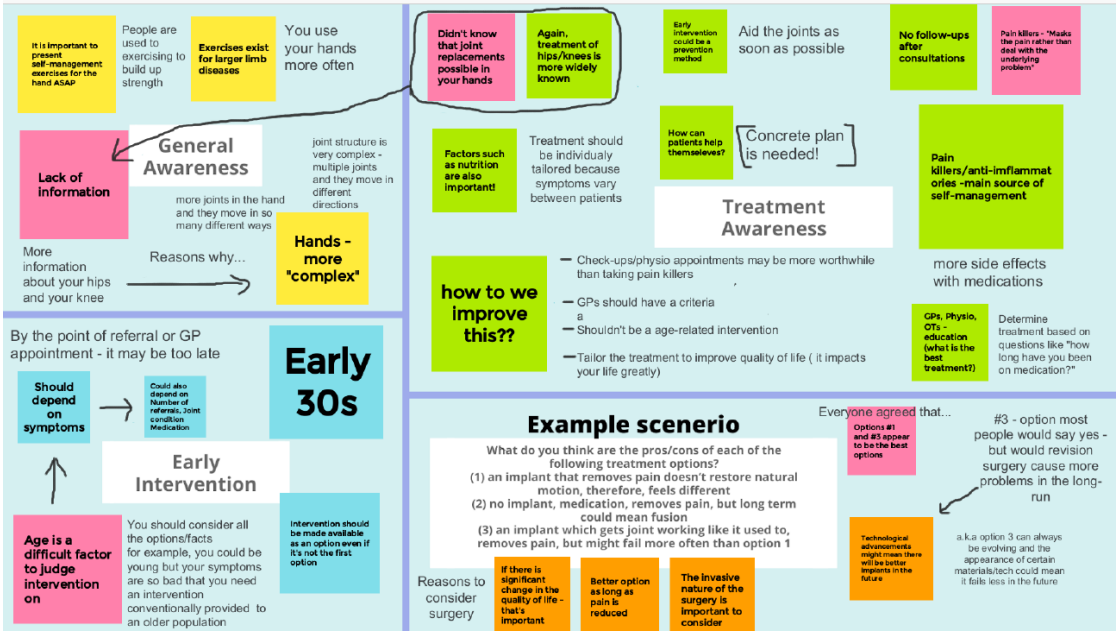

Figure 7 Interactive whiteboard created using Jamboard to depict our session 4 discussions

In subsequent meetings, we reviewed our discussions and categorised key factors into three main groups (Table 9):

1. **General Experience**: Factors that describe the daily experience of living with hand OA.
2. **Considerations for researchers**: Factors that public contributors feel could be more thoroughly considered in biomechanical research about hand OA
3. **Recommendations for interventions and research tools**: Opinions on research tools and inventions that researchers could also consider.

Table 9 Key hand OA lived-experience factors discussed during early-stage PPI consultations

Factor	Description
1.1 Daily Considerations	Nutritional, environmental and activity factors impact OA symptoms. Avoiding inflammatory foods while staying active and hydrated are important for managing the severity of symptoms.
1.2 Impact on Activities of Daily Living (ADLs)	Activities of daily living that require precise and repeated movements of the joints are the most challenging.
1.3 Adaptation Techniques	Self-management techniques are necessary to adapt to the unpredictability of OA. Pain medications tend to mask the symptoms.
2.1 Patient Variability	"Not one size fits all" – everyone living with OA has different experiences with symptoms and therefore the conditions of their joints may vary.
2.2 Joint Instability	Joint instability is considered as a major challenge in living with hand OA. It is unpredictable and causes a lack of trust in joints.
2.3 Raising Hand OA Awareness	There is greater exposure to hip and knee OA compared to hand OA. Therefore, there is a need to raise awareness of hand OA and its impact of daily living.
3.1 Treatment Preferences	Exercise is key. Pain killers only "mask the pain than deal with the underlying problem." Treatment should aim to restore trust in joints rather than exclusively remove pain
3.2 Computational Modelling	A model could be useful educative tool that could give patients "hope and confidence" as well as understanding of their joints is preferable.
3.3 Novel Implant Design	User-driven preferences for development of a novel implant for small joint OA

3.4.1.1 Daily Considerations

Public contributors said that their OA-affected joints often 'lock in place' in response to various nutritional, environmental and activity factors. They all agreed that pain and stiffness occurred frequently with inactivity and after rest. Therefore, keeping active and hydrated was discussed as helpful for managing the severity of symptoms. Public contributors also emphasized how the effects of these factors are not always consistent for an individual, or between individuals. This was even evident within the group where, even between three people, the severity of symptoms differed.

3.4.1.2 Impact on Activities of Daily Living (ADLs)

Public contributors listed activities of daily living (ADLs) that are affected by hand OA. These mainly related to hobbies (e.g. playing instruments and writing), using IT equipment (e.g. mouse control and typing), manual handling (i.e. using screwdrivers and scissors), and cooking (e.g. whisking and opening jars). Amongst these ADLs, it concluded that the activities listed that were most affected by hand OA were those that require precise, repeated or longer-duration movements of the finger joints. Maintaining small grips was also shared to be often challenging.

3.4.1.3 Adaptation Techniques

Due to the unpredictable daily impact of hand OA, public contributors revealed that they must self-manage, continuously adapting and adjusting to symptoms. They described several movement modifications they make to compensate for hand function loss. This includes changing the size of the movement, resting, using one finger at a time, or using other parts of the body (e.g. using the shoulder to hold the phone). Other methods listed for adapting included seeking assistance from other people or using assistive devices. However, it also mentioned that even using electrical devices to adapt can exacerbate symptoms; for example, the vibrations from an electric whisk after long periods can be debilitating.

3.4.1.4 Patient Variability

There was a consistent referral to the statement made by a contributor during our discussions: *"not one size fits all"*. It was important to public contributors for researchers to consider that everyone is different, meaning that symptoms, joint conditions and diseases vary from person to person. This factor was previously referred to as *'age representativeness'* which initially arose as a result discussing how OA is not a condition that only impacts the "older" population. However, with the additional emphasis placed on the variation of symptoms, effectiveness of

self-management treatments, joint conditions and hand sizes between people during our sessions, we found it more appropriate to encompass all these aspects under ‘patient variability’.

3.4.1.5 Joint Instability

Public contributors repeatedly mentioned joint instability as a major challenge in living with OA. When asked to define what joint instability means to them, the public contributors said that is *“unpredictable, changing from day to day and throughout the day”*. Public contributors associated joint instability with 'clumsiness' and dropping items unexpectedly (e.g. when taking things out of the oven). Overall, it was related to a significant loss of function. It was from these discussions that it was revealed that from their perspective, pain is not as great an issue as the loss of hand function. For this reason, they strongly suggested that treatment should aim to restore trust in their joints rather than exclusively remove pain.

3.4.1.6 Raising Hand OA Awareness

The group was unanimous in the belief that there was a greater gap in recognition of OA pain as experienced in the smaller hand joints, compared to the larger joints such as the hip and knee. Public contributors added that the hand is more “complex” and has more joints that move in many different ways in comparison to larger joints. Everyone in the group (i.e. both public contributors and researchers) were aware of hip and knee OA-specific self-management exercises however were not fully aware there were also exercises for the hands. This incomparable level of understanding of hand OA was further emphasised by the fact that before their involvement in this project, public contributors did not know there were joint replacements available for the hand like there are for the hip and knee. In addition, we hypothesized that most people’s go-to reference for OA is often either the hip or knee. Therefore, the group recognised a need to raise awareness of the hand OA lived-experience within both the public and research community.

3.4.1.7 Treatment Preferences

The public contributors were very vocal when discussing treatment preferences. These discussions included recommending areas of improvement and providing suggestions for bettering the way clinicians diagnose and treat people living with OA. Public contributors revealed that they have seen how people within their community try to evaluate how they can help themselves (i.e. self-managing symptoms by exercising, monitoring nutrition, or taking medication). It was stated that whilst painkillers and anti-inflammatory drugs are the main

sources of relief, they only *"mask the pain rather than deal with the underlying problem"*. This was a very powerful statement from a PPI contributor, alluding that hand OA treatment should aim to do more than solely relieve pain. Overall, public contributors stated that they would prefer to have an implant than undergo joint fusion or take painkillers long-term. This drew further attention to the public contributors' views on the importance of treatment restoring the confidence they have in their joints, rather than solely reducing pain.

3.4.1.8 Computational Modelling

When asked about who would most benefit from a computational model of the human hand, public contributors stated that it could be a useful educative tool that could give patients *"hope and confidence"*. They also suggested that consultants and occupational therapists could benefit from such a tool in their clinical practice to explain interventions and therapy. This led the researcher to interrogate the current accessibility of engineering research outcomes and thus, highlighted the importance of sharing research findings and tools. These discussions also motivated the researcher to think the ways to facilitate the two-way process that the project was advocating.

3.4.1.9 Novel Implant Design

Discussions concerning contributor recommendations for a new implant were mainly related to the public involvement objectives of the APRICOT project and therefore outside the scope of this thesis. These APRICOT-related conversations allowed the group to evaluate the potential of a novel implant design from a patient perspective which had been missing from the APRICOT project until then.

3.4.2 PPI Influence on Project Structure

3.4.2.1 Research Aims and Objectives

Without a pre-existing PPI infrastructure within the project's research faculty, it was initially challenging to navigate the administrative and managerial needs of PPI. However, it was important to not view the lack of field-specific training, guidance or infrastructure as a deterrent, but rather as an opportunity to understand how this project, which was largely quantitative based, could be driven by public contributor perspectives. If the PPI evidence-base favours qualitative research, instead of investigating 'why' PPI isn't as integrated in quantitative research, this project aimed to explore 'how' it could be, thus presenting itself as a case-study

and continuing to work with members of the public throughout the engineering research process.

From a researcher perspective, the early-stage PPI efforts widened my understanding of hand OA and its impact on everyday life, opening up the discussions to topics that I had yet to prioritise in my literature search and determination of the research question. Overall, PPI encouraged me to look beyond generating a computational model as an end-goal and instead, explore the ways that the project resources could be used to acknowledge the research priorities recommended by public contributors.

The idea of using the available datasets for developing a computational model was predetermined by the academic and clinical professionals who collected the original data. While this decision was made prior to any public involvement, this project aimed to ensure future decisions could be made with the public's input. Therefore, following the early-stage PPI meetings, we discussed which factors could be addressed by using the datasets and any additional project resources available. Ultimately, we decided on focusing on *patient variability, joint instability and raising hand OA awareness*, which the public contributors believed could be more thoroughly considered in hand OA research.

This led to the diversification of the research outputs into two methodological groups:

a) computational modelling and,
b) public engagement (PE)

3.4.2.2 The Research Cycle

As stated by Staley and Barron [183], PPI is commonly described as an evolutionary process and "*immediate outcomes of involvement in terms of what researchers learn are subjective (specific to the researcher) and unpredictable (because researchers don't know what they don't know at the start).*" This may not be considered as compatible with engineering research which is often orientated to be "objective", focusing on investigating hypotheses using proven laws and behaviours. In addition, this makes PPI outcomes difficult to hypothesize or quantify because human interaction is complex. In other words, a project with PPI cannot be directly compared to a 'control' study conducted without PPI. However, this emphasizes the importance of valuing mutual learning as an outcome. Staley and Barron [183] suggest that providing transparency of the process, through personal accounts of what was learnt, is an equally valid method of evaluating whether PPI has made a difference. With this in mind, while this chapter acts as a prelude to understanding the role of PPI in this project, Chapter 7 provides a comprehensive

overview and critical reflection of the entire approach. In their paper reflecting on including PPI in doctoral research, Dawson *et al.* [17], suggest the strength of the PPI influence on research is dependent on the relationships developed. Therefore, while this thesis has been written to best present the PPI approach taken, it must be noted that significant behind-the-scenes efforts which cannot be wholly captured in written form, also went into developing meaningful partnerships and managerial strategies to effectively facilitate the PPI approach.

The nature of PPI at each research stage and their associated impacts and outcomes is summarised in Table 10. This table acts as a precursor to the following technical chapters which explore in-depth the efforts made to conduct the project in the context of the three research priorities.

Table 10 Summary of PPI influence, impact and outcomes throughout research cycle

Research Stage	Approach	Contributor role/influence	Impacts and Outcomes
Identifying the research problem	Consultation: *PPI group meetings*	Highlighted the importance of acknowledging the public contributor insights in all stages of the project as well as at the beginning.	Improved understanding of hand OA lived-experience. Project aim and structure redefined. Further validation of the scope for more active PPI in engineering. Agreement to extend our partnership throughout the research process.
Project design	Consultation and Collaboration: *PPI group meetings, group email discussions, review of early-stage discussion notes*	Summarised key lived experience factors to facilitate project restructure. Reviewed and agreed to suggested PPI activities within the study.	Three core research priorities to drive the project workflow were identified. These included: patient variability, joint instability and raising hand OA awareness. Contributors accepted invitation to sit on the project's multidisciplinary steering committee.
Commissioning: Internal funding for public engagement activity	Consultation and Collaboration: *PPI group meetings, steering group meetings, group email discussions, review and approval of funding applications via email*	Became co-applicants on the funding call. Reviewed and agreed on suggested PPI activities within the study	Funding approved by Public Engagement with Research unit
Designing, managing and undertaking: Statistical Shape Modelling	Consultation: *PPI group meetings, group email discussions, steering group meetings, attending modelling and data collection demonstration*	Highlighted the importance of considering how products or interventions may perform on different hand and finger shapes and sizes (i.e. "one size does not fit all,"). Feedback and interpretation given during model generation	Supported researcher's critical thinking and approach to analysis: Guided data processing workflow (characterise the datasets before generating a dynamic model), purpose and usability (datasets publicly available with instructions of use - https://github.com/abel-research/OpenHands)
Designing, managing and undertaking: Kinematic Analysis	Consultation: *PPI group meetings, steering group meetings, attending modelling and data processing demonstrations*	Highlighted joint instability as a major challenge associated with OA, likening it to a significant loss of function compared to what they would consider their ordinary level.	Supported researcher's critical thinking and approach to analysis: The emphasis on function impacted the decision to combine the morphological data with associated kinematic data collected to further characterize the population in a joint instability context

Research Stage	Approach	Contributor role/influence	Impacts and Outcomes
		Feedback and interpretation given during workflow design	
Designing, managing and undertaking: Public Engagement	Collaboration and Co-production: *PPI group meetings, steering group meetings, public engagement project meetings*	Highlighted a need to raise awareness of the hand OA lived experience within both the public and research community. Attended meetings with student interns, guiding their work and enhancing their professional development. Co-created and reviewed content for website and infographic. Social media written content was reviewed to improve language for readability and accessibility. Suggested events to attend and target audiences to engage	A published website (https://handlethis.org/) and accompanying infographic sharing the contributor's lived experience with OA, delivery of PPI training material for engineering students, promotion of PPI within student, university-wide and community spaces and supporting student education and professional development.
Dissemination and implementation: Project outcomes	Collaboration and Co-production: *PPI group meetings, group email discussion, reviewing documentation, presenting and teaching*	Co-designed and co-delivered dissemination material for target audiences Co-authored conference and journal papers, co-delivered training and co-presented at internal/external events	Dissemination of project outcomes and promotion of PPI within student, university-wide and community spaces, inspiring public members to get involved in research and encouraging researchers to create more PPI opportunities for public members
Evaluating impact	Collaboration: *PPI group meetings, group email discussions*	Offered reflections on overall PPI approach within the study	Recommendations for future work were devised based on views and feedback given in end-of-project reflective interviews.

3.4.2.3 Computational Modelling Efforts

Discussing data representativeness and usability with our public contributors provided the opportunity to refine the methodologies adopted from the project's start. The PPI approach adopted informed how the data could be processed to explore the contributor's perspectives and recommendations (see Chapter 4 and Chapter 5). Overall, the contributor's influence guided the technical workflow, providing context to research efforts and supporting critical thinking. For instance, the prioritisation of a statistical shape model to characterise the geometric variability within the data population came from the PPI discussions around patient variability. The additional emphasis on joint instability made by the public contributors and it being likened to a "loss of function" inspired correlation analysis between the statistical shape generated and kinematic data available, further characterising the data population. This analysis revealed that if trained with additional CT images, the model may be of use for investigating further the apparent associations between joint conformity, which plays a role in stabilising the joint during movement, and movement smoothness, which may be descriptive of joint stability.

The decision of the researcher likely impacts the results produced by a model or simulation, and thus the conclusions which are drawn. This makes establishing a strategy and maintaining a workflow important to ensuring the model can be reproduced [117][118]. Processing the data to address and investigate *patient variability* and *joint instability* provided focus, resulting in a purposeful data processing workflow. In addition, the modelling outputs were recommended to be designed in a way to be made available for clinicians or engineers to use for further research (i.e. evaluating treatment options). Whilst the datasets do not represent an OA population, we highlight the potential of generating a transferable modelling methodology from an exemplar dataset, albeit free from hand or wrist disease or injury, that could be used to address population variability [203] and risk of disease progression [3] and develop future pipelines for data more representative of the OA community.

The resultant models created are first publicly available statistical shape models of the fingers' skeletal anatomy generated from living participants [204]. The finger models describe a small, homogeneous population, and assumptions cannot be made about how it represents individuals outside the training dataset. In addition, the model was made with people who didn't have OA. This is a limitation of the available data used to build the model. To this end, while the absence of datasets with OA characteristics may limit the immediate value of the open source deliverable and its ability to understand the effects of OA, it does provide a baseline which may

provide a foundation for future comparison to OA models. In addition, this model can be supplemented with additional shape information [86], [90], reaffirming its value and need for it to be shared open-source; another decision affirmed by public contributors and academics alike.

3.4.2.4 Public Engagement Efforts

Research questions are often formulated using published literature and although it frequently reports hand OA to be highly common [37], [38], [51], [205], [206], the language used can impact our awareness of its impact on an individual's quality of life. For example, when discussing the burden of OA, Litwic *et al*. [41] state *that "even though the symptoms are often less disabling than when the knee or hip joints are involved, it can still significantly interfere with hand function."* In our PPI discussions it was felt that this was an unfair statement since no one type of OA is more or less debilitating, they all manifest and impact quality of life in different ways. Dziedzic *et al.* [56] reported that whilst hand OA is common and has a significant impact and associated disability, many people living with the condition perceive that nothing can be done, further emphasising the importance of raising awareness. Using semi-structured interviews, another study by Dziedzic *et al.* [207] aimed to explore the experiences of adults aged 50 years and over living with hand OA and reported 'maintaining independence' as a key goal; meaning people wanted to be self-reliant despite the limitations hand OA pose on daily living. In addition, they stated that hobbies and interests tended to be forgotten about to avoid the frustration associated with the inability to do them at the same pace or precision. This links closely with the discussions had during the initial PPI meetings for this project.

Overall, during the PPI meetings, we learnt a great deal about hand OA from each of our perspectives and that helped recognise that PE needed to be introduced to address the final research priority; *raising hand OA awareness* within public and research communities. It has been judged unlikely that we would have arrived at this outcome without embedding PPI into the research process, especially with the initial emphasis placed on the computational modelling outcomes. In addition, several factors already act as barriers to integrating public involvement in doctoral research [208] including lack of dedicated funding, limited time and resources, limited experience and limited training. Hence, by recognising the influence of PPI on the decision to introduce PE and, adopting a collaborative PPI approach, we decided to develop material to (1) raise hand OA awareness, (2) disseminate project outcomes and (3) increase PPI resources and awareness amongst biomechanical engineering academics and students.

3.4.3 Managing Diversity, Inclusion and Bias

Hand OA prevalence increases with age and is more common in women than men. A 2005 study reported the presence of radiographic OA in at least one hand joint in 67% of the women and 54.8% of the men, among persons 55 years and older [209]. The public contributors involved in this project are part of this demographic of people living with hand OA, with the severity of symptoms varying between them and ranging from mildly to severely impacting their quality of life. They all volunteered to be part of this project and had no previous experience of PPI to the extent presented in this thesis.

Opportunities to get involved were advertised to the public throughout the project at community events, science festivals and via our social media campaign. Unfortunately, the level of engagement and retention was low; when someone did attend a meeting, it was often just once. However, despite the low uptake, we kept the invitation open throughout the project and were keen to welcome contributions at any stage. Although the number of contributors involved throughout the project's timeline was small, it allowed for meaningful and long-lasting partnerships to be developed which are often absent in biomechanical engineering studies of this nature. While the quality of the partnerships formed between researchers and the public are considered to significantly influence the effectiveness of PPI [17], the enhanced robustness that a larger and more diverse group could provide, particularly in terms of transferability to the wider populations of individuals with hand OA, is acknowledged and encouraged for future studies.

It is also recognised that the small number of contributors meant it was difficult to manage bias. For instance, even with providing spaces for anonymity, with only two contributors, the chances of identifying the author of any feedback was more likely than with a larger group. To address this potential issue, we encouraged open discussions. Additionally, as the researcher, I tried to remain aware of potential power imbalances and facilitated opportunities for feedback by regularly checking in with everyone involved. A Steering Committee was also formed soon after our early-stage meetings to help identify, prioritize, and oversee the decisions and progress made throughout the project. The committee's core members included public contributors, project supervisors, project collaborators and PPIE officers. Quarterly meetings served as effective forums for clarifying any misunderstandings and gathering feedback as they brought together a larger and diverse range of expertise at different stages of the project's completion. If there were any misrepresentations or if one perspective appeared to dominate the conversation, these meetings provided an opportunity to identify such issues.

As this project began when the COVID-19 social distancing restrictions were still being enacted, our early meetings took place online. As stated by principle 2d of the INVOVLE PPI values and principles framework, it is essential that *"public members' expenses are covered, and they are informed in advance if payment will be offered for their time"* [147]. This includes remote working and is outlined in the NIHR guidelines on how to support contributors in joining meetings remotely. To this end, home-working access needs were discussed with contributors and £5 was added to the reimbursement rate to support the cost of telephone calls, paper, printing ink and paper, internet connection etc. When COVID-19 social distancing restrictions were lifted, we took a hybrid working approach, retaining online meetings but also introducing opportunities to work in-person. The preference on whether to meet in-person or online was always sought to ensure that the equality of opportunity was upheld. Alongside the payment offered for their time, the cost of travel was covered for any PPI activity held in-person (i.e. meeting, conference, presentation etc.) Event registration, overnight accommodation and subsistence expenses for members of the public were also covered during the project.

'Data sharing' is referred to as *"the act of releasing data in a form that can be used by other individuals"* and data is considered to be 'reused' when it is *"retrieved by someone else and deployed for another project."* [210].There are benefits of data sharing, particularly in enhancing the lifespan of data but also in reproducibility, accessibility, investment and innovation. Therefore, while the project's design was restricted by the use of datasets collected prior to the public's involvement, there remained an opportunity to work with members of the public, a group frequently overlooked in quantitative research settings, to ensure the data's reuse remained relevant and accessible. To this end, it was also acknowledged that while the training datasets do not represent an OA population, the processing of this exemplar dataset could support the advancement of biomechanical understanding of the hand joints such as for addressing population variability [203] and developing future transferable modelling methodology for data more representative of the OA community.

3.4.4 Theory Development

As a result of early-stage PPI, this research project shifted its aims to explore the ways in which the resources available could be used to address the contributor-recommended research priorities. Two of the three original contributors involved in informing these project decisions continued to be involved until the project's completion, continuing to share their expertise and support project efforts. Despite the limited evidence base, biomechanical engineering especially lends itself to a PPIE-driven research approach since research often concerns a

health condition that impacts a population. This further strengthens the relevance of the statement from Hewlett et al. [170] that patients "*have a personal experience of disease that is not available to most researchers, but that complements researchers' analytical skills and scientific perspective*". Our experience in this project has led us to strongly agree with the complementary skills involved and its benefits to collaborative research, which is often highlighted as a requirement for effective multidisciplinary teams [211], [212].

To avoid devaluing PPI, Ocloo and Matthews [176] suggest that researchers need to be trained and supported when undertaking public involvement. They state that by developing models of healthcare that are more co-designed and co-produced between all stakeholders, we can move beyond tokenism, share power, and create more equity in the decision-making process. This highlights the importance of increasing both the education and evidence-base of PPIE in quantitative-based methodology as even if there has been a recent commitment to PPIE from the engineering community, educational and practical barriers can still exist due to a lack of understanding from researchers regarding what it involves, how to support a diverse range of lay members, and the difference between PPIE and qualitative research methods [178]. To support continued efforts to increase PPIE in this field, it is important to continue contributing to the evidence base and share the lessons learnt from such an approach.

3.5 Chapter Summary

This chapter presented the main outcomes of the early-stage PPI activities and how the public contributors' expertise and enthusiasm to be involved in subsequent stages of the project's development ultimately re-informed the project's purpose and structure. Expanding our public-researcher partnership notably influenced and supported critical thinking as well as encouraged a new perspective and attitude toward the involvement of public members in quantitative-based engineering research. This chapter also acts as a prelude to understanding the role of PPI throughout this project, providing a glimpse into research methods selected to address the public contributors' research priorities. The subsequent chapters describe:

- Computational methods used to assess shape and motion trends within existing datasets to define levels of *variability* and *joint instability* (Chapter 4 and Chapter 5)
- Public engagement efforts developed to *raise awareness of hand OA* and the value of PPI, including conducting workshops and creating digital and physical resources (Chapter 6)

Chapter 4 Characterising Shape Variability within an Exemplar Training Dataset of Finger Bone Triangular Surface Meshes

4.1 Overview

Public involvement consultations identified *variability* as one of the project's research priorities to be explored using the available datasets (see Chapter 3). To this end, statistical shape modelling (SSM) was a favoured data processing technique. A multi-body statistical shape modelling pipeline was implemented on an exemplar training dataset of computed tomography (CT) scans of 10 right hands (5F:5M, 27–37 years, free from disease or injury) imaged at 0.3 mm resolution, segmented, meshed and aligned. The model generated included pose neutralisation to remove joint angle variation during imaging. Repositioning was successful; no joint flexion variation was observed in the resulting model. These models have been published for open use to support wider community efforts in hand biomechanical analysis, providing bony anatomy descriptions whilst preserving the security of the underlying imaging data and privacy of the

participants. The model describes a small, homogeneous population, and assumptions cannot be made about how it represents individuals outside the training dataset. However, it supplements anthropometric datasets with additional shape information and may be useful for investigating factors such as joint morphology and the design of hand-interfacing devices and products.

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4.2 Introduction

Computational biomechanical modelling is a useful tool for surgical planning, clinical assessment, and testing of new devices for disease interventions and consumer products. Musculoskeletal (MSK) modelling and Finite Element Analysis (FEA) studies are commonly informed by parameters obtained from a variety of sources or are subject-specific. However, variability and uncertainty are present in factors such as patient geometry, material properties of tissues, kinematics, joint loading, and clinical outcomes. Therefore, to further broaden the interpretation of these studies' outputs, it is possible to combine these modelling techniques with population-based approaches [213]. In these cases, biomechanical models can be varied systemically to describe individuals representative of a population, enabling model outputs to be interpreted relative to the trends observed in the wider population. This method also allows existing models to be applied to new individuals with relatively low expense, which may support clinical translation [120]. As encouraged by Saxby *et al.* [214], this approach relies on the research community to share models and technologies.

Statistical shape modelling (SSM) employs dimensionality reduction methods for characterising variations in factors including anatomic shape and tissue composition in a population [203]. A statistical shape model provides a mean geometry of the training dataset and describes the shape variability as a series of modes. The total variation in a training dataset is decomposed

into a compact set of new variables. Some researchers size-normalise their data to separate the effects of size and shape variation [215], [216]. Population-based analysis of bone morphology using SSM may inform the design and testing of treatment devices and consumer products, as well as fundamental biomechanics studies. These models can be descriptive or predictive. Descriptive models [91], [92], [94] facilitate the study of shape characteristics and enable classification, measurement and investigation of any trends, clusters, or outliers within the dataset. Predictive models [75], [83], [217], [218] can be used to study the relationships between shape and clinical or functional parameters and to reconstruct complete subject-specific geometries from incomplete data which is useful for informing other types of models.

This method has been employed to characterise the morphology of musculoskeletal structures including the mandible, residual limbs following amputation, and joints in the foot, knee and hip [94]–[97]. By extracting the variation in size, position and orientation, statistical shape models (SSMs) have applications in several areas including, the design of products that account for diversity in anthropometrics like orthopaedic implants and consumer devices, and studies looking at how nature of bone/geometry can affect propensity for conditions such as arthritis.

Considering the joints of the hand, SSMs have focused so far on the thumb, demonstrating morphological variation in the carpometacarpal (CMC) joint. Rusli and Kedgley [100] present the impact of morphology variation on joint instability across their study population, highlighting the significance of these findings for developing future CMC osteoarthritis studies. In another study, Schneider *et al*. [101] focused on characterising the morphological sex and age patterns amongst their study population of CMC joint bones. For example, they found that a female cohort had similarly shaped trapezium and first metacarpal bones as men.

Although statistical models of the full hand's external anatomy have been reported [102], there is no current SSM report on the proximal (PIP) and distal (DIP) interphalangeal joints found in the thumb or those found across the fingers, despite the prevalence of their degeneration [103] and scope to improve outcomes of their surgical interventions [64]. Few researchers have access to the anatomic data required for such analysis, and there is cost, inconvenience, and risk associated with CT or MRI scanning volunteers. Therefore, this section presents multi-body SSMs of the four fingers of the hand, providing models that can be published for open use whilst

preserving the security of the underlying imaging data, to support wider community efforts in hand biomechanical analysis.

4.3 Materials and Methods

4.3.1 Public Involvement Statement

During public involvement consultations at the project design stage, perspectives on the available datasets and usability of a computational model of the hand were explored with three members of the public living with hand OA. Public contributors stated that *"one size does not fit all"* and thus, they believed it was more important to understand the dataset before trying to create a fully functional computational model. As potential end-users of treatment interventions, the public contributors also suggested that researchers consider how these products may perform on different hand and finger shapes and sizes. To this end, characterisation of the variability within the dataset was prioritised. Their expertise also supported critical thinking, guiding technical workflow, data interpretation and data useability. For instance, contributors emphasized creating a model that would be accessible to the wider community as it could serve as a valuable educational resource for the public as well as a tool for clinicians and researchers. They recommended developing the model with this educational and ease-of-use goal in mind. Throughout the development of this study, a consultation PPI approach was adopted with progress consistently shared at a diverse range of gatherings including steering committee meetings, public community events and academic conferences. Finally, public contributors also suggested that future iterations of a statistical model could include datasets from other pathologies such as osteoarthritic datasets. Public contributors were offered and fully reimbursed for their time and any expenses related to this study.

4.3.2 Training Dataset

Ethical approval was granted for Secondary Data Analysis of an existing dataset (ERGO Ref: 61718). The training dataset represented ten consenting participants (5F:5M, mean age 31yrs, range 27 – 37yrs), who were free from hand or wrist disease or injury and had been recruited for a finger motion capture and imaging study (IRAS Ref: 14/LO/1059) [4]. Each participant's right

hand was CT scanned (Discovery CT750 HD 128 scanner, GE Healthcare Inc., United States of America) with 0.3 mm voxels. Three scans were collected for each participant with the fingers in full extension, mid-flexion, and near-full-flexion. The resultant volume images were segmented to isolate the bony anatomy and meshed (ScanIP +FE, Synopsys Inc., United States of America). The resultant triangular surface meshes of the proximal phalanges (PP), medial phalanges (MP) and distal phalanges (DP) were imported into a MATLAB (MathWorks, Massachusetts, United States of America) environment. The data from the three positional scans were then aligned by the PP bones and moved into a coordinate system [4] in which the origin lay at the PP centroid, and the sagittal plane was estimated from the movement of the MP bone during PIP flexion. The subsequent shape analysis used the meshes obtained from the fully-extended (scan position 1) dataset, and scan positions 2 and 3 were used solely to estimate joint flexion axes for pose neutralisation.

4.3.3 Statistical Model Generation

A multi-body SSM pipeline, capable of computing the main modes of variation or 'principal components' (PCs) within the training dataset of three-dimensional surface meshes of the phalanges, consisted of three main stages:

4.3.3.1 Non-rigid registration for point correspondence between datasets

To enable geometrical comparison between the training datasets, a single reference mesh was mapped to the surface meshes of each phalanx using an Iterative Closest Point (ICP) based non-rigid registration algorithm [219], establishing a nodal correspondence. The mesh with a length closest to the average of the dataset was selected as the reference mesh.

The registration error was calculated by computing the Root-Mean-Square-Error (RMSE) of the Euclidean Distances between the target shape and the registered shape vertices. Additionally, a linear regression analysis was conducted to compare the mesh volumes before and after registration.

$$\mathrm{RMSE}\ (x) = \sqrt{\frac{1}{N}\sum_{n=1}^{N} \|x_n\|^2}$$

where x_n is the array of Euclidean Distances computed using a k-nearest neighbour (kNN) search.

4.3.3.2 Removal of alignment variation generated during imaging ('Full Extension Pose Neutralisation')

To assess how shape and scale variation could be captured in the statistical shape model with minimal influence of pose during scanning, the joint flexion in the "full extension" scan datasets was corrected (Figure 8). Two reference coordinate systems were estimated to describe the bone positions relative to the PP and MP (CS1 and CS2 respectively) using the principal axes and centroids of the bone surface mesh vertices in their surface meshes, as reported previously [4].

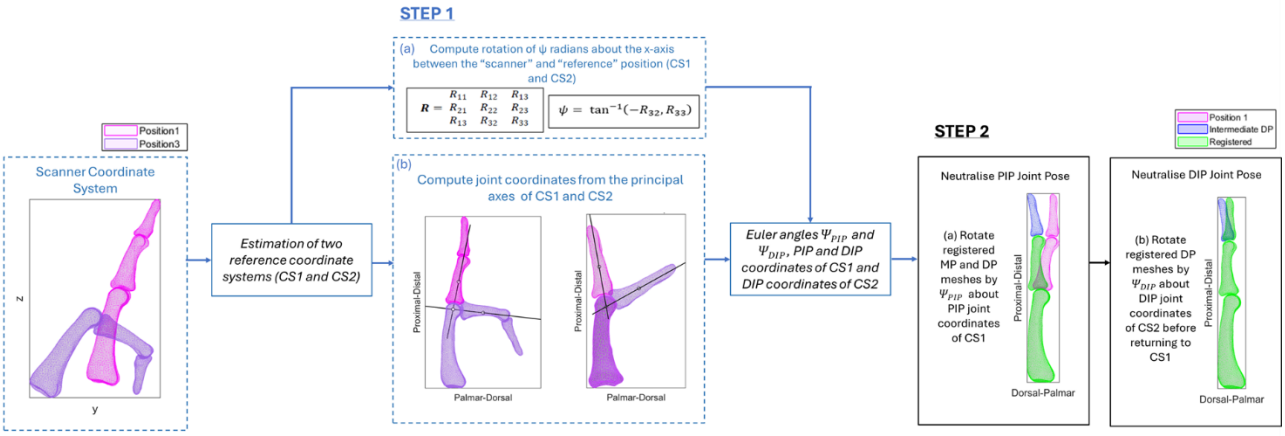

Figure 8 Flow diagram describing the joint pose neutralisation, to remove bone location variation generated during imaging. Step 1 computes the angles and centroids required for neutralisation. Step 2 involves the pose neutralisation of the PIP and DIP joint in the two reference coordinate systems (CS1 and CS2 respectively).

The use of transformation matrices to compute the intrinsic sequence of rotations of the mesh vertices around the three different axes, known as a Euler rotation, is commonly used in biomechanics to study joint motion. For instance, the Euler angles between the femoral and patellar coordinate systems have been used to study the patellofemoral motion within a dynamic knee simulation model [220] and an Euler rotation has been applied to extract PIP joint angles in a cadaveric study [221].

In this study, singular value decomposition on vertex coordinates was used to calculate transformation matrices $\boldsymbol{M_{4\times4}}$, that describes the transformation of MP or DP from its position as scanned ('scanner coordinate system'; i.e. Position 1 or 3) to the new reference coordinate system (CS1 and CS2). Euler angles Ψ_{PIP} and Ψ_{DIP} were used to estimate the PIP and DIP joint flexion-extension angles, and were calculated from the rotation matrix, $\boldsymbol{R_{3\times3}}$, extracted from $\boldsymbol{M}$. These were used to align the joints into an approximately "neutral" pose, by rotation about the estimated centroids of the PIP and DIP joints.

The angles computed using transformation matrices were verified against the angles computed using an alternative method by Metcalf *et al.* [4]. Their method used vector and trigonometric operations in MATLAB (i.e. the CT method) and was validated, strongly correlating with the Hand and Wrist Kinematic (HAWK) measurement technique utilized during data acquisition [4]. The HAWK system's repeatability (inter-rater reliability) and accuracy has been demonstrated in previous work [222]. Therefore, it was justified to directly compare the resultant angles from Euler Angle method adopted for pose correction to those generated from the CT method (Figure 9 and Figure 10).

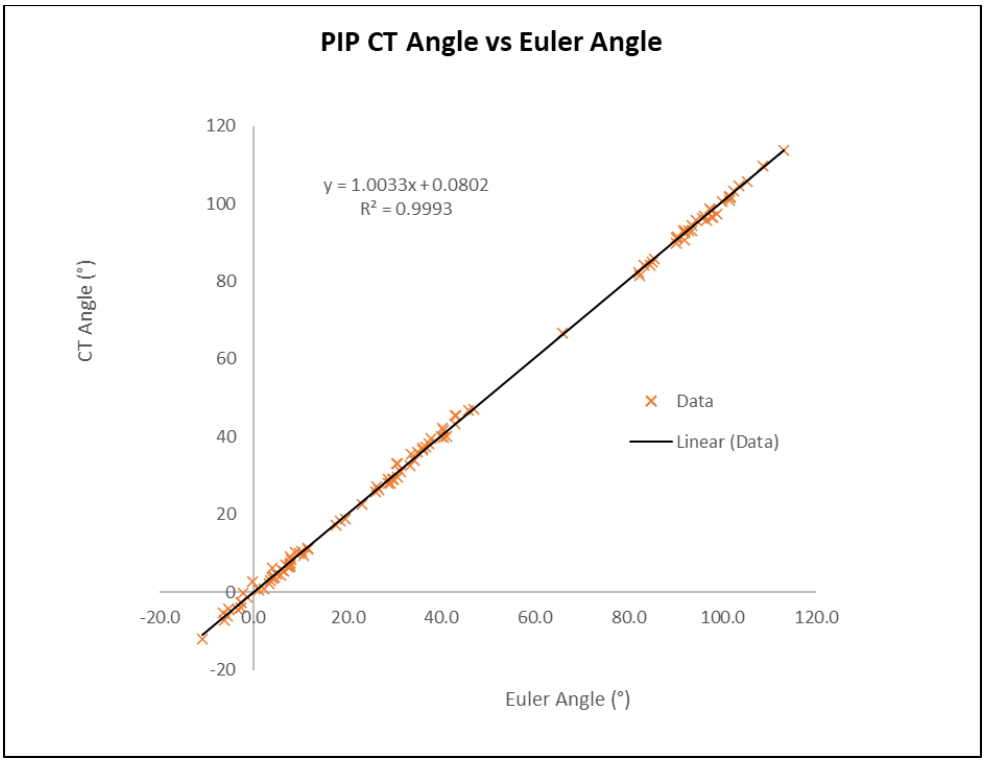

Figure 9 Correlation of PIP joint angle obtained from bone principal axes ('CT') and transformation matrices ('Euler')

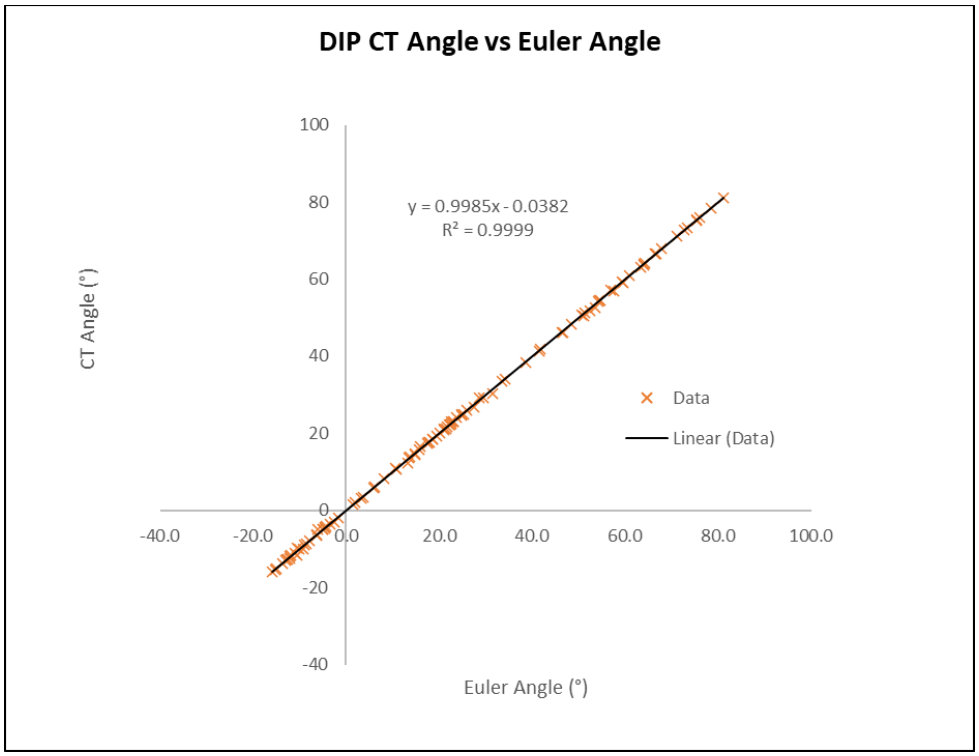

Figure 10 Correlation of DIP joint angle obtained from bone principal axes ('CT') and transformation matrices ('Euler')

The PIP joint axis was estimated in CS1 by finding the intersection point between the MP bones' long principal axes in the extended and flexed CT scans (Figure 11). This point was projected onto a plane through the PP and MP bone centroids in extension and full flexion to which the joint axis was assumed to be perpendicular. The same process was then applied to the DP mesh's principal axes to estimate the DIP joint axis in CS2 (Figure 12).

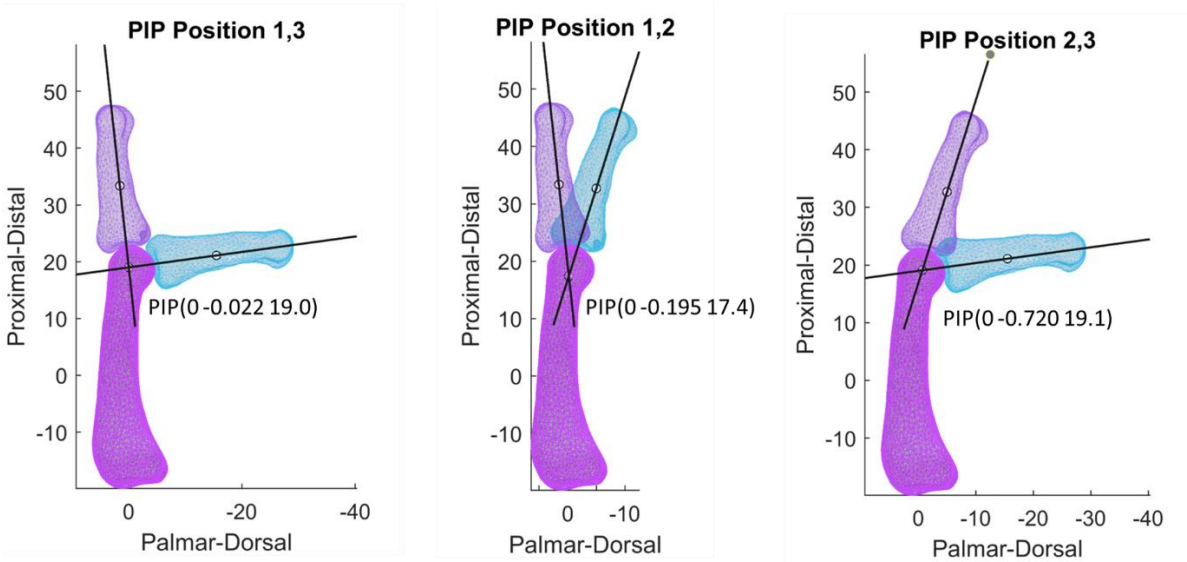

Figure 11 Computation of the index finger PIP joint centroids with a different combination of scanning positions

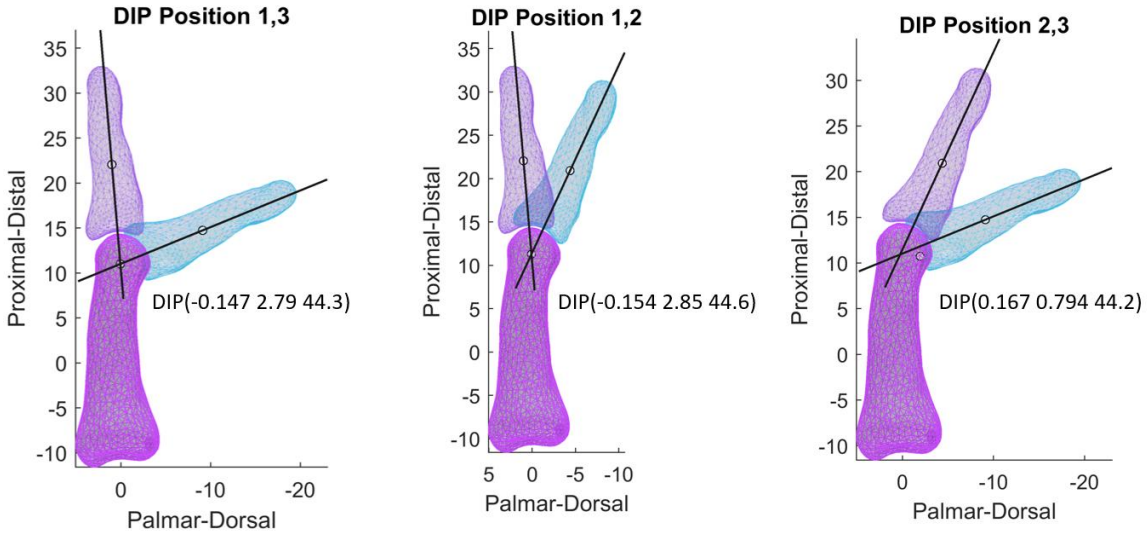

Figure 12 Computation of the index finger DIP joint centroids with a different combination of scanning positions

Finally, each finger's pose was neutralised by rotating the bone geometry by the angle measured between the PP and DP principal axes in the "full-extension" scan.

4.3.3.3 Principal component analysis (PCA) for dimensionality reduction of size and shape variation

The three phalanx mesh files for each dataset were compiled into a column vector:

$$\boldsymbol{x} = [x_1 \quad y_1 \quad z_1, \cdots, x_m \quad y_m \quad z_m]^T$$

where m represents the total number of nodes in the combined DP, MP and PP baseline meshes, and x, y, and z are the vertex coordinates.

A vector describing the mean finger shape was calculated by:

$$\overline{\boldsymbol{x}} = \frac{1}{n}\sum_{i=1}^{n} \boldsymbol{x}_i$$

where *i* represents each instance in the training dataset, and *n* is the total number of instances.

Principal component analysis (PCA) was applied to reduce the dimensionality of the training data by finding a new set of parameters (principal components or 'PCs') which can be linearly combined to recreate the original 3*m* parameters that describe each instance *i* of the training data.

The 3*m*-*by*-3*m* sample covariance matrix:

$$\boldsymbol{S} = \frac{1}{n-1}\sum_{i=1}^{n} (\boldsymbol{x}_i - \overline{\boldsymbol{x}})(\boldsymbol{x}_i - \overline{\boldsymbol{x}})^T$$

is used to find these PCs. For a dataset where all the parameters describing variation between instances are uncorrelated, $\boldsymbol{S}$ will be diagonal. It can be shown that the eigenvectors ($\boldsymbol{\varphi}_j$) of $\boldsymbol{S}$ can be used with a vector of weighting coefficients ($\boldsymbol{d}_j$) to reconstruct the training data [223]:

$$\boldsymbol{x} = \overline{\boldsymbol{x}} + \sum_{j=1}^{c} \boldsymbol{\varphi}_j \, \boldsymbol{d}_j$$

This constitutes a transformation of the original basis (3*m* parameters) into a new, much more compact, basis (the *c* PCs). These PCs are uncorrelated - their covariance matrix is diagonal -

and ordered by decreasing variance (the first PC captures the dimension with the largest variability in the training data).

Singular value decomposition was performed over the analogous eigen analysis to undertake the PCA. The weighting coefficients ($\boldsymbol{d}_j$) used to generate new shapes, which show each PC deviation from the mean, represent the 5th and 95th percentile range of the training dataset mode score and fit within the minimum and maximum mode scores bounds for each individual.

4.3.4 Model Evaluation

To select a preferred model to publish open source, four SSMs were compared, to assess the relative influences of pose neutralisation and size normalisation, upon the resulting anatomic variance characterisation: 1) Original pose without scaling effects, 2) Original pose with scale effects, 3) Corrected pose without scaling effects, and 4) Corrected pose with scale effects.

Mode shapes were visualised by perturbing the mean shape from the 5th to 95th percentile range of the training dataset (i.e. by $\pm 1.654\sigma$), one PC at a time. To observe the potential similarities in variation between fingers, linear regression analysis was performed to assess the mode score correlation. Mode scores for each finger's PCs were compared to the corresponding PC of the index finger. To describe the training datasets and resulting model shapes, the length of individual bones and the whole finger were calculated, along with an estimate for the joint spacing. A Shapiro-Wilk test indicated that these measures were normally distributed for the training shapes ($p>0.05$) so parametric statistics could be used. The joint space was calculated using a kNN search with k=1, to find the Euclidean distance from each vertex on the joint's proximal surface to the distal surface, from which the median was calculated.

Four SSM model performance measures are commonly used for model evaluation. These include model compactness, accuracy, generalization and specificity [106], [108]. We elected not to perform a specificity test because the generation of virtual individuals was outside the scope, owing to the relatively small training dataset.

Compactness: To observe how much variation is captured within the resultant PCs, the compactness was calculated and is defined as the cumulative variance of the m^{th} mode or PC, used in the shape reconstruction [108]:

$$C(PC) = \sum_{m=0}^{PC} \lambda_m$$

Accuracy: The average RMSE was calculated to observe the accuracy of the mean shape reconstruction with a limited training dataset [106]:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} \|\bar{\boldsymbol{x}} - \boldsymbol{x}_i'(PC)\|^2}$$

where $\bar{\boldsymbol{x}}$ is the mean shape constructed with the complete dataset and $\boldsymbol{x}_i'$ is the reconstructed mean, a linear combination of the training datasets.

Generalization: To evaluate the quality of the constructed statistical shape model, a Leave-One-Out cross-validation test was performed, calculating the average deviation between the resultant statistical model's mean and mode extremes ($\pm 1.654\sigma$) shapes and those reconstructed by removing one dataset from the PCA calculation. [106], [224].

$$\text{Average Deviation} = \frac{\sum \sqrt{\frac{1}{n}\sum_{i=1}^{n} \|\boldsymbol{X} - \boldsymbol{X}_i'(PC)\|^2}}{n} = \frac{\sum RSME}{n}$$

where $\boldsymbol{X}$ is the shape constructed with the complete dataset from the statistical model and the shape $\boldsymbol{X}_i$ constructed using (n-1) training datasets.

4.4 Results

4.4.1 Model Evaluation and Selection

The registration error across all fingers was less than 0.4mm for each phalanx mesh (Figure 13), and the registered bone volumes were within 3% of the target bone shapes (R^2 = 0.95).

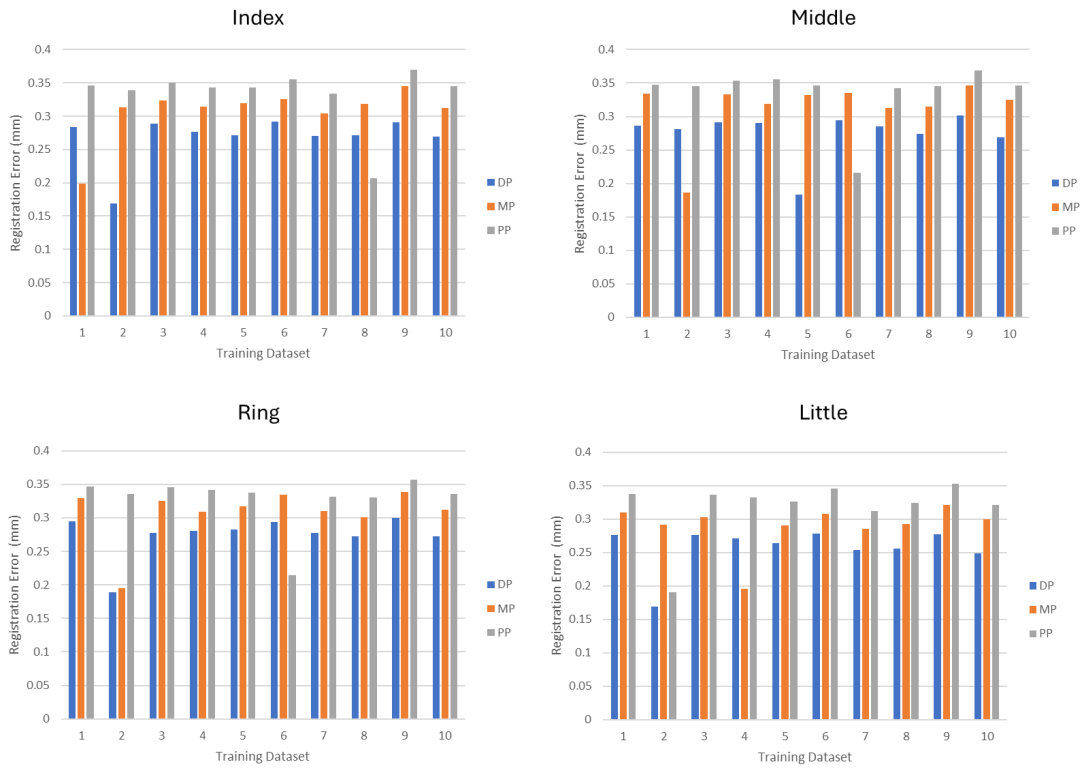

Figure 13 Registration Error in mm: Euclidean distances between registered and target meshes

Nine principal components (PC1 – PC9) representing the main morphological variation were found for the three phalanges of the index, middle, ring and little fingers. Observation of compactness for models with and without size normalisation and pose neutralisation indicated that over 75% of shape variability was captured within the first four modes and 90% within seven modes for three of the model types (Figure 14). The model constructed with corrected pose and normalized scale was less compact with only 59% of shape variability captured in the first four modes. The model constructed using pose neutralisation and full scaling had the combination of high compactness and a small error in mean shape reconstruction, so all subsequent results (Figure 15 to Figure 20 and Table 11 to Table 13), are based on using the "Corrected Pose, including scale effects" model.

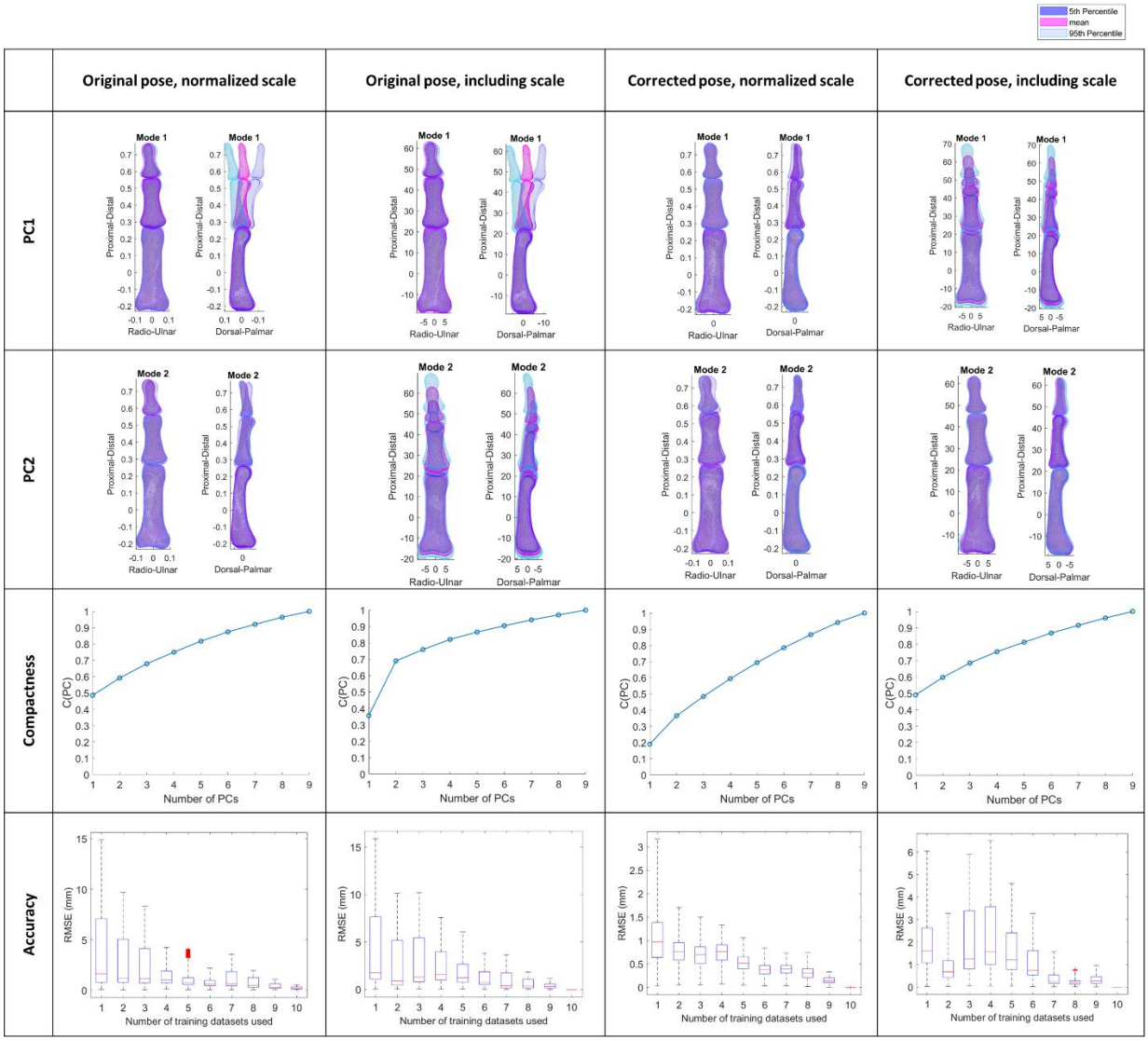

Figure 14 Impact on pose neutralisation and normalising scale on resultant principal components. Note for normalized shapes (columns 1 and 3): since the proximal phalanx's centroid lies at [0 0 0], the mean (against which dimensions are normalized) has a full-scale length of one but is represented between approximately -0.25 to 0.75 along the Proximal-Distal axis.

4.4.2 Description of Selected Statistical Model

The Leave-One-Out test highlighted a minimal deviation (<0.2 mm in the mean and<0.5 mm in the mode shape extremes) between the resultant statistical shape model and the reconstructed model (Figure 15).

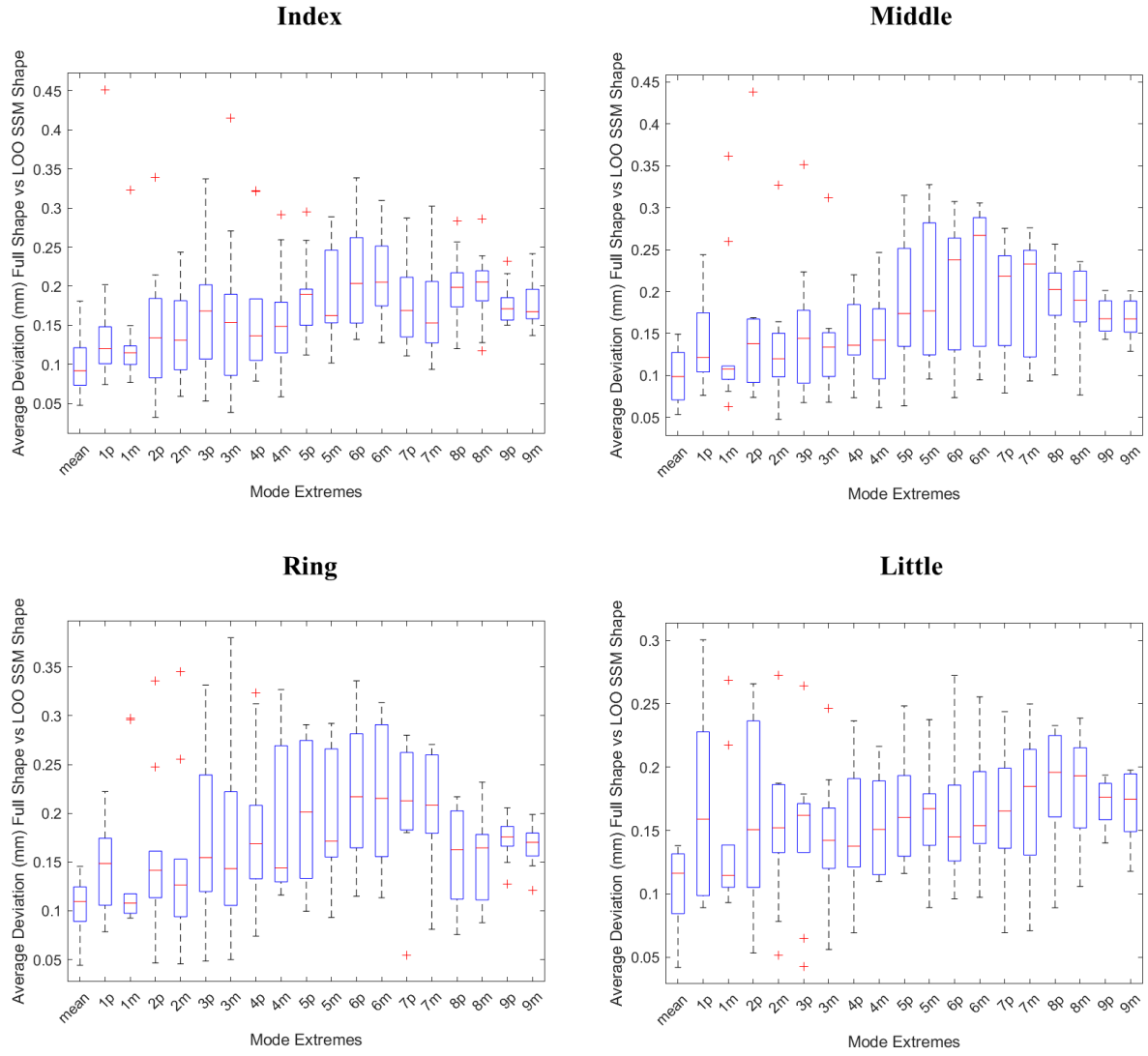

Figure 15 Deviation between the mean and mode extreme shapes generated using n = 10 (Full Shape) and the mean and mode extreme shapes (p represents minimum shape and m represents maximum shape for PC1 – PC9) generated when one dataset is removed (n = 9, LOO SSM Shape)

The first four PCs across all fingers accounted for over 75% of the total variation within the training population, of which over 45% was attributed to the first PC representing phalanx size for all fingers (Figure 16).

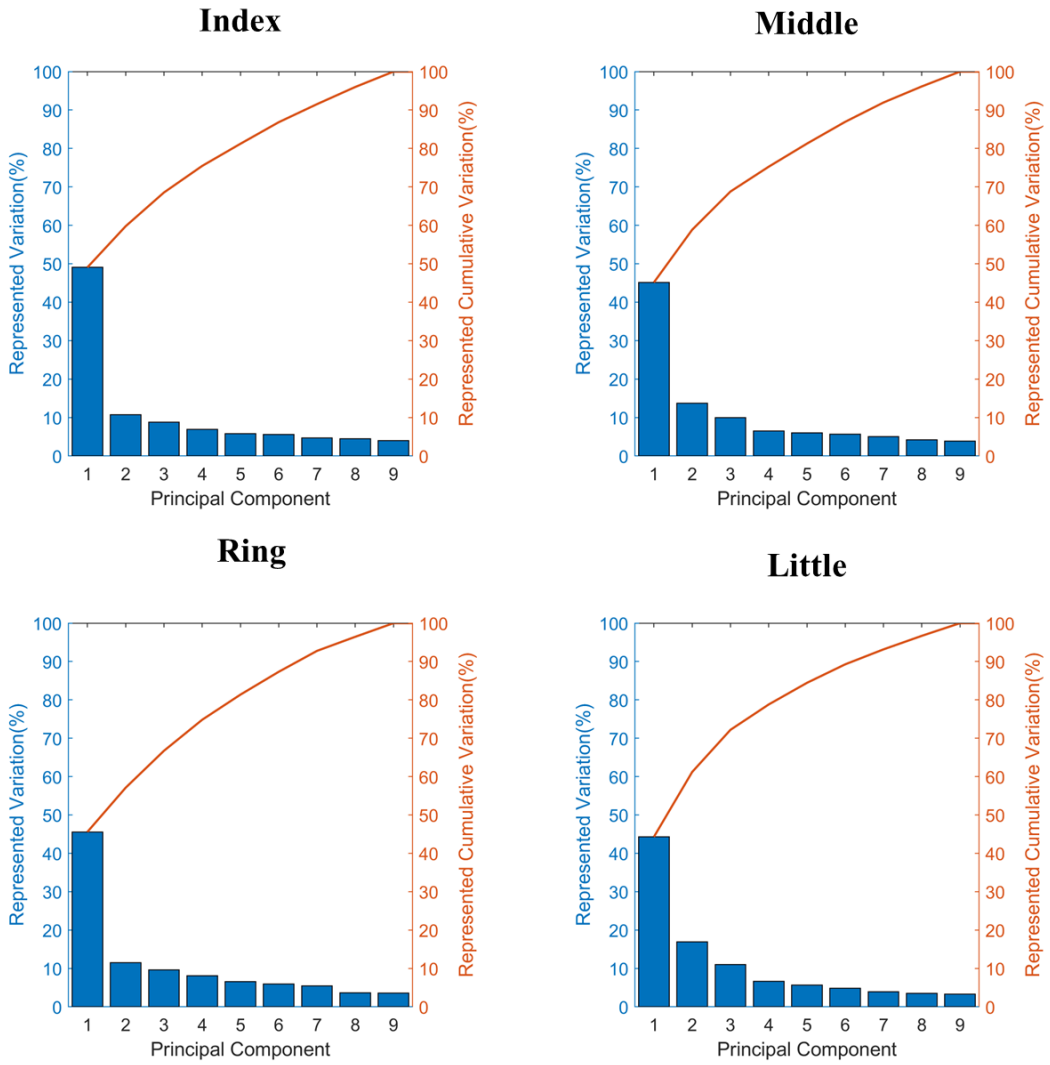

Figure 16 Variance (bar) and cumulative Variance (line) captured by all PCs for index, middle, ring and little finger

A strong correlation was observed (Table 11) between PC1 of the index finger and PC1 of the remaining fingers ($R^2 > 0.869$). The PC1 mode score correlation agrees with the visualization of PC1 for all fingers, whereby size was the dominating PC. The R^2 values for subsequent mode

scores were lower ($0.01 < R^2 < 0.77$), indicating that the variation described by each mode was not always the same.

Table 11 R2 and p-value from linear regression analysis of the PC weights of the index finger compared to the PC weights of the middle, ring and little fingers.

Principal Component	**Finger**	**R^2**
PC1	Index vs Middle	0.938*
PC1	Index vs Ring	0.892*
PC1	Index vs Little	0.869*
PC2	Index vs Middle	0.771*
PC2	Index vs Ring	0.760*
PC2	Index vs Little	0.062
PC3	Index vs Middle	0.373
PC3	Index vs Ring	0.106
PC3	Index vs Little	0.200
PC4	Index vs Middle	0.429*
PC4	Index vs Ring	0.013
PC4	Index vs Little	0.064

* denotes $p<0.05$

Visual inspection of the PCs (Figure 17) suggests that PC1 presented variation in bone size, PC2 described positional variation of the bones along the palmar-dorsal axis, PC3 represented variation in ab/ad-duction in the dorsal-palmar plane and PC4 indicated variation in bone breadth. PC1 – PC4 for the middle, ring and index finger can be found in Appendix B.

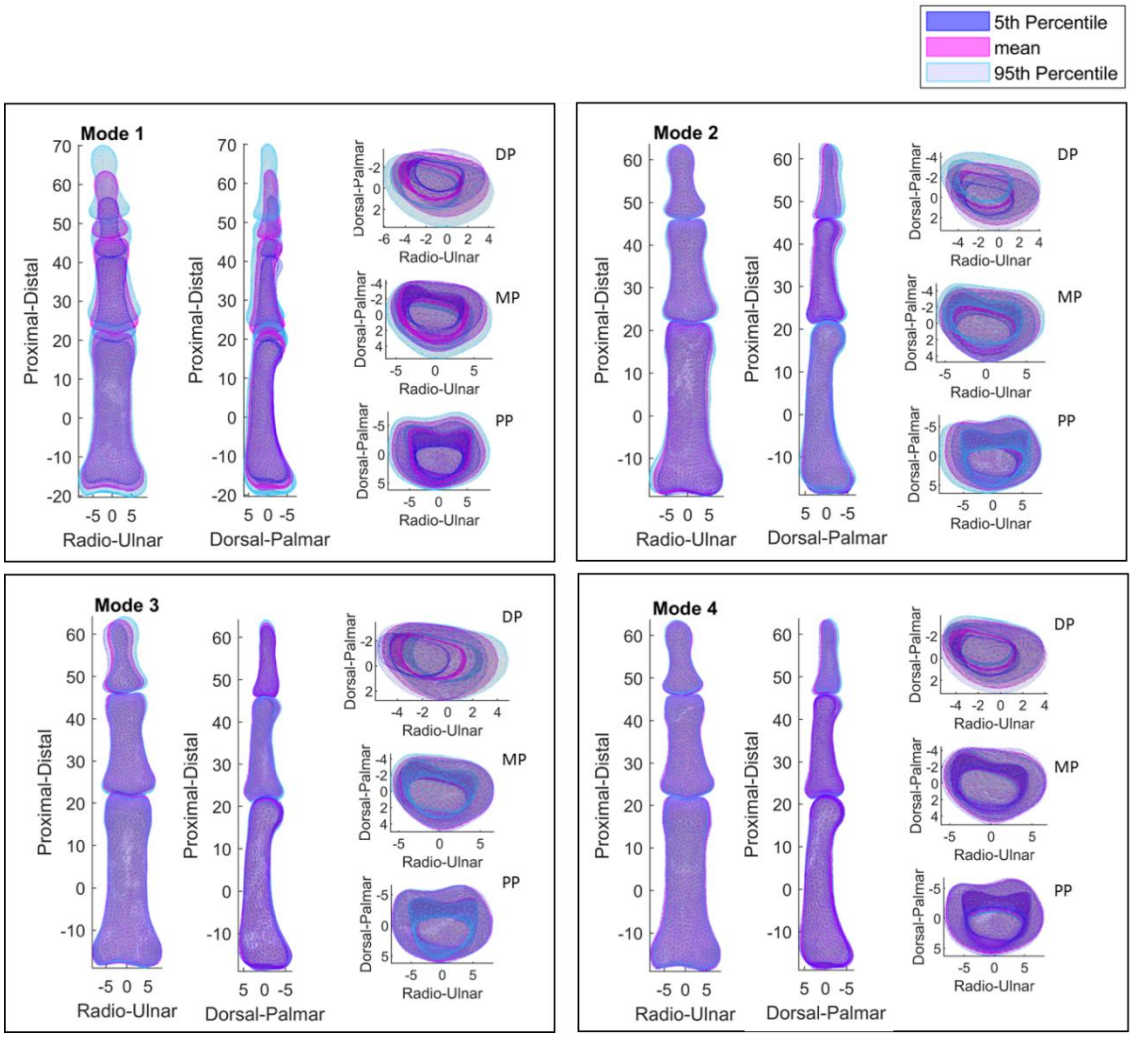

Figure 17 Index Finger PCs: The first principal component shows variation in bone size, the second principal component shows positional variation along the Palmar-Dorsal axis, the third principal component shows orientation variation, and the fourth principal component shows variation in bone breadth.

Gross measures (Table 12 and Table 13) were extracted from the mean and 5th-95th percentile range in the shape of PC1 and compared to the same measures taken directly from the training datasets ('CT') to illustrate the model's ability to represent the population's size range. (Figure 18, Figure 19 and Figure 20). This indicates that the PCA method was able to extract the size variation within the training dataset, predominantly within a single mode (PC1).

Table 12 Average (5th – 95th percentile) index finger bone lengths (in mm) from training dataset and PC1 shape instances

Dataset	DP Length (mm)	MP Length (mm)	PP Length (mm)	Total Length (mm)
Training Population	17.5 (15.3 - 19.7)	24.6 (22.7-26.8)	40.9 (37.7 - 43.9)	83.0 (75.7 - 90.4)
Statistical Model PC1	17.4 (15.6 - 19.5)	24.8 (22.0 - 27.7)	41.2 (37.5 - 45.0)	83.5 (75.1 - 92.2)

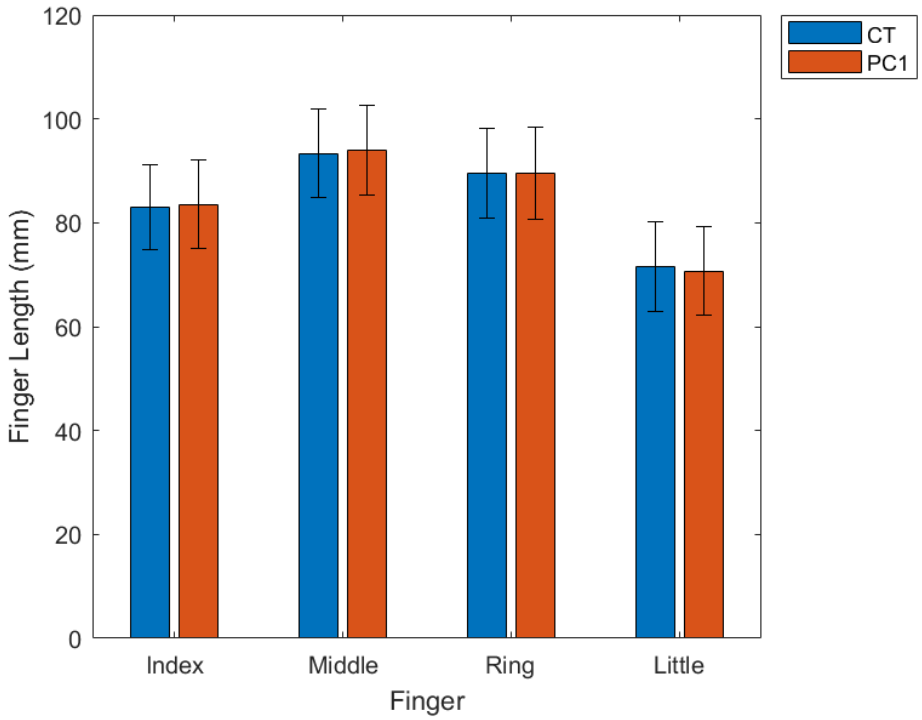

Figure 18 Average and 5th to 95th percentile range (error bars) finger length in mm across training datasets and PC1 shape instances

Conversely, though the mean joint space from the statistical shape model was in close agreement with that of the training dataset, the variance in this measure was greater than that contained within PC1 indicating that it is distributed across subsequent modes. The training

datasets indicated that finger length and joint space were not associated (R^2=0.1 and 0.007 for DIP and PIP, respectively).

Table 13 Average (5th – 95th percentile) index finger DIP and PIP joint space (in mm) from training dataset and PC1 shape instances

Dataset	DIP Joint Space (mm)	PIP Joint Space (mm)
Training Population	2.2 (1.9 – 2.5)	2.5 (2.3 – 2.9)
Statistical Model PC1	2.2 (2.1 – 2.3)	2.5 (2.5 – 2.6)

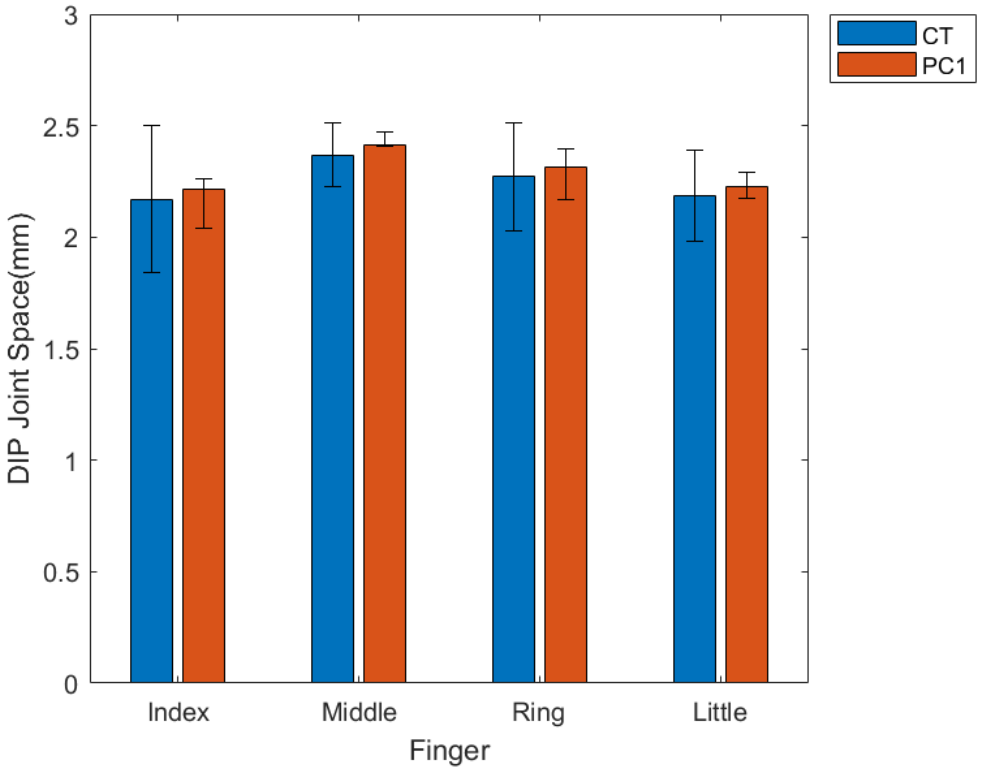

Figure 19 Average and 5th to 95th percentile range (error bars) for DIP joint space in mm across training datasets and PC1 shape instances

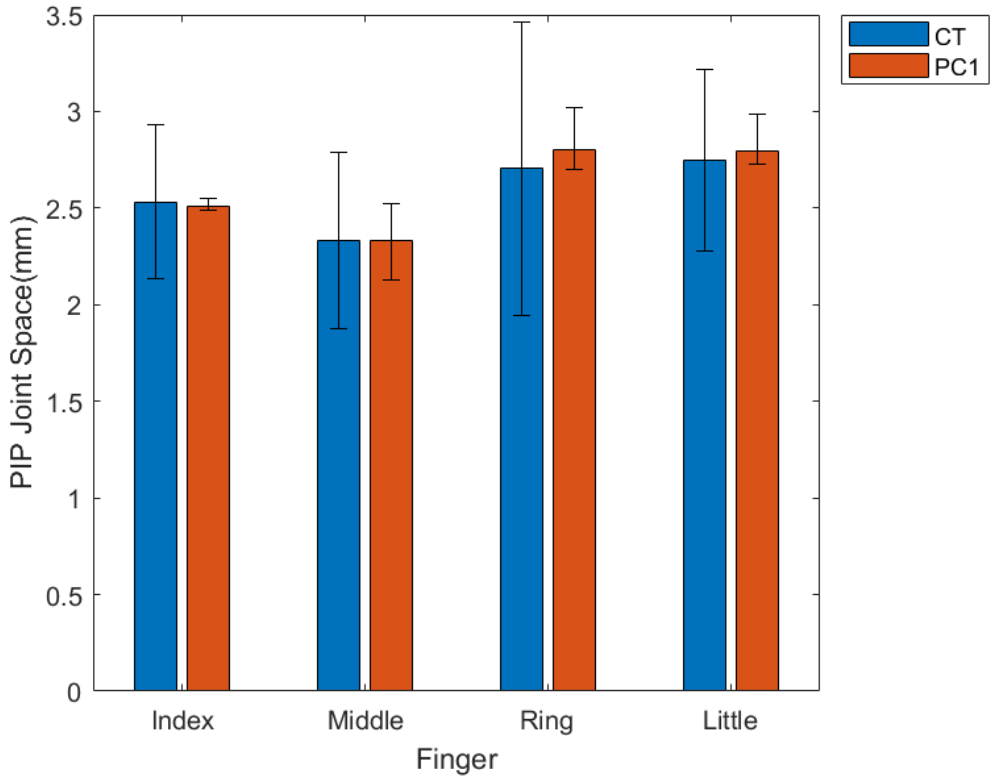

Figure 20 Average and 5th to 95th percentile range (error bars) for PIP joint space in mm across training datasets and PC1 shape instances

4.5 Discussion

This chapter presents a pipeline for generating a statistical shape model of the fingers. It has novelty in being trained using medical imaging from living participants, free from hand or wrist injury, and the process estimates the removal of pose variation during imaging, to maximise the observable size and shape variation from a small dataset.

Scale is a common mode of variation and dominates as the largest portion of morphological variation amongst a population. It is argued to largely contribute to morphological variation. For instance, an increase in the size of a structure suggests an increase in the skeletal dimensions such as bone shaft, breadth and articulating surface. Whether scale variation is an important PC is at the discretion of the user, however for the extraction of gross measures from each PC such as bone length and joint space, the pose corrected model with scale effects was used for further analysis and publication on the open-repository. Bone lengths were extracted to illustrate this variation within our training dataset, and these were significantly larger than finger lengths reported in previous studies [225], [226] (i.e. mean index finger length for right hands [225] was 79.7mm ± 5.1mm for male participants and 73.6mm ± 5.0mm for female participants whereas for the training datasets, the mean index finger length for right-hands was 86.6mm ± 3.4mm for male participants and 79.3mm ± 2.7mm for female participants). However, these may not be completely comparable measures, as the present data are direct bone length measures whereas the cited prior data are estimated finger segment lengths based on fingertip-to-finger-palm crease distance and are inclusive of distal soft tissue. All considered, our method remains objective and repeatable across different fingers and datasets and may avoid the subjectivity of external measurements.

While sizes are likely to be important for anthropometrics and ergonomics, in other research studies, shape may be of more interest. For example, Bruse *et al.* [215] excluded size effects when applying a SSM framework to extract 3D shape biomarkers of repaired aortic coarctation arches. Similarly, Cerveri *et al.* [97] were solely interested in knee joint instability and therefore selected non-size-related PCs, such as the height of the femoral and tibial shafts, the curvature of the femoral shaft and the frontal plane. The present study provides researchers with the opportunity to study both size- and shape-dominated phenomena.

According to Wang and Shi [108], a compact statistical model represents the population variance with a small number of PCs. The number of modes retained in a model is often simply

determined by selecting those which cover a percentage threshold of the total variance (most popularly a 95% variance threshold). Limited by the training dataset size, we would need to retain all the modes to achieve this. This limitation is discussed by Mei *et al.* [227] who show that this retention method is highly dependent on sample size, recommending that mode retention should ideally correspond to genuine anatomical variation.

It is believed that these are the first publicly available SSMs of the fingers' skeletal anatomy generated from living participants. The nearest comparable dataset is that generated by Van Houtte *et al.* [102] who present an articulation-based registration method for three-dimensional meshes of human hands. In this study, SSM was successfully applied to 100 human hand shapes and provided insight into the anatomic variation of the lower arm and hand with their main focus on presenting the effectiveness of the proposed registration framework for the design of well-fitting products.

This study is limited primarily by a small training dataset representing a homogeneous population of young, healthy participants, mainly working in tertiary or quaternary sectors. This might represent a portion of the UK population but may not describe those who use their hands more heavily, such as those who work in primary and secondary sectors. In addition, the exemplar model produced in this study does not capture the influences of pathology or surgery on the condition of the soft and hard tissue. These models solely focus on the morphology of the phalanx skeletal structure. If one were to use these models to study the kinematics and kinetics of the hand, more data would be needed, hence why they have been made available for contribution and collaboration. However, the inclusion of additional datasets is non-trivial because the phalanges should be aligned neutrally, which cannot be guaranteed at the point of imaging. This workflow corrected the phalanx alignment using an estimation of the position and angle of the DIP and PIP joints using scans of the participants' hands in at least two positions, which is not a standard clinical imaging protocol. However, it may be possible to expand the model's training dataset from single-position CT images by further development of functional joint axis estimation using motion capture [228]. Further, pose neutralisation only corrected PIP and DIP flexion-extension, assuming that abduction-adduction and internal-external rotations in the full-extension scans were relatively small, and this may be valid because the flexion corrections averaged 1.0° and ranged from ±16° for all except one dataset (23°).

4.6 Chapter Summary

This chapter presented the efforts undertaken to leverage the finger CT data to address *patient variability;* one of the three research priorities reported by public contributors during the project design stage (see Chapter 3). A robust SSM methodology was generated to investigate the skeletal shape variation within the training dataset population. This multi-body modelling workflow gave rise to nine modes of variation for each finger, describing variations such as bone size, breadth and alignment.

This exemplar dataset has been published as open source (https://github.com/abel-research/OpenHands) for community use. The shared model describes a small, homogeneous population, and assumptions cannot be made about how it represents individuals outside the training dataset. However, such a model can supplement gross anthropometric datasets with additional shape information, and if trained with additional CT images the model may be of use for investigating factors such as joint morphology, and for the design of hand-interfacing devices and products.

Chapter 5 The Investigation of Potential Joint Instability Indicators from Shape and Motion Data

5.1 Overview

In response to identifying *'patient variability'* as one of the three contributor-recommended research priorities, Chapter 4 details how the hand imaging dataset available was used to generate statistical shape models (SSMs) of the hands, giving rise to size and morphological modes of variation. During consultations, public contributors also highlighted *joint instability* as a major challenge associated with hand osteoarthritis (OA), identifying it as the second research priority. A joint's structure and surrounding tissues (i.e. ligaments and muscles) determine its ability to move freely (i.e. mobility) while remaining aligned and resisting abnormal movement under various loads (i.e. stability). Given this relationship in facilitating function, this chapter aims to quantify 'movement smoothness' within hand joint kinematic data and leverage the morphological data from the skeletal SSMs to investigate potential markers of stability.

5.2 Introduction

5.2.1 Joint Stability and Mobility

Public involvement consultations with people living with hand osteoarthritis (OA) highlighted joint instability as a major challenge associated with the musculoskeletal condition. When asked to define what joint instability meant to them, the public contributors said that is *"unpredictable, changing from day to day and throughout the day"*. From a lived experience perspective, they associated the phenomenon with 'clumsiness' and dropping items unexpectedly (e.g. when taking things out of the oven). Overall, it was likened to a significant loss of function compared to what they would consider their ordinary level.

A joint's structure and surrounding tissues determine its ability to move freely (i.e. mobility) while remaining aligned and resisting abnormal movement under various loads (i.e. stability). Maintaining joint stability requires a range of static and dynamic components. The static components of joint stability include the ligaments, joint capsule, cartilage, friction, and the bony geometry of the articulation while it is the neuromuscular control of the skeletal muscles that make up the dynamic components. [229], [230]

5.2.2 PIP Joint Anatomy

Flexion and extension of the proximal interphalangeal (PIP) joint is essential for adequate grip strength [231]. This joint is commonly described as uniaxial however the slight anatomical differences in the radial and ulnar condyles of the proximal phalanx (PP) facilitate some extent of lateral movement and rotation during flexion. These anatomic discrepancies also exist between fingers, whereby the index and middle fingers exhibit a more prominent ulnar condyle, and the ring and little fingers have a more prominent radial condyle. A combination of soft tissue structures and the articular bony geometry provide additional support and guide its motion [231]. The primary stabilizers (Figure 21) include collateral ligaments which prevent lateral deviation and the volar plate which limits hyperextension [232]. The secondary stabilizers, which facilitate motion, consist of the central slip, the lateral bands, and the flexor tendons [233]. The structural changes of a joint that may result from injury or disease can affect its function [30]. Computational methods, such as statistical shape modelling (SSM), have previously been used to identify structural indicators of joint instability in the knee [97], [98], [234] but little attention has been paid to the hand.

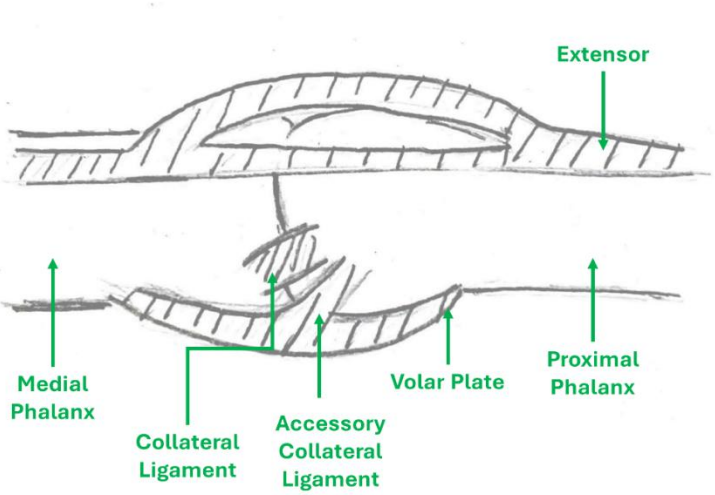

Figure 21 Anatomy of the soft-tissue stabilizers of the PIP joint.

5.2.3 Morphological and Kinematic Data Analysis

SSM has previously been applied to investigate the relationship between structure and function [90], [93], [97]. For instance, due to the limited knowledge on the effects of bone shape on knee kinematics after anterior cruciate ligament (ACL) injury and reconstruction, Lansdown *et al.* [235] investigated the relationship between bony morphology and alterations in knee kinematics after ACL injury and reconstruction. Collectively this relatively little-investigated area has shown some promise but focused heavily to date on the lower limb, with knowledge gaps in the hand and wrist.

While the contribution of *both* the musculoskeletal and neuromuscular systems to maintain stability is acknowledged, without force or electromyographic data from the available training population, this study cannot draw any conclusions regarding the dynamic components of stability. However, the existence of shape (from SSMs) and kinematic data (angle-time series data from range of motion tests) for this cohort provides the means of identifying potential markers of stability within the bony geometry of the articulation. Therefore, this study aims to quantify 'movement smoothness' within kinematic data and leverage associated morphological data from the skeletal SSMs to investigate any potential associations.

5.3 Materials and Methods

5.3.1 Public Involvement Statement

During consultations at the project design stage, public contributors identified *joint instability* as a key research priority. Additional insights gained from consulting with the surgeon who played a key role in gathering the original data, highlighted the potential of leveraging the kinematic data available. To this end, research was conducted to understand the mechanisms of joint stability and joint function. A PPI consultation approach was adopted, and additional public involvement sessions were organised to support the contributors' feedback and explore how joint instability could be investigated within the current scope of research (i.e. post-SSM). The contributors' focus seemed to be on understanding how stability impacts function, especially regarding its influences on performing activities of daily living (ADLs). Overall, the clinical and public consultations supported critical thinking and the approach to analysis, inspiring the decision to combine the morphological data generated in Chapter 4 with associated kinematic data available to further characterize the population in a joint instability context. Public contributors were offered and fully reimbursed for their time and any expenses related to this study.

5.3.2 Kinematic Datasets

As part of the same study from whose imaging data the SSMs were generated (see Chapter 4), the same ten participants performed range of motion activities which were measured using a motion capture system (12 camera Vicon T-Series). The Hand and Wrist Kinematics (HAWK) marker set and post-processing method [222] was applied to capture the resulting flexion angle at each joint over the duration of these activities. Ethical approval was granted for Secondary Data Analysis (ERGO Ref: 61718). The index finger PIP flexion time series data during the tip-to-tip range of motion tests were used for this study (Figure 22). This particular test consisted of the participant bringing the tips of the index finger and thumb together three times, resulting in a flexion-time signal with three peaks.

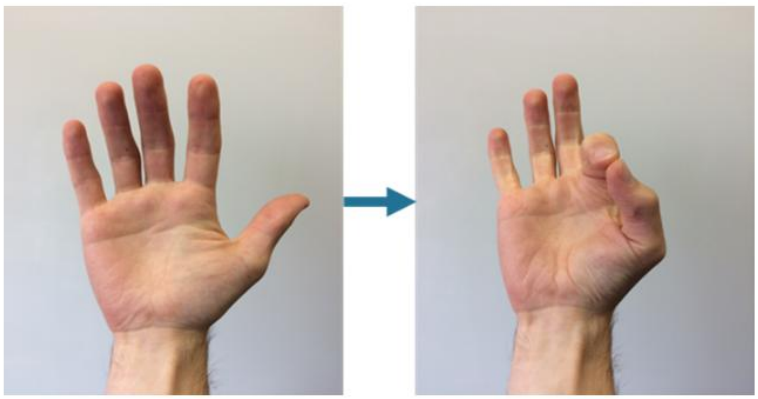

Figure 22 Static example of the tip-to-tip range of motion test (index finger to thumb) conducted during motion capture study.

5.3.3 Proposed Signal Composition

The first derivative of the flexion-time series of the tip-to-tip range of motion test was computed in MATLAB (MathWorks, Massachusetts, United States of America) to obtain the angular velocity-time signals (Figure 23).

$$\omega = \frac{d\theta}{dt}$$

where ω is angular velocity, θ is flexion and t is time.

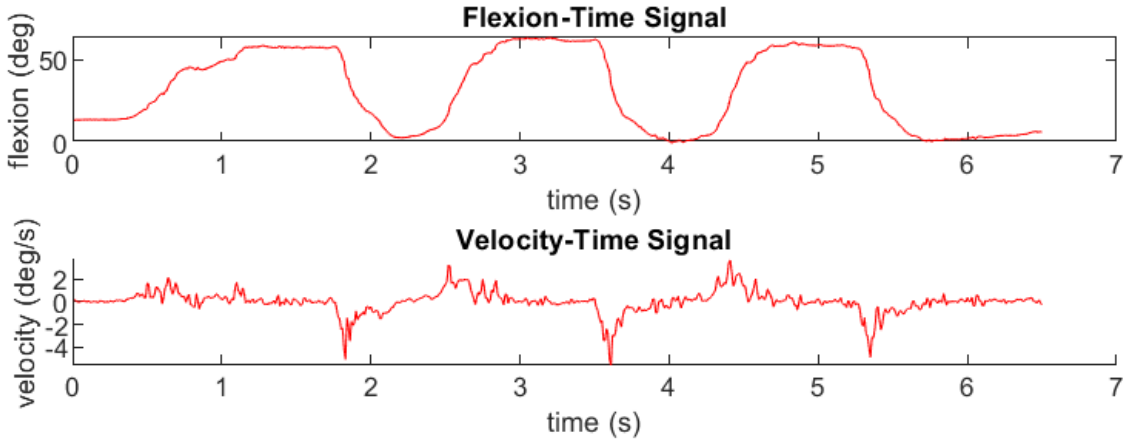

Figure 23 Original flexion-time signal (top) and derived angular velocity-time signal (bottom)

The power spectral density (PSD) of the velocity-time signals was analysed (Figure 24). The PSD is the measurement of how a signal's power, or energy, is distributed across different frequencies from 0 Hz to the Nyquist frequency (half the sampling frequency, in this case 100 Hz). The PSD graphs for each dataset can be found in Appendix C. Across all datasets, there was a high power peak at a low frequency (0-1Hz) which was hypothesized to represent

the gross movement (i.e. overall trend of the input data). The lower-power, high-frequency constituents were assumed to represent the proportion of 'conventional' background noise (i.e. associated with potential errors from marker placement, soft tissue movement and the effects of differentiation) [236].

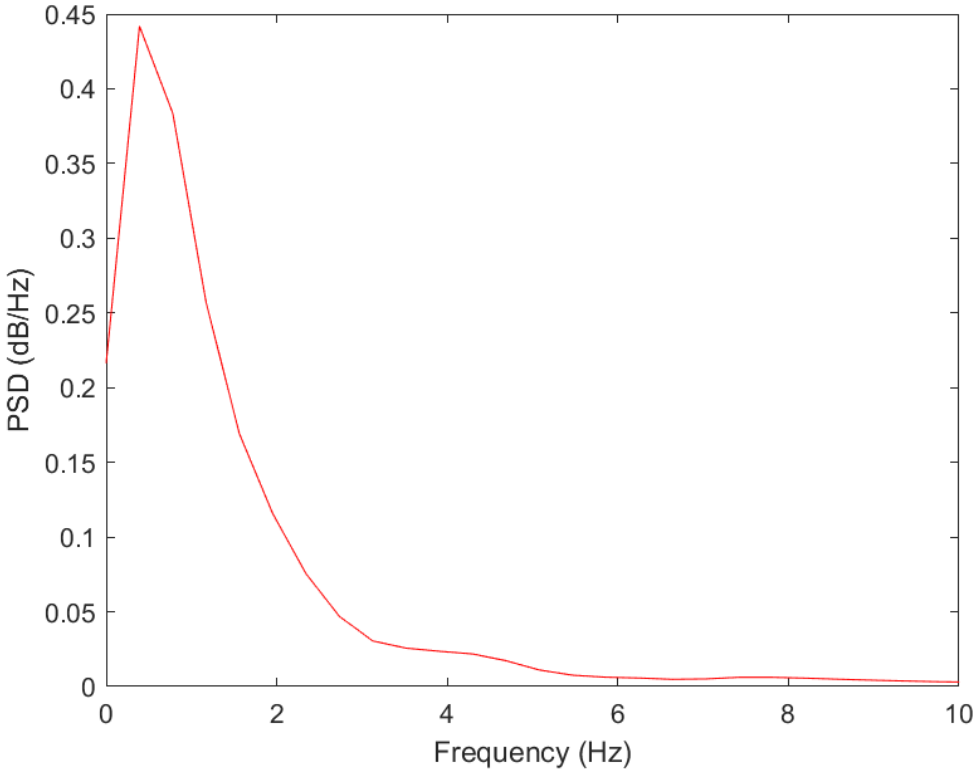

Figure 24 Power Spectral Density (PSD) of input angular velocity signal

5.3.4 Movement Smoothness

Within the present study, it is hypothesized that there exists a sub-component within the velocity-time signal, alongside the gross movement and conventional noise, that could represent the "smoothness". To this end, this study proposes quantification of the strength of what remains of the signal (i.e. smoothness) when gross movement and conventional noise are extracted using denoising and decomposition algorithms. This study refers to this quantity as the movement smoothness indicator or 'MSI'.

With regards to their development of a unified framework for the analysis of smoothness of arbitrary movements, Balasubramanian *et al*. [237] define movement smoothness as *"a quality related to the continuality or non-intermittency of a movement, independent of its amplitude and duration"* [237]. In other words, a movement is considered smooth when it occurs

continually without interruptions, while “jerky” or uneven movement are considered less smooth.

Balasubramanian *et al.* [237] regard the smoothness measure as a task-dependent function:

$$Smoothness = \lambda_s(M_m|T)$$

where M_m represents measured information given movement, M (e.g. kinematics) and T, represents a task.

5.3.5 Wavelet Transforms vs Fourier Transforms

The purpose of the signal decomposition is to extract the sub-component within the velocity-time signal that best represents the level of continuality or ‘smoothness’. While Fast Fourier Transforms (FFTs) can measure the frequency content within a stationary signal, it cannot capture the time-frequency characteristics in non-stationary signals because the method assumes sinusoidal waves which are constant over time [238]. Alternatively, time-varying sinusoidal waves, known as wavelets, are localised in both time and frequency, providing information about both high and low-frequency components at different time points [239]–[241]. This is particularly useful for biomechanical signals such as velocity-time series as they are non-stationary transients [242]. In addition, the decomposition of a signal into coefficients using wavelets is useful for feature detection as each coefficient represents different frequency bands of the signal [243]–[245]. Therefore, wavelets, rather than the conventionally employed FFTs, were used to extract the desired signal components of the velocity-time series.

There are two types of wavelet decomposition: continuous (CWT) and discrete wavelet transform (DWT). They analyse signals at different levels of detail and efficiency. The DWT employs a limited set of wavelets that are scaled and shifted versions of a single function (i.e. the mother wavelet). This facilitates multiresolution analysis, capturing both high-frequency (i.e. noise) and low-frequency information (i.e. which may reveal trends and discontinuities in the signal) [246]. The main difference between CWT and DWT is how the scale parameter is discretized. The information the CWT provides is highly redundant whereas the DWT can provide sufficient information with lower computation time [247]–[249]. Due to this, a DWT was used in this study to decompose the velocity-time signal to capture its subcomponents.

5.3.6 Signal Decomposition

5.3.6.1 Signal denoising

Before extracting the movement smoothness signal component, the noise must be removed. The MATLAB wavelet denoising function ('wdenoise') was used to denoise the velocity-time signal. The function denoises the signal using an empirical Bayesian method with a Cauchy prior:

$$s(n) = f(n) + \sigma e(n)$$

where time n is equally spaced. In the simplest model, suppose that $e(n)$ is a Gaussian white noise $N(0,1)$ and the noise level σ is equal to 1. The denoising objective is to suppress the noise part of the signal s and to recover f.

The denoising procedure occurs in three stages:

(1) Decomposition - *the sym4 wavelet is used during the five-level decomposition*

(2) Thresholding - *a posterior median threshold rule is applied for soft thresholding*

(3) Reconstruction - *wavelet reconstruction is based on the original approximation coefficients and modified detail coefficients computed during thresholding.*

A moving average (MA) filter was introduced as an alternative approach to wavelet denoising to assess the degree in which each method effectively denoised the signal. As a commonly used tool, an MA filter computes the average value of a set of samples within a predetermined window [250]. In this case, the window width was set to 10.

$$y_n = \frac{1}{M}\sum_{k=0}^{N-1} x_{n-k}$$

where x is the input signal, y is the output signal and M is the number of points used in the moving average.

The signal-to-noise ratio (SNR) was computed to compare the level of the input signal, x_i, and background noise, N.

$$SNR = 20\log_{10}\left(\frac{\sqrt{\sum|x_i|^2}}{\sqrt{\sum|N|^2}}\right)$$

5.3.6.2 Extracting the Movement Smoothness using Multi-Level Wavelet Discrete Transform

To extract the movement smoothness signal component, a five-level maximal overlap discrete wavelet transform (MODWT) was applied to decompose the *denoised* velocity-time signal into an approximation (A5) and five detail (D1-D5) coefficients (Figure 25). Inspiration for figure arrangement was taken from the following cited study [251]. The MODWT is a linear filtering process that converts a series into coefficients that reflect variations across different scales. This makes it advantageous over a standard DWT. For instance, it allows ready comparison between the original signal and its decomposition since it facilitates alignment of the wavelet coefficients at each level with the original time series [252].

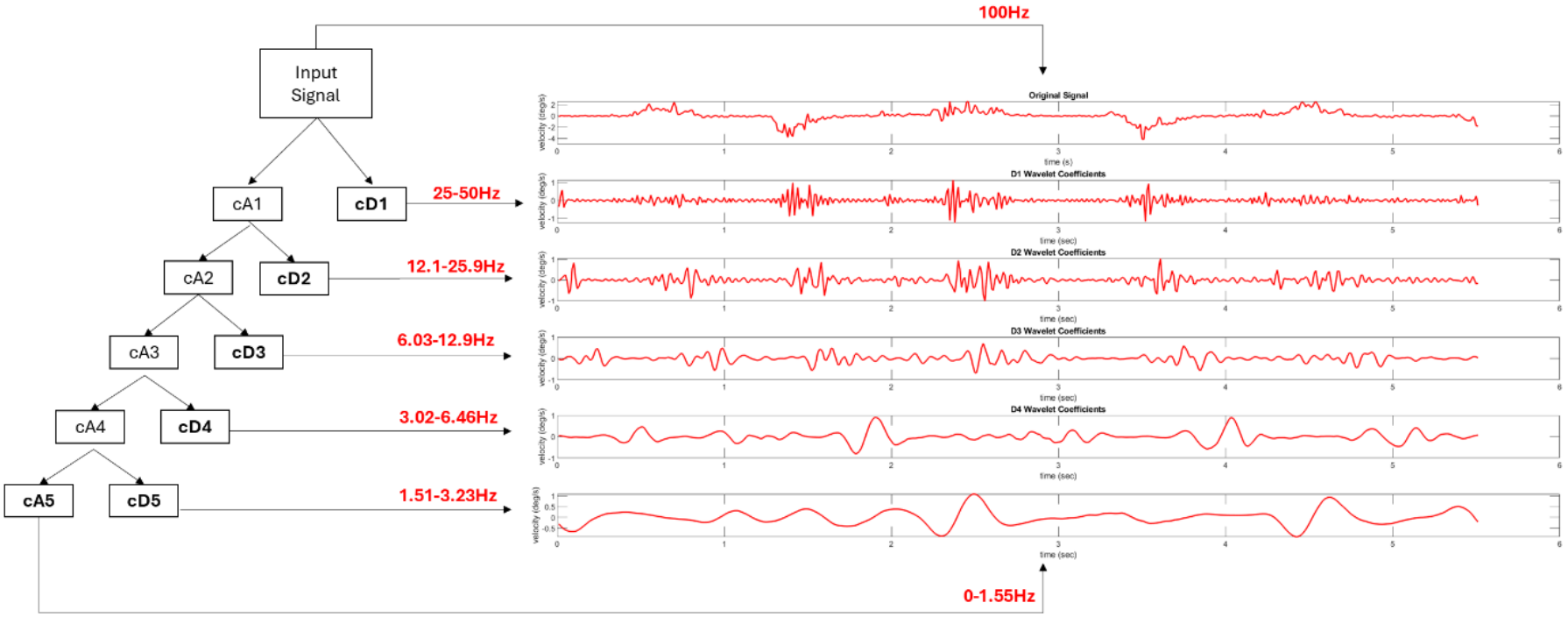

Figure 25 Multi-level wavelet decomposition diagram, where cAj represents the approximate function and cDj represents the detailed function

Decomposing an infinite sequence $\{X_t\}$ of Gaussian random variables with the MODWT up to J_0 (5 levels in this case) require the use of J_0 pairs of filters. The filtering operation at the jth level consists of applying a high-pass filter $\{\tilde{h}_{j,l}\}$ to yield a set of wavelet (or 'detailed') coefficients

$$cDj = \bar{W}_{j,t} = \sum_{l=0}^{L_{j-1}} \tilde{h}_{j,l} X_{t-l}$$

and a low-pass filter $\{\tilde{g}_{j,l}\}$ to yield a set of scaling (or 'approximation') coefficients across the time series, t [240], [252].

$$cAj = \bar{V}_{j,t} = \sum_{l=0}^{L_{j-1}} \tilde{g}_{j,l} X_{t-l}$$

With the assumption that the noise has been removed after the denoising stage, the next stage involves reconstructing the signal without, 'A5, the approximation coefficient (Table 14). The approximation coefficients commonly provide information regarding the overall trend of the input data (i.e. gross movement) and the detailed coefficients can capture subtle temporal variation (i.e. changes in the signal that can be used to quantify the movement smoothness) [251]. Therefore, the reconstructed signal (using D1-D5) is considered to represent the movement smoothness behaviour within the signal.

Table 14 Frequency range for each wavelet coefficient. Sampling frequency at 100Hz.

Coefficient	Frequency (Hz)
Level 1 (D1)	25-50
Level 2 (D2)	12.1 – 25.9
Level 3 (D3)	6.03- 12.9
Level 4 (D4)	3.02 – 6.46
Level 5 (D5)	1.51 – 3.23
Approx. (A5)	0 – 1.55

5.3.6.3 Quantifying the Movement Smoothness

In this study, the movement smoothness indicator (MSI) was defined as the ratio between the denoised signal x_{d} and the reconstructed 'movement smoothness' signal z. This quantity compares the strength of the denoised signal to the strength of the smoothness behaviour (i.e. the resultant signal once gross movement and noise has been removed).

$$MSI = 20\log_{10}\left(\frac{\sqrt{\sum|x_d|^2}}{\sqrt{\sum|z|^2}}\right)$$

5.3.7 Correlation Analysis between Principal Components and MSIs

Linear regression analysis was performed to assess the correlation between the MSI of each velocity-time series and the mode scores of the index finger SSMs. The models used excluded scale effects to focus on morphological markers rather than those relating to size. The Pearson correlation coefficient (R) was calculated to measure the strength of the relationship between these two variables. This was repeated for i) the full index finger SSM, and subset-SSMs using ii) the full proximal and medial phalanx bones and iii) truncated proximal and medial phalanx bones containing just the PIP joint metaphyses.

5.4 Results

5.4.1 Signal Processing

The wavelet-based method for denoising and decomposing the signal for the quantification of the movement smoothness was applied to all ten datasets however, three of the input datasets did not exhibit the predicted behaviour (i.e. at least three distinct cycles of the repeated tip-to-tip range of motion tests). Instead, these datasets either exhibited abnormal minima and maxima or signal artefacts, which likely occurred during data collection and cannot be corrected at this stage (Figure 26). Therefore, for the purposes of this analysis, these datasets were excluded from further correlation analysis.

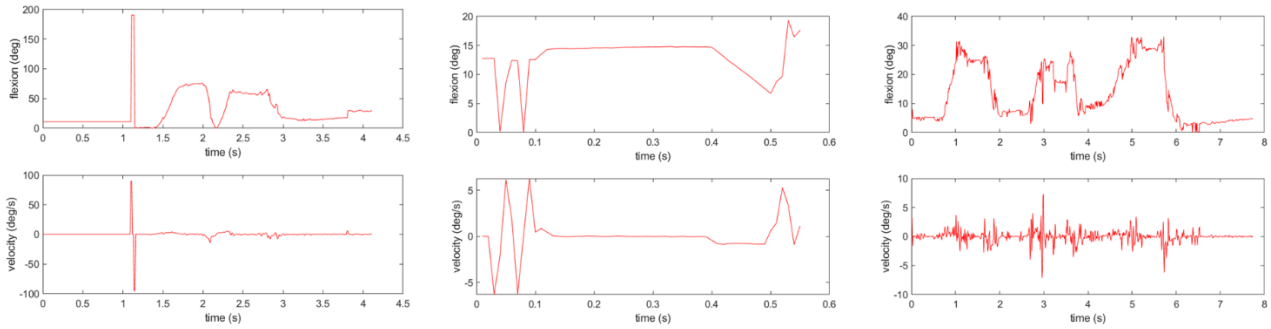

Figure 26 Unusual flexion-time signals and the resultant angular velocity-time signals omitted from further processing

5.4.2 Signal Denoising

The derived angular velocity signal was decomposed, denoised and reconstructed (Figure 27). The following figures represent those for one of the datasets however the signal denoising and decomposition results for each dataset can be found in Appendix C.

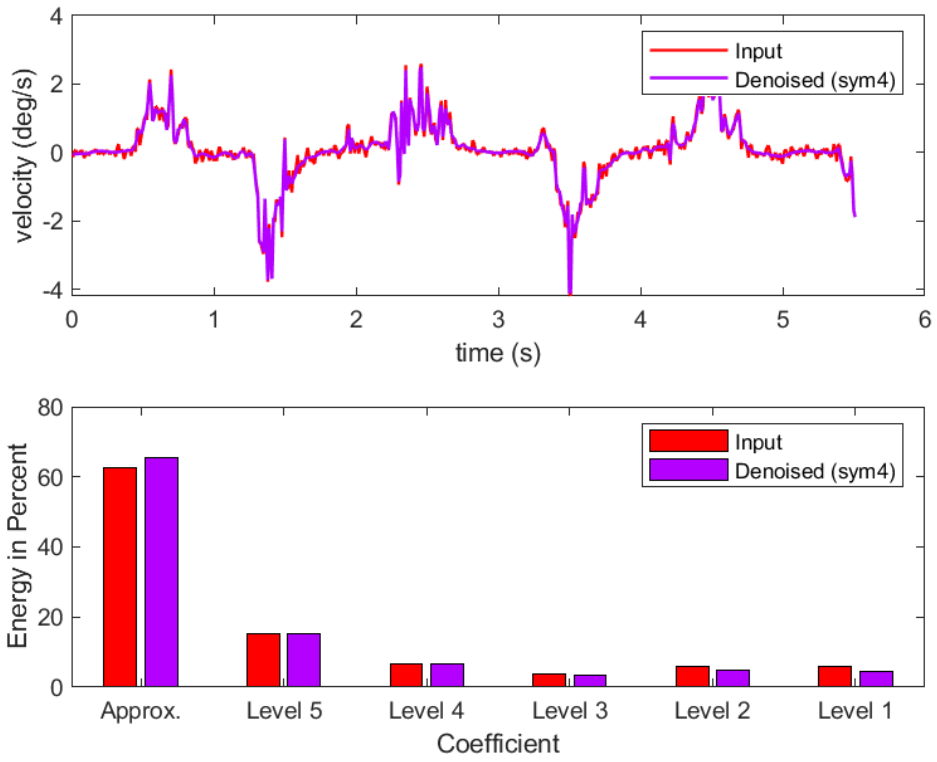

Figure 27 Comparison of the original velocity-time graph (in red) and the signal denoised using wavelets (in violet), alongside the energy distribution of wavelet coefficients for both signals before and after denoising

The effectiveness of the denoising is shown by the percentage change in the energy contained with each coefficient after denoising (Table 15). The energy contained in the high frequency components has decreased. Meanwhile, coefficients D4 and D5 saw marginal decrease and increase, respectively. However, despite the algorithm identifying and removing some of the higher-frequency components, a considerable portion, notably those hypothesized to have been magnified by the differentiation formula still remains.

Table 15 – Percentage change of coefficient energy before and after denoising using wavelets

Coefficient	Pre-Denoising	Post-Denoising	%Change
Level 1 (D1)	5.84	4.45	-31.29
Level 2 (D2)	6.07	4.80	-26.28
Level 3 (D3)	3.78	3.36	-12.67
Level 4 (D4)	6.70	6.63	-1.06
Level 5 (D5)	15.14	15.36	+1.43
Approx. (A5)	62.48	65.40	+4.48

The use of an MA filter gave rise to a smoother signal that more closely follows the pattern of the gross movement without the high noise peaks (Figure 28). In addition, as expected from denoising, the energy redistributed across the lower frequency constituents after denoising with the MA filter (Table 16). Therefore, the signal denoised with the MA filter was selected for further processing to allow a focus on characterising the smoothness of movement without the influence of substantial noise.

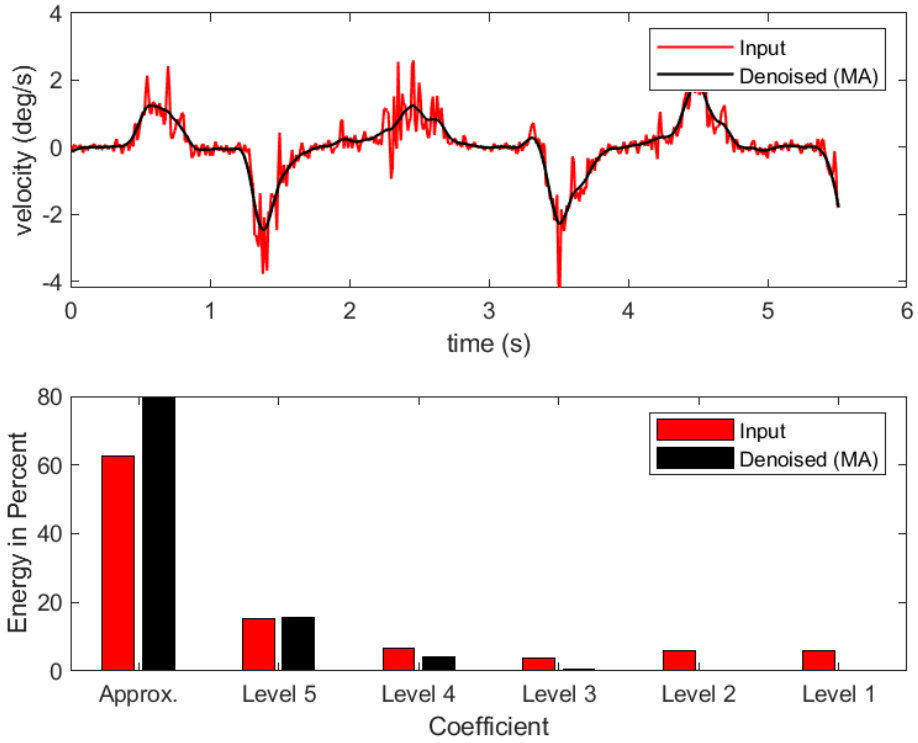

Figure 28 Comparison of the original velocity-time graph (in red) and the signal denoised using a MA filter (in black), alongside the energy distribution of wavelet coefficients for both signals before and after denoising

Table 16 – Percentage change of coefficient energy before and after denoising using the MA filter

Coefficient	Pre-Denoising	Post-Denoising	%Change
Level 1 (D1)	5.84	0.16	-97.2
Level 2 (D2)	6.07	0.24	-96.0
Level 3 (D3)	3.78	0.64	-83.0
Level 4 (D4)	6.70	3.96	-40.9
Level 5 (D5)	15.14	15.52	+2.5
Approx. (A5)	62.48	79.47	+27.2

5.4.3 Movement Smoothness Extraction and Quantification

The movement smoothness signal was extracted under the assumption that it is what remains in the signal after the noise is removed, and the gross movement ('approximation coefficient') is isolated. The complete processing workflow used to do this is presented in Figure 29.

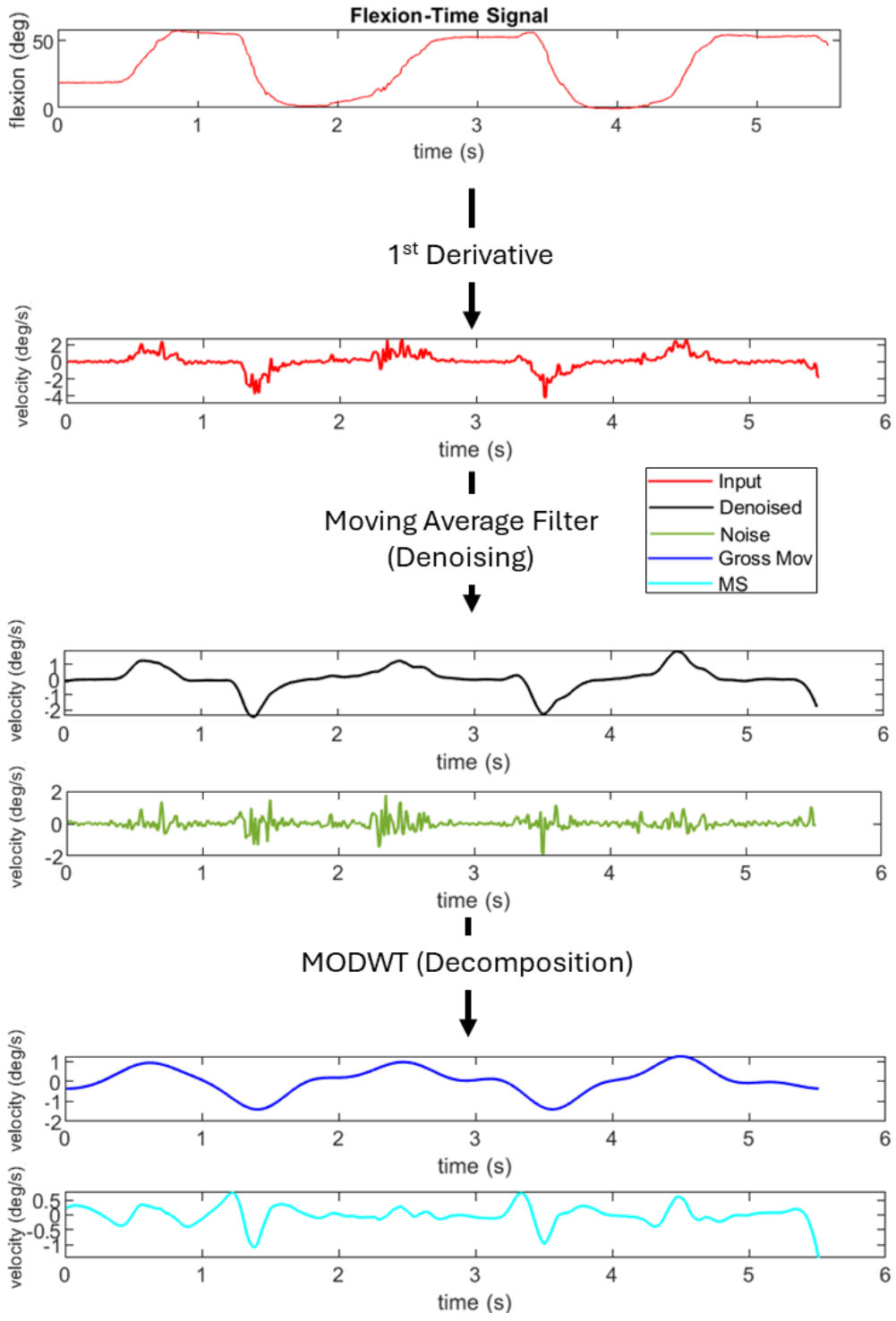

Figure 29 The signal processing workflow used to characterise the angular velocity-time signals into three main components: Gross Movement, Noise, and Movement smoothness (MS)

To localise the three signal components (i.e. noise, movement smoothness, gross movement) of the signal in the frequency domain, a PSD graph was generated (Figure 30 and Figure 31). It shows that the pipeline employed successfully decomposed the signal into the proposed constituents. The gross movement represents the high-power but low-frequency range, and the noise with low power occupies the higher frequency range, whereas the movement smoothness behaviour with slightly more power than the noise, represents the remainder of the signal.

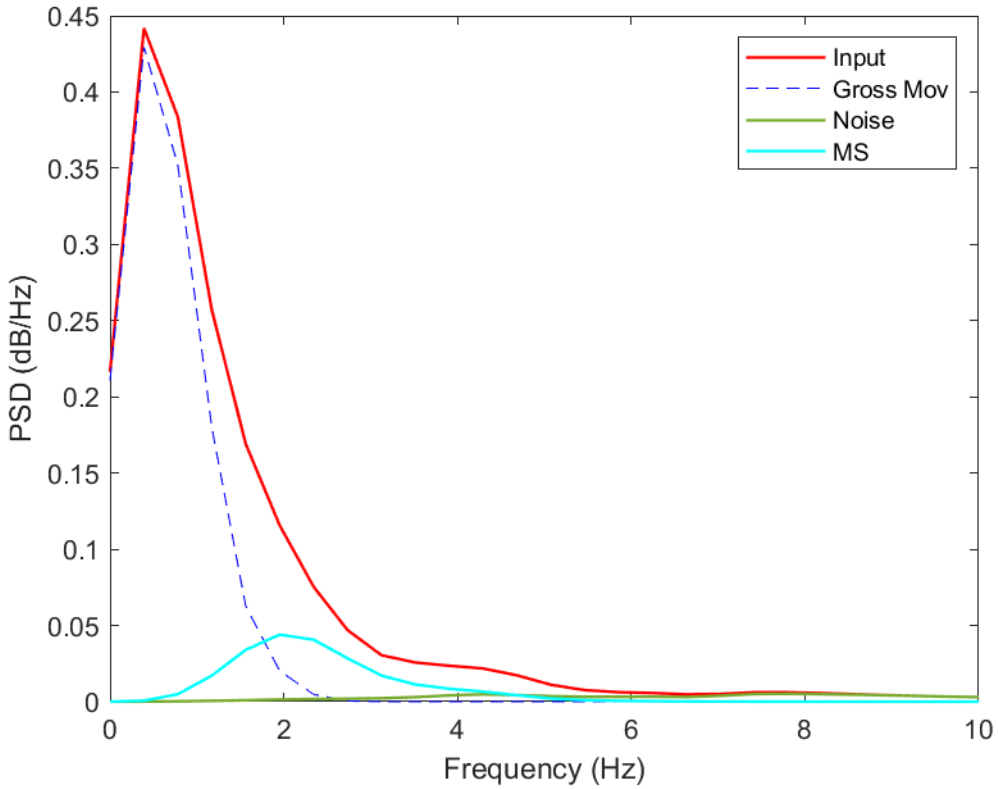

Figure 30 A PSD graph (0-10Hz) displaying the input signal and its key components – Gross Movement, Noise, and Movement Smoothness (MS)

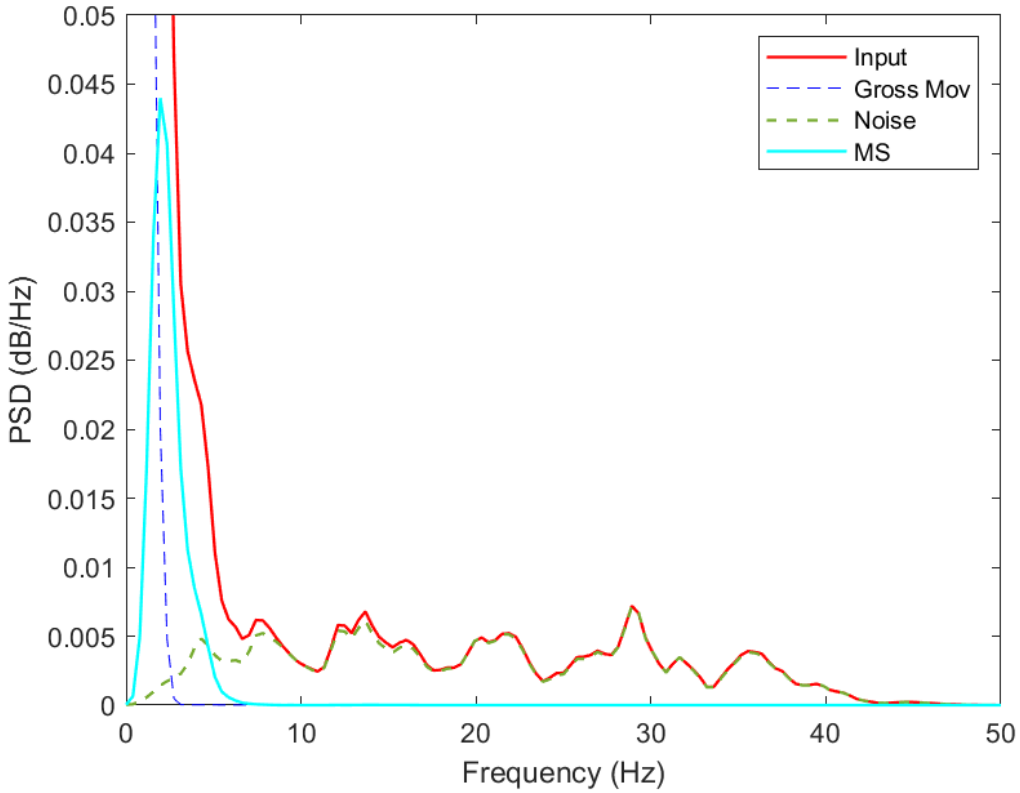

Figure 31A PSD graph (0-50Hz) displaying the input signal and its key components – Gross Movement, Noise, and Movement Smoothness (MS)

The MSI values across the cohort further justified the omission of the three datasets which exhibited significant signal artefacts. They are represented by the cluster of outliers in the scatter plot of MSI and SNR values across the cohort (Figure 32).

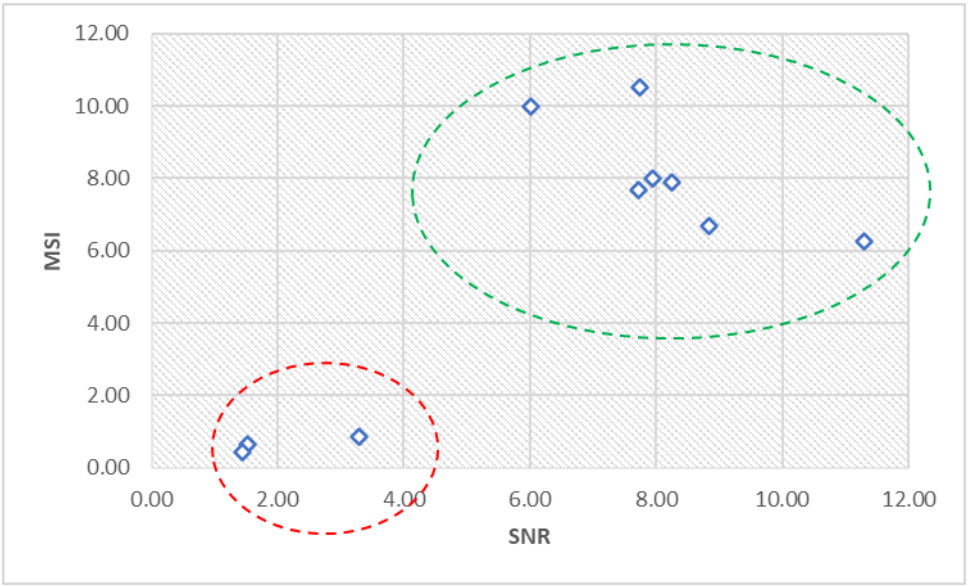

Figure 32 Scatter plot of the movement smoothness indicator (MSI) and the signal-to-noise ratio (SNR), highlighting the outliers as the three datasets excluded from further data analysis.

5.4.4 Correlation between Movement Smoothness and Bone Shape

Linear regression analysis between the MSI values and the SSMs mode scores was performed. Pearson correlation coefficient values (Table 17) for the three different levels of SSMs were generated.

Table 17 Pearson correlation coefficient (R) between MSI and shape model mode scores

SSM Mode	Pearson correlation coefficient for Full Finger model	Pearson correlation coefficient for PIP Bones model	Pearson correlation coefficient for PIP Joint model
1	0.231	-0.050	0.024
2	-0.728	-0.194	0.638
3	-0.545	0.725	0.165
4	0.099	0.007	-0.340
5	0.307	-0.579	0.304
6	0.502	0.087	-0.261
7	0.135	-0.362	-0.625
8	0.250	0.047	0.423
9	0.340	-0.288	-0.003

5.4.4.1 Full Finger model

The first model used for the correlation analysis represents the full finger model as presented in Chapter 4. In this case, the strongest correlation with the MSI values was exhibited by the score of the second principal component (PC) which represents 18% of the total variation in the model. The percentiles shape instances (Figure 33) relate to the positive and negative mode scores as shown on the scatter plot. Of this mode, it appeared joint conformity variation could be seen on lateral condyle of PP, suggesting that the 5th percentile shape is more conforming. Since this is a three-body model, it also takes in account the morphological variation of the distal phalanx (DP) and thus, the variation occurring at the distal interphalangeal (DIP) joint which is out-of-scope for this study. Therefore, another statistical shape model was generated from the MP and PP meshes to filter down the modes of variation most relevant to the PIP joint.

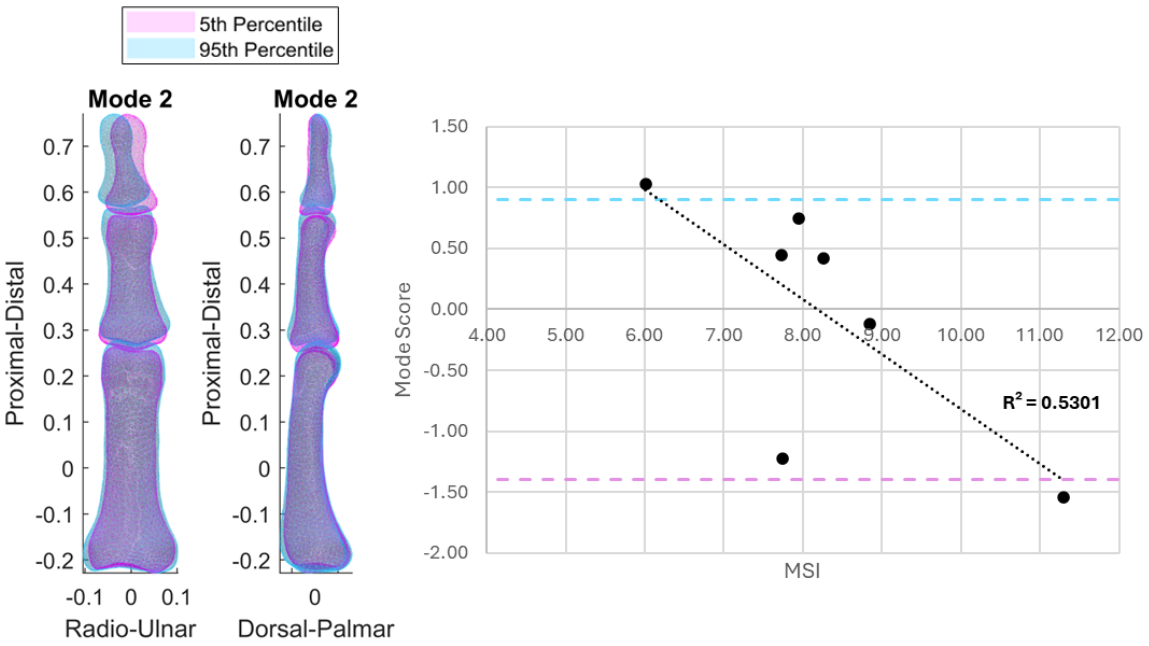

Figure 33 PC2 Visualization of 5th and 95th percentile instances of Full Finger SSMs, indicating an element of potential variation in joint conformity at the PIP joint (left) and, associated scatter plot (right), illustrating the relationship between mode scores and the MSI

5.4.4.2 PIP Bones model

The SSM pipeline in Chapter 4 was successfully applied to the ten pose corrected and size normalized MP and PP meshes to create a statistical shape model that focused more on the PIP joint. Nine PCs representing the main morphological variation were found (Figure 34). The linear regression analysis of this model's mode scores with the MSI values identified the third PC (representing 13% of the total variation) to have the strongest R-value. The visualisation of PC3 (Figure 35) appeared to also suggest variation in joint conformity between shape instances (i.e. variation at the more ulnar condyle of the PP mesh and at the more dorsal aspect of the MP mesh). The two-body SSMs regression analysis (Figure 36) successfully identified a mode score with shape variation similar to observed in section 5.4.4.1. Consequently, another model was generated ('PIP joint level' model) using the same pipeline but this time using MP and PP meshes with a significant portion of the mesh volume removed, providing an even greater focus on the PIP articular surfaces.

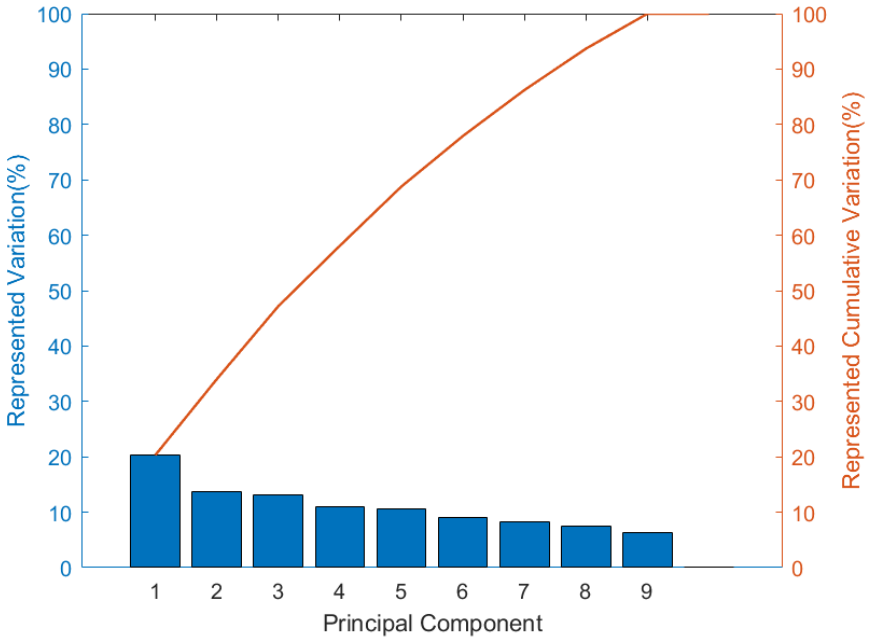

Figure 34 Variance (bar) and Cumulative Variance (line) captured by all PCs of the Index Finger PIP Bones statistical shape model

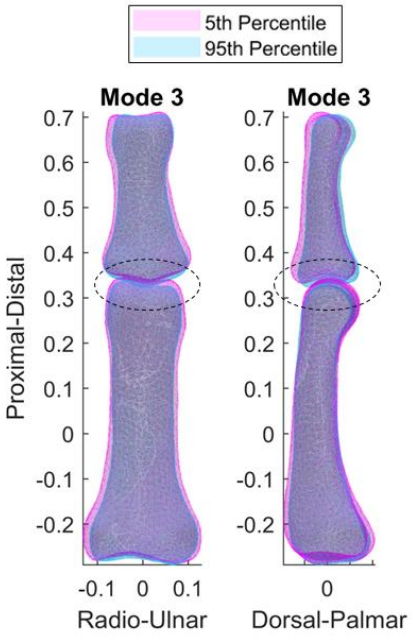

Figure 35 PC3 Visualization of 5th and 95th Percentile instances of PIP Bones statistical shape model, including an element of potential variation in joint conformity at the PIP joint

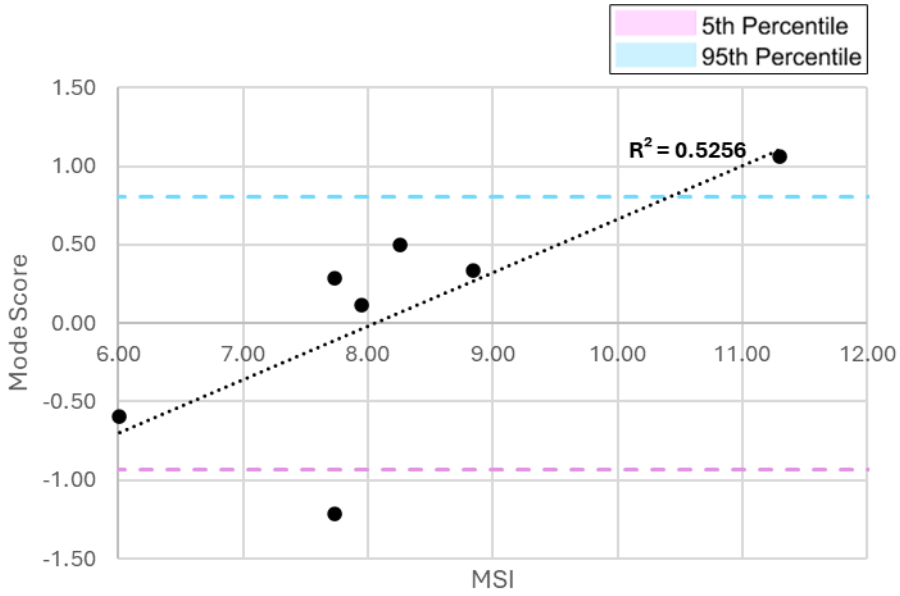

Figure 36 PIP Bones model scatter plot illustrating the relationship between PC3 mode scores and MSI, featuring the linear regression line to highlight the trend and the 5th and 95th percentile shapes mode scores

5.4.4.3 PIP Joint model

The developed SSM pipeline was also successfully applied to cropped MP and PP meshes to generate mode scores more related to the PIP joint morphology. Nine PCs representing the main morphological variation were found (Figure 37). The second PC exhibited the strongest correlation with the MSI and represented 14% of the total variation captured. Morphologically, PC2 appeared to correspond with PC3 of the PIP bones model. This variation in joint conformity can be more clearly seen in the cross-sectional image of the shape instances (Figure 38), whereby the joint surfaces in the 5th percentile shape appears to be more conforming than the 95th percentile shape. The scatter plot of this reduced model (Figure 39) exhibited similar behaviour to the scatter plots of the PIP Bones models (i.e. positive correlation). Therefore, from the relationship presented by the scatter plots and the morphological correlations found, this suggests the shapes with a more negative mode score and thus joint surfaces that are more conforming, have more erratic movement smoothness signals (i.e. lower MSI) whereas the movement smoothness signal of the more positive mode scores, which have fewer conforming joints, are smoother (i.e. higher MSI).

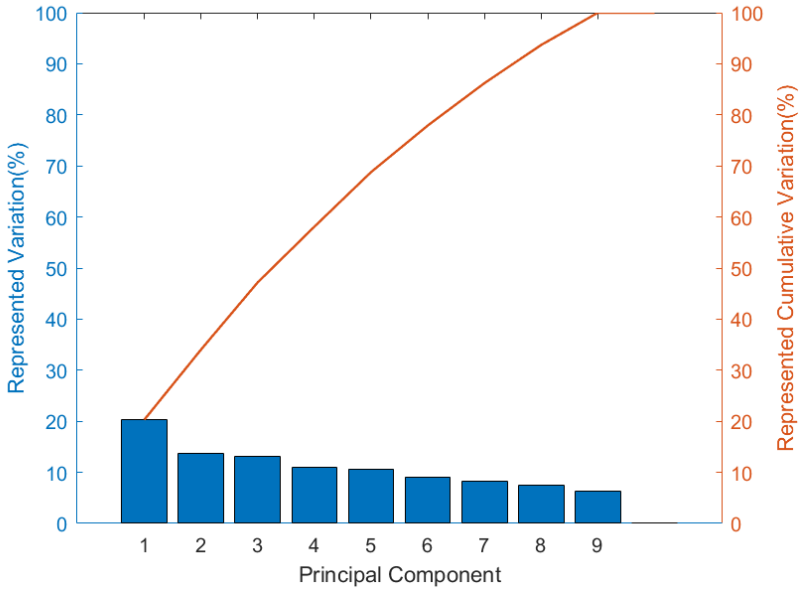

Figure 37 Variance (bar) and Cumulative Variance (line) captured by all PCs of the Index Finger PIP Joint statistical shape model

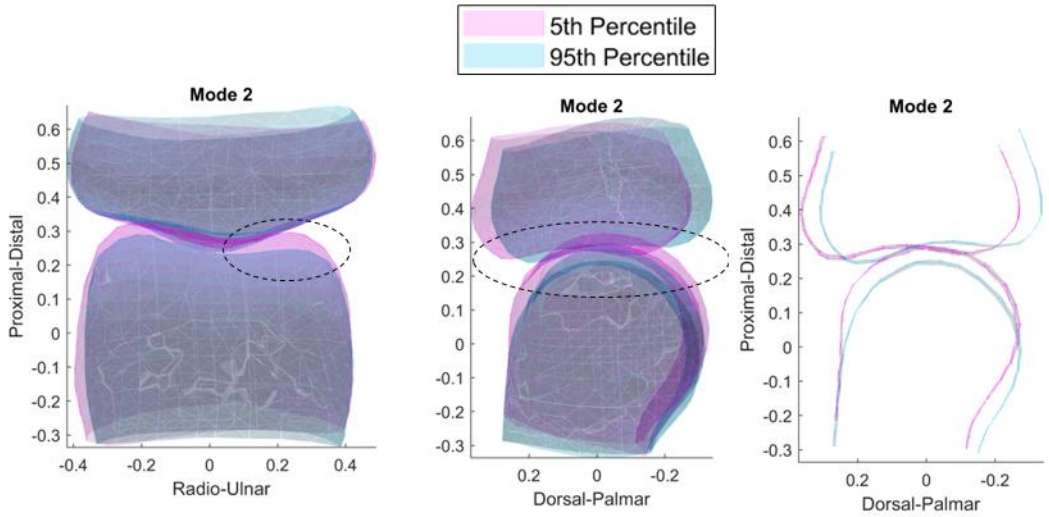

Figure 38 PC2 Full (in dorsal-palmar and radio-ulnar plane views) and cross-sectional visualization (in radio-ulnar plane view) of 5th and 95th Percentile instances of PIP Joint statistical shape model representing variation in joint conformity and relative dorsal-palmar bone positioning at the PIP joint

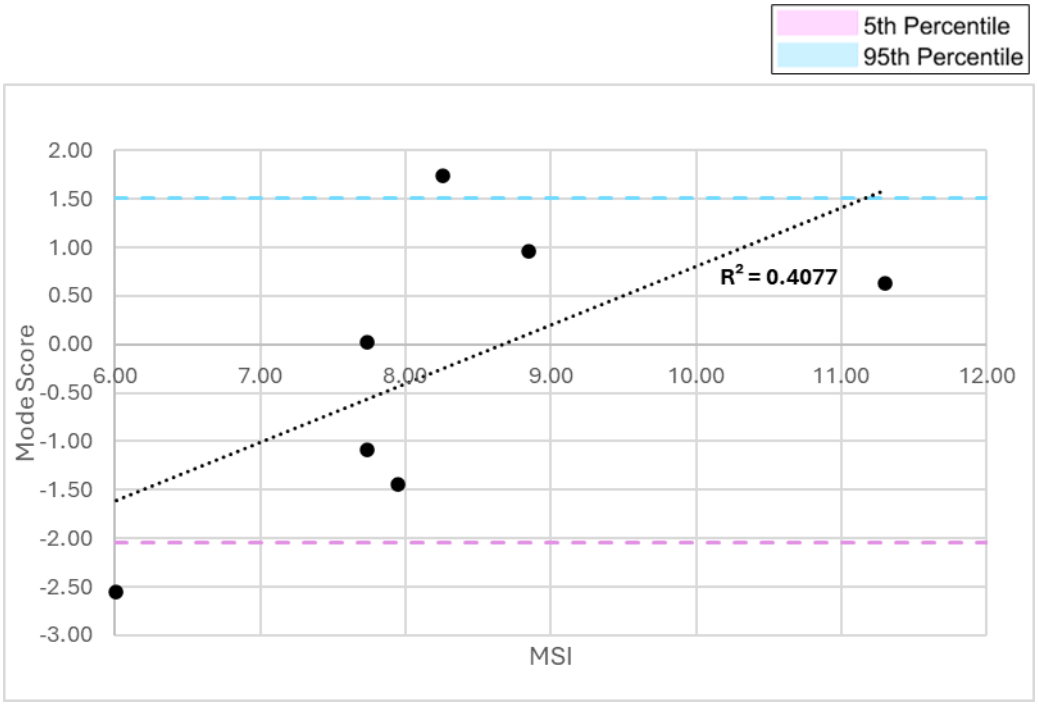

Figure 39 PIP Joint model scatter plot illustrating the relationship between PC2 mode scores and MSI, featuring the linear regression line to highlight the trend and the 5th and 95th percentile shapes mode scores

5.5 Discussion

Consultations with public contributors and insights from a surgeon, informed and governed the use of the datasets to further characterise the training population dataset under a joint stability context. In the absence of force and neuromuscular data but given the relationship between joint stability and mobility in facilitating function, this study focused on assessing the smoothness of the movement during a tip-to-tip range of motion test data to investigate potential markers of stability within the bony geometry of the articulation.

While an established method for movement analysis, marker-based motion capture has its limitations including potential errors from marker placement and soft tissue movement relative to the underlying bony structures [253]. The systematic error of the motion capture system and marker set employed to collect the data used in this study was reported by Metcalf *et al.* [4]. That study, published prior to the secondary use of the datasets, assessed the accuracy of marker-based kinematic analysis of the fingers, considering soft tissue artefacts and marker imaging uncertainty. The root-mean-square error (RSME) of the resultant soft tissue artefact displacements of the PIP joint markers was found to be 0.894mm. The correlation between HAWK (marker position) and CT (underlying anatomy) joint range of motion for PIP joints across

the whole cohort and per finger, yielded a coefficient of determination (R^2) value of 0.945 and RSME of 3.572° for the index finger. To determine the error associated with the motion capture system, the authors used markers mounted on a rigid, custom wand representing an extended finger. The results gave rise to a 95% imaging uncertainty interval smaller than ± 1° for angles in both PIP and DIP joints and less than ± 0.25 mm for segment lengths [4]. Taking these results into account, while the limitations of external marker motion analysis is acknowledged as part of the secondary kinematic analysis conducted during the present study, the assessment by Metcalf *et al.* [4] is deemed sufficient for addressing the associated systematic errors.

The wavelet-based approach applied to a denoised angular velocity-time signal successfully decomposed the signal to compute the movement smoothness indicator ('MSI') for correlation analysis with the SSMs mode scores. The MSI is not a typical smoothness metric; rather, it is a quantity assigned arbitrarily to characterise the strength of what remains of the signal (i. when gross movement and conventional noise are isolated. While there is a notable focus on assessing movement smoothness in stroke recovery conditions [254]–[256], one study evaluated the smoothness of the knee joint movement in patients with severe knee OA. In this study, Fukaya *et al.* [257] used normalized angular jerk as an indicator for walking knee joint smoothness. They found that while smoothness of joint movement decreases in the single leg supporting phase of the stance phase, this metric did not differ according to the severity of the OA. Balasubramanian *et al*. [237] state intermittency exhibited in movement smoothness assessment could be a cause of neurological impairments, lack of familiarity with the task or the environment, and/or injury to the musculoskeletal system. It must be noted that the nature of the task may cause lead to intermittent behaviour that is not related to control level but the task constraints. For instance, "healthy" datasets may exhibit sharp peaks in speed profile depending on the nature of the task [237]. Therefore, while the cause of the intermittency in the less smooth datasets presented in this study is not known, it serves as an interesting opportunity for future study to assess how similar analysis of tip-to-tip range of motion tests from an OA cohort would compare.

The computation of the MSI facilitated the correlation analysis between the training population kinematics and shape data. SSMs have been used to predict or characterize joint instability, particularly for the knee joint with limited evidence for the same done for the PIP joint [97], [98]. Cerveri *et al*. [97] used SSM of tibiofemoral bone shapes to identify modes of variation associated with knee instability and predicted potential misalignment of the patient's knee without the need to measure clinical markers. Other SSM studies have also considered the

relationship between kinematics and shape without a focus on stability, such as the study done by Lansdown *et al*. [235] whereby due to the limited knowledge of the effects of bone shape on knee kinematics after anterior cruciate ligament (ACL) injury and reconstruction, they aimed to investigate the relationship between bony morphology and alterations in knee kinematics after ACL injury and reconstruction. They found multiple bone shape features in the Kinematic MRI-segmented tibia and femurs that may be associated with abnormal kinematics after ACL injury and ACL reconstruction including, the height of the medial femoral condyle, the length of the anterior aspect of the lateral tibial plateau, the sphericity of the medial femoral condyle and tibial slope. The most comparable study is one by Fitzpatrick *et al*. [258] in which they developed SSMs of the patellofemoral joint to investigate the relationship between shape and function. Contrasting to the approach taken during this study, Fitzpatrick *et al*. computed their kinematics from a subject-specific finite element analysis rather than having kinematic data from range of motion activities.

The availability of data from the same cohort allowed a direct comparison of the kinematic data to the shape data. Size variation was excluded from the analysis which allowed a focus on joint morphology and position in relation to function. This analysis yielded joint conformity as the morphological variation with the strongest correlation with the MSI across all three SSMs used (i.e. full finger, PIP bones and PIP joint-level). This is an interesting result since the conformity of the articulating surfaces can impact the joint congruence, which can vary between individuals. As discussed by Burson-Thomas *et al.* [259] incongruence may be more ideal for joint lubrication whereby articulation is not feasible if the two surfaces are to be congruent in all positions. Within the training population used, the more congruent joint displayed a lower MSI and thus, is suggested to have performed the range of motion activities “less smoothly”. This is an aspect of the work that can be taken further to understand the relationship between joint conformity and congruence and its impact on joint function and stability.

The SSMs describe a small, homogeneous population, and assumptions cannot be made about how it represents individuals outside the training dataset. However, since variation in joint conformity was present in the SSM mode with the highest MSI correlation, it may be a marker of interest. Therefore, if trained with additional CT images the model may also be of use for investigating further the apparent associations between joint conformity, which plays a role in stabilising the joint during flexion-extension movement, and movement smoothness, which may be descriptive of joint stability.

This study advances the understanding of the relationship between PIP shape and mechanics however, at this stage, the clinical relevance is unknown. In addition, the influence of soft tissue and the impact of contact mechanics have not been investigated and thus, is proposed for future work. Given that the majority of research in this area concentrates on knee joints, this study highlights the scope for further investigation of hand joint instability.

5.6 Chapter Summary

Using wavelet denoising and decomposition, a signal sub-component was extracted from the angular velocity-time series to represent movement smoothness for the investigation of potential markers of stability within the bony geometry of the articulation. Linear regression analysis recognized SSMs modes with variation in joint conformity to have the strongest correlation with MSI values. The indicated association between joint conformity and movement smoothness is logical and should it be confirmed by further data analysis as this may provide insights into identifying individuals at risk of finger joint instability and thus inform physiotherapy and surgical interventions.

In the context of PPI influence, Chapter 4 and Chapter 5 illustrated how the data was processed in the context of *patient variability* and *joint instability* (i.e. two of the three contributor-recommended research priorities). During these studies, contributors guided the technical workflow and supported critical thinking. The next chapter dives into the efforts made to disseminate these findings and address the third and final contributor reported priority: *raising awareness of hand OA*.

Chapter 6 Raising OA and PPI Awareness amongst Public, Community and Academic Audiences

6.1 Overview

The final contributor-recommended research priority (*raising hand OA awareness)* arose from the group's unanimous belief that there was a greater gap in recognition of OA pain as experienced in the smaller hand joints, compared to the larger joints, such as the hip and knee. The strategy to address this priority differed from the others as it did not directly concern the secondary use of the hand datasets made available for biomechanical analysis. Instead, a patient and public involvement and engagement (PPIE) approach was introduced to develop material to (1) raise hand OA awareness in public spaces, (2) disseminate project outcomes and (3) increase public involvement resources and awareness amongst biomechanical engineering academics and students. This chapter presents the design and development of these materials as well as reflects on the successes and challenges of handling the competing demands of the conducting these PPIE activities while developing the biomechanical analysis outputs presented in previous chapters.

6.2 Introduction

6.2.1 Purpose

The gap in recognition of OA pain as experienced in the smaller hand joints, compared to the larger joints, such as the hip and knee, has been widely discussed in published literature. For instance, Kloppenburg *et al.* [260] highlight that although hand OA is a prevalent musculoskeletal disease with a significant impact on an individual's quality of life, the knowledge and research results in the field are limited. On the other hand, the degree of impact of hand OA and other joints has been compared in literature, such as in a review on the epidemiology and burden of OA by Litwic *et al.* [41] whereby they state that *"even though the symptoms are often less disabling than when the knee or hip joints are involved, it can still significantly interfere with hand function."* Whilst they acknowledge the significant disruption hand OA has on hand function; the comparison and the language used minimises the experiences of those whose daily lives are impacted by hand OA. In terms of the need to increase awareness, Dziedzic *et al.* [56] suggest that many people, particularly those directly impacted by hand OA, perceive that nothing can be done. In addition, there is minimal focus on the impact of hand OA on everyday function for individuals who are not awaiting joint arthroplasty and joint replacements, which are procedures only recommended for moderate to severe cases and when conservative treatments fail [58], [261]. To combat this discrepancy in the knowledge base compared to the more widely replaced osteoarthritic joints, Kloppenburg *et al.* [260] suggest that outcomes of hand OA should be explored in research but should also include the patient's perspective of disease activity, damage and functioning.

On a different note, the decisions to further develop our public-researcher partnership and focus project efforts on three contributor-recommended priorities came as a result of public involvement. As discussed throughout this thesis, the conceptual and practical barriers of integrating public involvement into research are often attributed to a lack of understanding from researchers regarding what public involvement is, how to support a diverse range of lay members and the difference between public involvement and qualitative research methods [178]. Hence, as well as the aim to raise hand OA awareness, the opportunity to increase public involvement resources and awareness of the methodology and its importance amongst biomechanical engineering academics and students, was also seized.

The approach taken to address the final research priority differed from the approaches used to acknowledge the other two priorities (i.e. patient variability and joint instability), whereby it did

not directly concern the secondary use of the hand datasets. Instead, a patient and public involvement and engagement (PPIE) approach was introduced, collaborating with the public contributors to develop material to (1) raise hand OA awareness in public spaces, (2) disseminate project outcomes and (3) increase public involvement resources and awareness amongst biomechanical engineering academics and students.

To best present the public involvement influence on the development of the various activities discussed, this chapter was written following the short-form Guidance for Reporting Involvement of Patients and the Public (GRIPP2-SF) checklist [161]. The full checklist can be found in Appendix D.

6.2.2 Terminology, Activity and Audience

The National Co-ordinating Centre for Public Engagement (NCCPE) defines Public Engagement (PE) as *"the myriad of ways in which the activity and benefits of higher education can be shared with the public"* [262]. As stated by Holmes *et al*. [124], combining PE activity with patient and public involvement (PPI) can enhance outcomes, ensuring that what is being communicated and the way it is communicated is relevant to the target communities.

The public, academics and engineering students were selected as the core target groups to interact with throughout the project. The activities (Table 18) undertaken to do so, can be organised into three different categories: (1) PE, (2) Academic Dissemination and (3) Education. All PE activities were developed in consideration of the NCCPE categories of purpose [263] (Table 19). While the 'PPI for Engineers' workshops conducted fall under the 'Education' rather than the 'PE' category, it is incorporated in this chapter to showcase the efforts made to increase public involvement resources and awareness amongst biomechanical engineering academics and students. To this end, this chapter is organised to provide a detailed insight into the design and delivery of the following activities:

- Hand OA Digital Engagement Campaign
- Exhibition and Community Events
- Conferences and Research Forums
- 'PPI for Engineers' Workshops

Table 18 Breakdown of the activities used to interact with each target group

Activity	**Category**	**Target group**	**Purpose**	**PPI Approach**
Digital Campaign (Website and social media)	PE	Public	Raise hand OA awareness, highlight PPI opportunities and share project outcomes	Co-design
Exhibitions and Community Events	PE	Public	Raise hand OA awareness, highlight PPI opportunities and share project outcomes	Collaboration
Conferences and Research Forums	Academic Dissemination	Engineering Researchers	Disseminate project outcomes, network with researchers in similar fields, increase PPI awareness	Co-delivery
'PPI for Engineers' Workshops	Education	Engineering Students	Increase PPI resources and awareness of the methodology and its importance amongst biomechanical engineering academics and students	Co-design and Co-delivery

Table 19 The NCCPE public engagement standards of purpose for PE activities conducted during the doctoral research study.

NCCPE Purpose	Approach Taken
Creating/applying knowledge together	• Co-design of digital and physical resources that raise awareness of a condition that public contributors live with. • Co-delivery and co-authorship of presentations and workshops to share project outcomes.
Responding to societal needs	• Raising hand OA awareness, sharing its impact on daily living and describing potential areas of research. • Sharing project outcomes and increasing PPI resources and awareness, particularly within the biomechanical engineering community.
Learning from others	• Learning from public contributors about hand OA and their lived experiences. • Working with contributors, students and academics to generate high-quality PE content.
Changing attitudes/behaviour	• Engaging with multiple public/community groups; increasing the university's visibility within the community and encouraging the public's involvement in research. • Highlighting the value of PPIE approach that sees researchers and the public work together, sharing power and responsibility throughout the project.

6.2.3 Public Involvement Statement

During consultations at the project design stage, public contributors highlighted the scope for *raising hand OA awareness*; a recommendation informed by the group's unanimous belief in the gap of recognition of OA pain as experience in smaller joints (i.e. hands) compared to larger joints (i.e. hips and knees). To acknowledge this, the project aimed to engage with both public and research communities to increase awareness of hand OA as well as PPI, which played a key role in the decision-making.

This stage of the research can appropriately be considered as 'dissemination'. During this stage, a collaborative approach was adopted to work with contributors to identify target audiences and produce appropriate material. The nature of their involvement can also be considered more 'active' compared to their involvement in the development of the biomechanical analysis outputs presented in previous chapters, in which their role was mainly consultative. The preferred level of involvement was discussed with contributors prior to any research activity conducted and in this case, contributors communicated that this stage of

research aligned more with their interests and expertise. That said, while they did not conduct the biomechanical analysis, they played a key role in disseminating the project outcomes. Their contributions to address the final research priority included but were not limited to sharing their experiences with collaborators and audiences, co-designing graphic material, writing digital content, disseminating research outputs at conferences and delivering PPI training to the engineering researchers and students.

As the decisions made and content created for public, research and student communities was done in collaboration with the public contributors, the collective term, PPIE can be used to best describe the strategy adopted throughout this stage of the research process. Co-delivery and co-authorship of published material was done as often as desired and possible to ensure that the everyone could speak upon their individual experiences and share their views. Public contributors were offered and fully reimbursed for their time and any expenses related to this project.

Since PPIE is inherently a collaborative endeavour, the author wishes to draw the reader's attention that the use of 'we' indicates decisions made as a team, whereas 'I' or the use of passive voice signifies the contribution and/or perspective of the project researcher.

6.3 Hand OA Digital Engagement Campaign

6.3.1 Purpose

The project team designed and launched a digital PE campaign, titled *'How Would You Handle This'* to raise hand OA awareness, highlight PPI opportunities and share project outcomes with public and community groups. This campaign included the development of a website and the launch of a social media strategy. Leveraging both types of media offered distinct yet complementary benefits for content creation and engaging with diverse audiences. While the website was the main output of the PE campaign, public contributors suggested that as well as a digital resource, a complimentary physical resource should be created for those who do not have access to a computer/Wi-Fi or prefer to consume information on paper. The final infographic was visually captivating, consistent with the website branding, easy to understand, and compelling and can be found on the published website [202].

6.3.2 People Involved

6.3.2.1.1 Target audiences

The primary audience of the digital campaign was determined as people living with hand function loss or a hand joint condition. The public contributors involved wanted people with experiences similar to their own to feel seen, learn more and potentially resonate with the published content. Nevertheless, the campaign was also marketed to anyone who wanted to learn more about hand OA or was just curious about this project and the team.

6.3.2.1.2 Partners

Our core partnerships included:

- the University of Southampton (UoS) Public Engagement with Research unit, who awarded the team £4000 (plus matched funding of £500 from the Institute of Life Science at UoS) to kickstart our PE efforts under their Development Fund Program, and,
- the APRICOT project, an EU project that aimed to develop a radically-new implant for small-joint OA, who provided additional funding to facilitate public involvement and channels to disseminate content

The project was also supported by academic members of staff who are members of existing research groups with a large PPIE influence (i.e. People Powered Prosthetics Research Group).

6.3.2.1.3 Delivery Team

All PE activities were co-designed by a multidisciplinary team. This team, led by the author, included the two permanent public contributors, three student interns who helped create the digital resources and two members of the APRICOT project.

6.3.3 Evaluation

A logic model (Figure 40) was used to develop the strategy for public and stakeholder engagement activities, along with additional teaching activities. According to the NCCPE [264], using a logic model in this way can help:

- To articulate a rationale and purpose for the activities
- To provide context for shaping what is possible to achieve

- To define success measures to highlight clear goals to aim for, help judge progress and share achievements.

An economic assessment was also conducted to ensure that the budget was followed closely to achieve both short-term and long-term goals.

Alongside the goals specified by the logic model, the outcomes of the digital and physical resources were measured by three different evaluation methodologies:

1. Monitoring increased public interest through the number of people added to our PPI network mailing list.
2. Monitoring interest by the comments left on social media, the website or verbally exchanged at festivals or during workshops.
3. Leveraging social media analytics to observe the impact of our online engagement strategies.

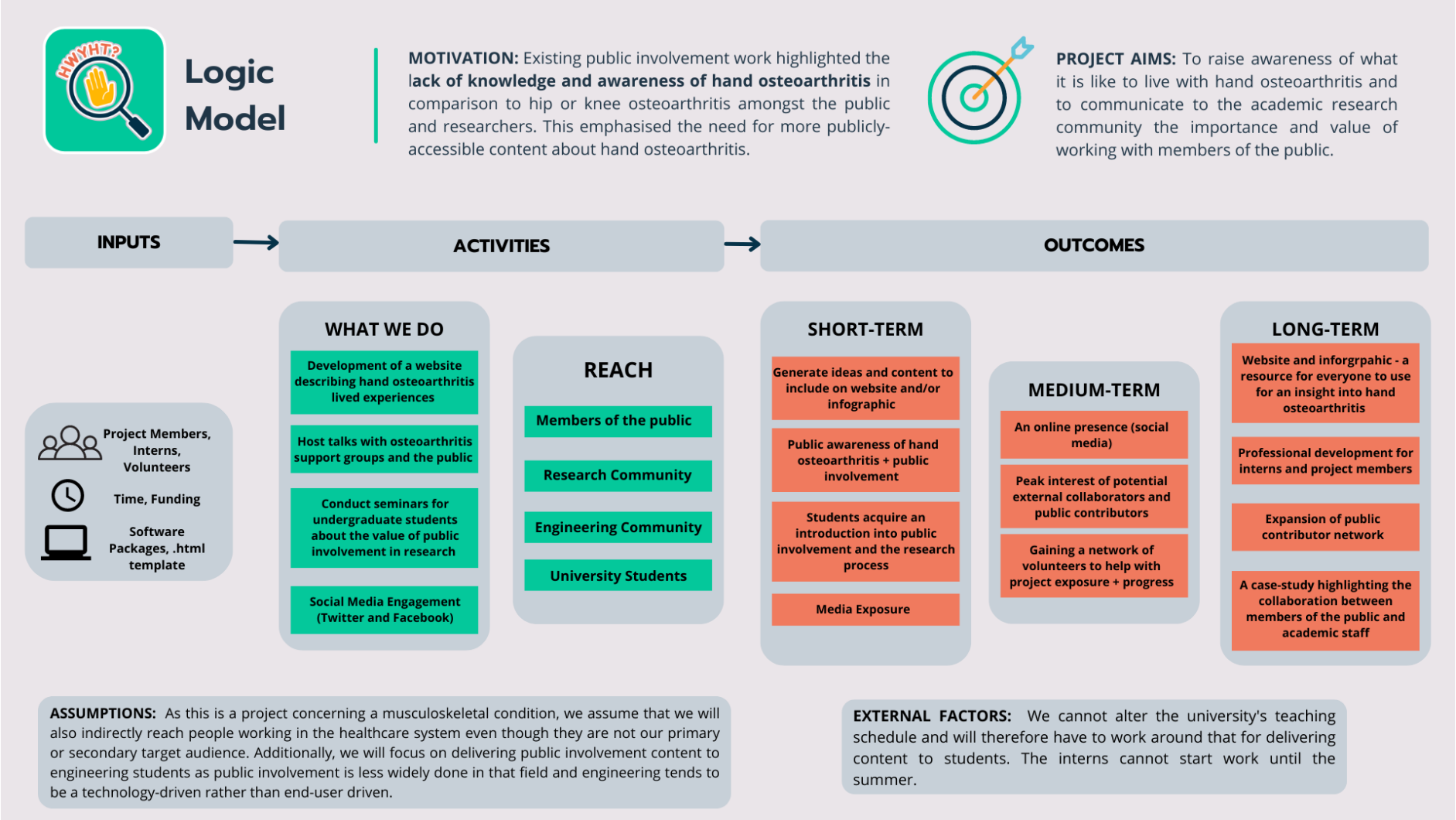

Figure 40 Logic Model used to develop Public and Stakeholder Engagement pilot strategy

6.3.4 Website Development

During the early-stage development of the website, an initial draft was generated using Hypertext Markup Language (HTML) coding (Figure 41). This initial draft was designed to summarise the key lived experience perspectives highlighted by the project's public contributors during the early-stage PPI consultations (see Chapter 3). Due to the funding acquired from APRICOT and the link to hand OA that the projects shared, this draft utilised their colour scheme/branding. In the end, the draft was crowded with text, lacked interactivity and, as the public contributors described, failed to "tell our story".

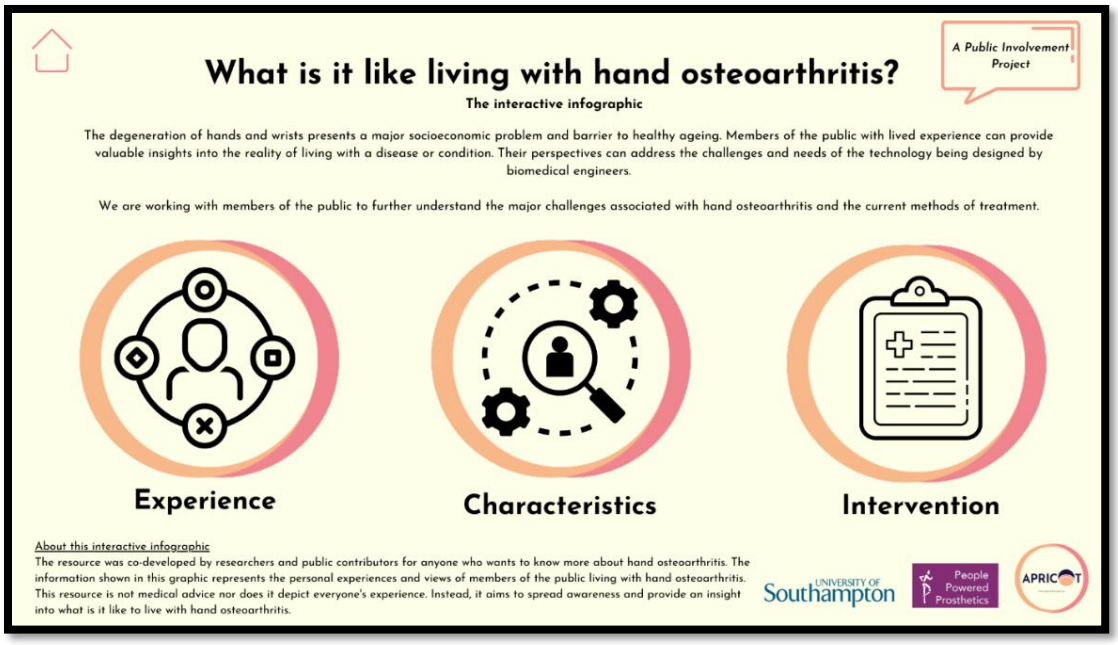

Figure 41 Front page of the initial design for interactive website

After rejecting this draft, design meetings were organised to brainstorm a new criteria for the website, which would include original branding, independent of the APRICOT project.

The updated website criteria (Figure 42) was co-created with public contributors to

- ensure that visitors to the website who can relate to the content "feel less alone," or in other words, feel acknowledged and welcomed, and;
- demonstrate to researchers that the public *"want to understand research in a way that they can use and access it,"*.

To fulfil these objectives, the delivery team included a range of expertise (i.e. contributors, researchers, graphic designers, social media managers and web developers) to create

appealing and appropriate dissemination material. Consequently, the website was designed to provide an insight into the impact of hand OA on daily living, advertise public involvement opportunities and share relevant resources.

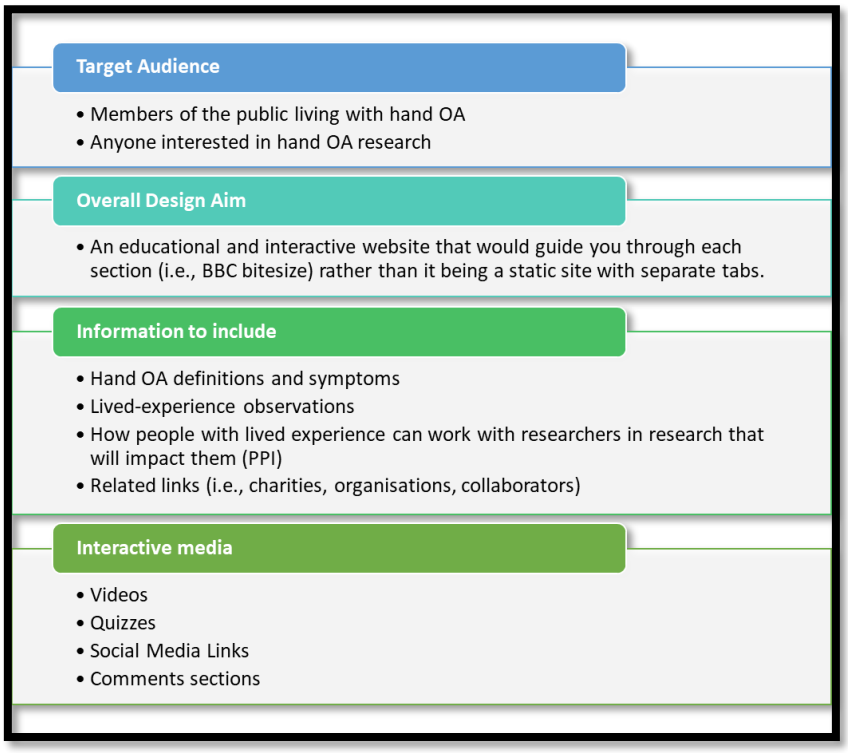

Figure 42 Website Design Criteria. PPI – Patient and Public Involvement

By leveraging existing HTML coding, the published website fulfils the outlined criteria. Since the website's domain lasts for ten years (starting from 2022), the website can be updated with additional content such as blog posts, relevant links and the outcomes/learnings from the doctoral research project, once ready.

The key features of the published website [202] include:

- Blog posts written by members of the public living with hand OA
- Blog posts written by researchers who have worked with members of the public
- Invitation to join our public involvement network
- Infographic highlighting the main factors associated with hand OA from a lived-experience perspective
- A list of resources including links to our key partners
- Quotes from project members
- Social Media Feed (and links to our Facebook, Twitter and Instagram)
- News page that includes project updates, blogs, and announcements

6.3.5 Social Media Performance

In 2022, there were 4.59 billion active social media users – this is almost double the number from 2017 which was 2.73 billion [265], [266]. Social media has become a widely used tool for dissemination amongst researchers [267]–[269], making science more accessible and relating to more people as discussed by Yammine *et al.* [270] in their commentary on how social media can be a vehicle for social change in science.

In short, social media in research has been reported to aid in:

- disseminating project outcomes to public and academic communities
- building a network of collaborators and followers
- improving and managing the project's reputation and influence

The '*How Would You Handle This?*' social media campaign aimed to direct traffic toward our website but also to expand our network and reach people beyond the University. We used Facebook, Instagram and X (formerly Twitter). At the time of use, X (formerly Twitter) had an embedded social media analytics service (Twitter Analytics[1]) which collated key performance indicators (KPIs). *Impressions*, count how many people saw the post, while *Engagement* counts measures, such as reposts, replies, clicks and other forms of tweet interaction. The *Engagement Rate* represents the percentage of people who saw the post and 'engaged' with it (i.e. reposted, shared, clicked the link etc.). In other words, it is the total engagements a post received divided by the total number of impressions on that post. Measuring impact is important because it reveals how well a social strategy is performing, how people are responding to it and ultimately how social media is having an impact on the overall brand and project outcomes [271]. Performance can be analysed using KPIs which can be quantitative or qualitative [272]. Leveraging both types of KPIs can provide insight into the scale and context of engagement.

According to Sprout Social (Chicago, Illinois, United States of America), a popular social media management and intelligence tool for various brands and agencies, the engagement rate is a metric often used in analyzing the efficacy of brand campaigns. For online campaigns, engagement leads to greater visibility, brand affinity, referrals, credibility and better relationships with users [273].

[1] Twitter Analytics has now been dissolved.

The highest form of engagement with our content was on X – where there was an engagement rate greater than approx. 5%. According to Adobe Inc. (San Jose, California, United States of America), most would consider 0.5% to be a "good" engagement rate for X, with anything above 1% "great" [274]. Our engagement rate indicates that out of the people who saw our posts, most interacted with them.

According to Twitter Analytics, the profile had 1900 impressions over the duration of the Development Fund program (July to September 2022). The top tweet occurred during National Co-production Week, gaining 876 impressions, 46 engagements and having an engagement rate of 5.3%. Whilst our other tweets do not have as many impressions, they demonstrate high engagement rates (Figure 43). For example, the tweet on the 6th of July 2022, which included hand OA facts, had an engagement rate of 22%, indicating that users were viewing the tweets but also sharing, liking or retweeting them.

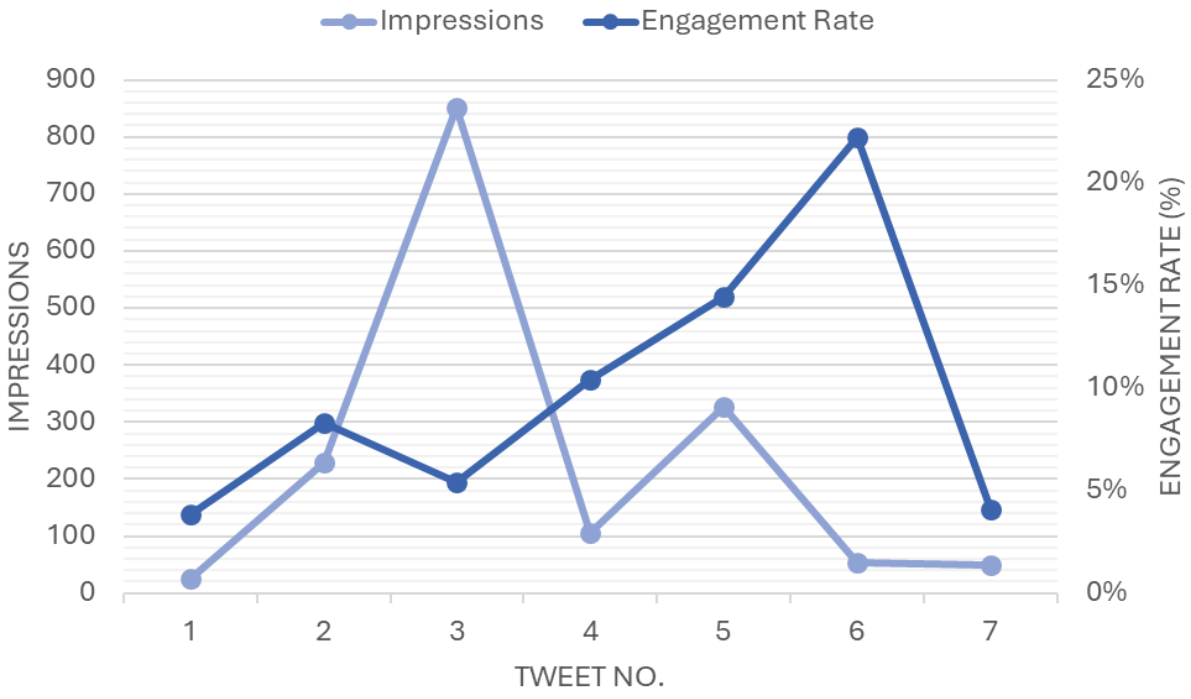

Figure 43 Impressions and Engagement Rate of HWYHT X (formerly Twitter) social media

While these efforts gave rise to a successful social media campaign, the reduction in delivery team members, completion of funding and the time and resource constraints of the doctoral research project caused our focus to shift, and thus, the social media campaign was de-prioritised. All social media activity migrated to personal or collaborator accounts (i.e. APRICOT twitter).

6.4 Exhibitions and Community Events

Additional PE efforts were made to disseminate project outcomes by attending PE, community and dissemination events (Table 20). Prioritizing interacting with public audiences from the early stages of the research process ensured the work was presented at increasing levels of completion, inviting feedback and encouraging the two-way nature of PE. It also allowed for showcasing the evolutionary nature of research, highlighting the benefits of sharing the outcomes and findings *throughout* the process, rather than solely at the project's end. With close links to the APRICOT project (i.e. funding and research topic), we also used events as an opportunity to represent both projects [275].

Table 20 List of in-person events attended throughout the project

Event	Event Description	Attendance Benefits
Science and Engineering Day (July 2022 and 2023)	Annual award-winning interdisciplinary science festival that allows everyone to explore and discover what the world of science, technology, engineering, art, and mathematics has to offer.	• A free family-friendly event taking place across University of Southampton campuses. • Public contributor network expansion • Help build scientific enquiry skills for all children.
New Forest Show (July 2022 and 2023)	An annual three-day agricultural Show was held at the end of July, attracting around 95,000 visitors over the duration.	• Engagement with members of the public from all age ranges • Discussions with people living with OA. • Public contributor network expansion • Help build scientific enquiry skills for all children.
Eastleigh Unwrapped (June 2023)	A family-friendly event, hosted in the Borough of Eastleigh, showcasing quality, hand-picked live performances and interactive activities.	• Engagement with members of the public from all age ranges • Discussions with people living with OA. • Help build scientific enquiry skills for all children. • Public contributor network expansion
Saint's Foundation Independence Day (July 2023)	A networking and drop-in advice session hosted by the Saint's Foundation to share best practices and innovations in how, as a sector, they support adults who have or are at risk of losing their independence	• Re-engage with members of the previously consulted group. • Public contributor network expansion • Disseminate project progress with the local OA community

Due to the COVID-19 pandemic, the number of large public gatherings before 2022 was limited, although once in-person events were permitted or a hybrid option was offered, we attended. These included exhibiting at science festivals and community events with attendees of all ages. This provided an opportunity to share the science behind the biomechanical analysis being conducted, raise hand OA awareness and recruit potential public contributors. Other than events attended as exhibitors, we delivered several talks, were guests on a podcast and published blog posts to depict project progress and share our PPI experiences (Table 21).

Table 21 List of external dissemination events attended throughout the project

Event Title	Description	Date Attended	Contributor's Attendance
Wessex PIN Coffee morning	Virtual coffee morning for researcher to talk to the Wessex Public Involvement Network about the research project	February 2021	No
Wessex PIN Coffee morning	Virtual coffee morning for researcher to give the Wessex Public Involvement Network a 12-month update on the project outcomes	Jan 2022	No
Working Together	Presented at a training workshop for staff, students and members of the public on participatory and co-produced research hosted by the Faculty of Medicine	July 2022	Yes
Collaboratively Speaking with UoS Podcast	Guest Speakers on podcast to discuss our public engagement efforts and the importance of involving the public in design and delivery of biomechanical engineering research	April 2023	Yes
NIHR ARC West Research Conversation	Virtual coffee morning for researcher to talk to NIHR ARC West community group about the research project and value of public involvement in the design and delivery of biomechanical engineering research.	April 2023	Yes
FortisNet Collaboration and Networking meeting	Delivered a talk at an in-person event hosted FortisNet – an interdisciplinary research network of clinical, academic and industrial partners that aims to develop products and services to transform musculoskeletal health – about the research project, giving insights on the public centred-approach taken	April 2024	Yes

6.5 Conferences and Research Forums

As a common practice in research, the project was also disseminated at conferences (Table 22). Conferences and journal papers with a PPI-focus were co-authored by public contributors with direct references to how PPI influences project outcomes.

Table 22 List of Conferences attended throughout project

Year Attended	Conference	Location	Paper
2022	International Federation of Societies for Surgery of the Hand, International Federation of Societies for Hand Therapy & Federation of European Societies for Surgery of the Hand Combined Congress	London, UK.	Presentation: The value of involving members of the public in developing bioengineering technology for hand arthritis-related research
2022	World Congress of Biomechanics	Taipei, Taiwan	Presentation: Statistical shape modelling to characterise morphological variation in the proximal interphalangeal joint
2022	World Congress of Biomechanics	Taipei, Taiwan	Presentation: Patient-reported recommendations for the biomechanical analysis of the human hand
2022	BioMedEng22	University College London, London, UK.	Workshop: The scope for integrating lived-experience insights in the design and implementation of research
2023	28th Congress of the European Society of Biomechanics	Maastricht, The Netherlands	Presentation: Open Hands: An Open-Source Statistical Finger Model
2024	BioMedEng24	Queen Mary University London, London, UK	Poster: Can potential indicators of finger joint instability be identified in statistical shape models and associated motion data?

6.6 'PPI for Engineers' Workshops

6.6.1 Purpose

Much of engineering research investigates outcomes by simplifying complex systems into manageable and measurable variables. Quantitative methods facilitate deductive approaches due to their effectiveness in analysing numerical data, testing hypotheses and establishing objective conclusions. On the other hand, qualitative research is conducted with an emphasis on contextual analysis of textual data, such as surveys, interviews, focus groups etc [23], [24]. Within engineering research and design, qualitative methods can be employed alongside quantitative methods (i.e. mixed methods approach) to explore experiences, opinions and contexts, such as user feedback analysis and observational studies [24]. As discussed by Borrego *et al.* [23], one research method is not privileged over any other. Instead, it is strongly agreed that the choice of method should be driven by the research question. Nevertheless, engineering research heavily relies on quantitative methods which is also reflected in its education. For instance, in a 2011 conference paper, engineers, Kelly and Bowe [276] questioned the absence of qualitative research within engineering education, arguing that engineering students should learn several research methods ranging from positivist quantitative approaches to more interpretive qualitative approaches.

As proposed in Chapter 1, the nature by which engineering research largely focuses on quantitative methods may serve as the following barriers for integrating public involvement approaches:

- an educational barrier; as researchers may not be aware of what public involvement requires, how it can benefit their work, how to support a diverse range of public members and the difference between public involvement and formal qualitative research; and
- a practical barrier; as quantitative methods tend to favour objectivity and replicability whereas public involvement in decision-making and research exhibits an evolutionary behaviour which cannot be predicted.

For this reason, there is scope to increase public involvement resources and awareness of the methodology and its importance amongst biomechanical engineering academics and students. Therefore, we decided to create and deliver complimentary PPI workshops targeted to biomechanical engineering students.

6.6.2 Workshop Design

6.6.2.1 Profile of your target audience

Our primary audience was biomedical engineering students at the University of Southampton (UoS). This allowed us to deliver the content locally and within a familiar framework. To this end, module leads were enquired about the opportunity for our workshops to be added to their teaching schedule. As a team, we believed it more impactful for students to be introduced to public involvement at an earlier stage of their education. This would also make it possible for them to apply it to their research projects as they progressed through the course. However, we took any opportunity to make a start. For instance, we piloted and delivered the workshop at a biomedical engineering conference - BioMedEng, the largest event for Biomedical Engineers, Medical Engineers, and Bioengineers in the UK.

Focusing on the biomedical engineering students and academics was especially important because of:

- The context of this doctoral research project;
- It is a research field that often directly impacts an individual (i.e. clinical impact); and
- Prior of 2021, there was only a single lecture given on public involvement within the mechanical engineering curriculum and it was on an optional, second semester and final-year module.

6.6.2.2 Writing learning outcomes

Using Bloom's taxonomy [277], which has been referenced in both medicine and engineering teaching guidance [278], [279], five core learning outcomes from the workshops were determined:

By the end of the workshop, students should be able to:

1. Define patient and public involvement and its principals
2. Identify the differences between public participation, engagement and involvement
3. Recognize the benefits and challenges associated with public involvement
4. Provide examples of public involvement in engineering-themed projects
5. Develop a better understanding of how to incorporate public involvement in their academic projects

6.6.2.3 Content and Activities

The content delivered (Table 23) was adapted to the module's core learning outcomes. For instance, a first-year module may focus on introductory concepts whereas a final-year module may have an emphasis on practical application. The workshops were co-authored and co-delivered by our public contributors, once again ensuring they were involved at every possible stage and at their desired level. This approach also ensured that the contributors could speak upon their individual experiences, share their views and provide the students with advice from their perspective.

The workshop content was structured to adopt a semi-active learning approach and embed relevant/relatable PPI case studies. Rooted in constructivism, active learning highlights that learning is a process of 'making meaning'. It emphasizes *how* students learn, not just *what* they learn, by encouraging them to think rather than passively receive information. It has also been cited as a learning approach within published medical and engineering education literature [280]–[282]. We achieved this approach by embedding interactive polls and word clouds into the workshop (Vevox, Auga Technologies Ltd, UK). These types of activities prompted students to evaluate their existing knowledge and explore new perspectives.

There were two main activities:

(1) Participation, Engagement or Involvement whereby students were given six PPI scenarios, and they had to vote whether it was an example of participation, engagement or involvement
(2) Word Clouds where students answered two questions at different points of the session:
    a. *What benefits might there be to involving the public/patients in research?*
    b. *What could be the challenges associated with involving members of the public in research?*

The responses to the embedded activities were anonymised (i.e. no personal data was requested or required to participate). It was also made explicitly clear to students that these were opt-in activities, and their consent was requested before collecting these responses. Ethical approval was granted to capture their responses (ERGO77117) for evaluation.

Table 23 General Plan for 'PPIE in Engineering' Workshop

Time	Section	Content/Activity
5 mins	Team Introductions and Session Outline	• Learning outcomes • Poll Question: Do you consent to your responses to all activities being used for purposes of a PhD project to demonstrate the value of public involvement in biomedical engineering? • Poll Question: Before today, had you heard of PPI?
15 – 20 mins	An introduction to public involvement	• Definition of PPI • Terminology (Participation vs Engagement vs Involvement) • Activity 1: Participation, Engagement, or Involvement?
5-10 mins	The Importance of the Public Perspective	• Word Cloud: What benefits might there be to involving the public/patients in research? • Benefits of PPI – why involve members of the public in research? • Why Public Involvement in Biomedical Engineering?
10 – 15 mins	Public Involvement in an Engineering Spaces	• Case study #1: PPI in joint simulator design • Case study #2: PhD project design • Case study#3: Electrotherapy in knee support • PPI Partner Experience
5-10 mins	Additional Considerations	• Word Cloud: What could be the challenges associated with involving members of the public in research? • Tips and Guidance on doing PPI • Ethical considerations
5 mins	Summary and Acknowledgements	• Session overview and key takeaways • Contact Details and Acknowledgements • Additional Resources

6.6.2.4 Formative Assessment Tasks

The embedded activities were used as a means of formative assessment as they were linked to the learning outcomes and emphasised the students' learning needs.

6.6.2.5 Summary

At the end of the workshop, a summary was provided, highlighting the main takeaways from the session, such as principals of PPI, the potential scope for increased PPI in biomedical

engineering, and the associated benefits. We also provided students with a list of PPI-related resources and advice on how to begin with incorporating PPI in their work. This advice was presented as workflow diagram (Figure 44).

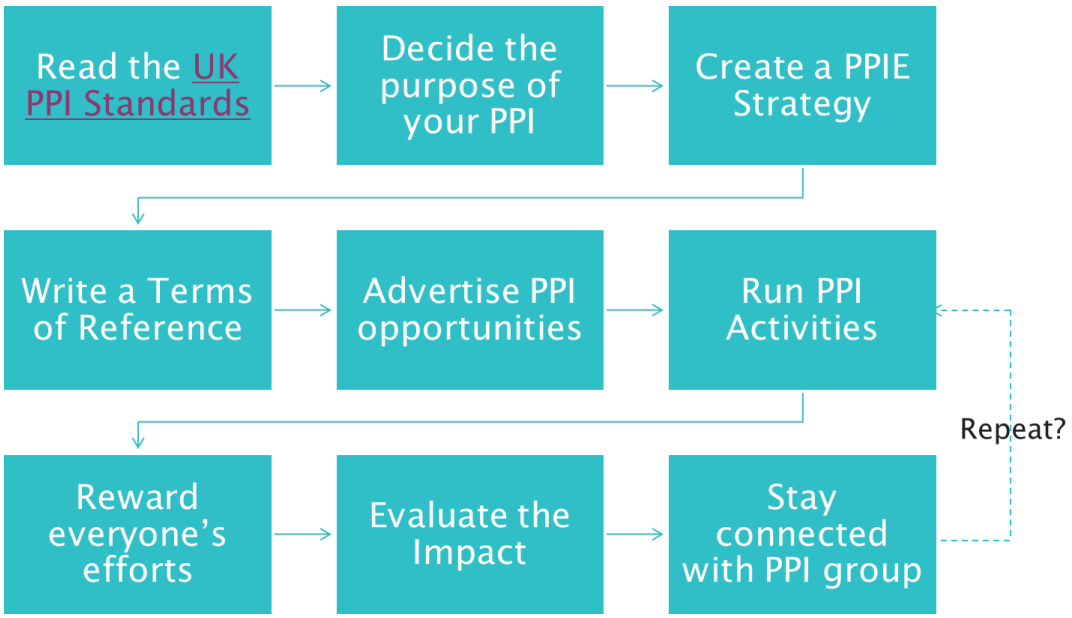

Figure 44 Recommended workflow for running PPI in a student project based on the strategy adopted in this doctoral research project which followed guidance from official PPI frameworks.

6.6.3 Delivery

A total of seven workshops were conducted over the course of the project Responses from the embedded interactive activities were collected for five out of seven workshops (Table 24), which included 48 participants. Two of the seven sessions were not teaching opportunities. Instead, they were consultations given to student seeking advice from our PPI team on their research projects. Thus, these two sessions were omitted from the following evaluation, but they have been included in the list to acknowledge the efforts made to enhance the PPI infrastructure in the UoS Mechanical Engineering department.

Table 24 List of workshops conducted between 2022 and 2024. *Attendance was based on Vevox responses

No.	Location/Year	Audience	Number of Attendees*	Data collected?
1	University of Southampton/2021	3rd and 4th year mechanical engineering students working on a biomedical engineering project	Approx. 10	No
2	BioMedEng/2022	Biomedical Engineers, Medical Engineers, and Bioengineers at the BioMedEng Conference hosted by BioMedEng Association	6	Yes
3	University of Southampton/2022	4th year mechanical engineering students working on a biomedical engineering project	5	Yes
4	University of Southampton/2023	4th year and MSc mechanical engineering students on teaching module titled 'Introduction to Biomedical Engineering'	9	Yes
5	University of Southampton/2023	1st year medical engineering students on teaching module titled 'Introduction to Biomedical Engineering'	11	Yes
6	University of Southampton/2023	4th year and MSc mechanical engineering students on teaching module titled 'Introduction to Biomedical Engineering'	17	Yes
7	University of Southampton/2024	Collaborative event between 3rd and 4th year mechanical engineering students	11 students and 5 members of the public	No

The percentage of activity participation (Table 25) explains the discrepancies between the number of responses and the total number of participants for each prompt. For instance, 17 people entered the Vevox session during workshop 6 but only 15 people answered the second poll question of Activity 2. Reasons for this include participants joining the session late,

encountering technical issues resulting in being signed out, or failing to answer the questions within the allotted time. Therefore, this must be kept in mind when reviewing the data below.

Table 25 Vevox Activity Participation Rate for each workshop

Workshop No.	%Participation
2	83%
3	100%
4	100%
5	82%
6	94%

Among the attendees who engaged in the Vevox activities, the majority revealed that they were not familiar with PPI at the beginning of the workshop (Figure 45). This further highlights, particularly for the sessions with the final year students, that PPI is introduced quite late in their education, if at all.

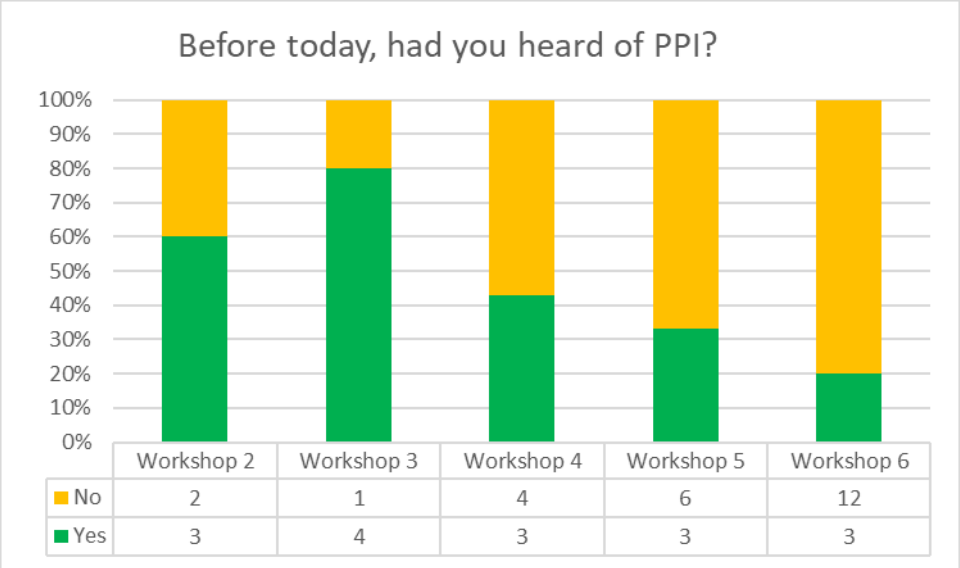

Figure 45 Vevox responses for the poll question 'Before today, had you heard of PPI?' from each workshop cohort

There was a higher proportion of correct answers than there were wrong answers overall for each cohort's responses to the *Participation, Engagement, or Involvement?* Activity (Figure 46). The cohort with the highest rate of correct answers was workshop 3, which was comprised of fourth-year biomedical engineering students working on their group design project. They

admittedly had the highest proportion of prior awareness of PPI and had decided before the session they would try to incorporate PPI into their design process. The workshop cohort with the lowest rate of correct answers was workshop 4 which consisted of a mix of Master's biomedical engineering students (e.g. MEng – an integrated 4-yr undergraduate engineering course and, MSc – a taught postgraduate course of which a degree in engineering is not a prerequisite). The sixth question, for all cohorts, seemed to be the stumbling block with students often confusing "participation" with "involvement." This may be related to how the prompt was worded but it highlighted the importance of understanding the context and nuance between qualitative data collection and public involvement. Overall, although students may have struggled with the prompt, it provided us with the opportunity to clarify the definitions and stress the importance of understanding the different ways of interacting with the public.

Figure 46 Vevox responses from the Participation, Engagement and Involvement activity for each workshop cohort

We received a diverse set of responses to the word cloud questions (Figure 47 and Figure 48). These served as a great way to capture people's understanding using their own words. The frequency of use across all cohorts is reflected by the size of the word however it must be noted that many responses were a variation of the same sentiment (i.e. 'different perspectives' and 'varying opinions'). In terms of responses associated with benefits of PPI, the attendees commonly replied with how it could provide alternative or lived-experience perspectives that are not often available. Other responses related to the improvement of research recruitment, relevance, useability and impact, all have been cited in existing PPI literature and guidance. Regarding the perceived challenges, attendees responded with barriers such as cost, maintaining privacy, avoiding bias and ethical implications but the most common answer was "finding people" to be involved.

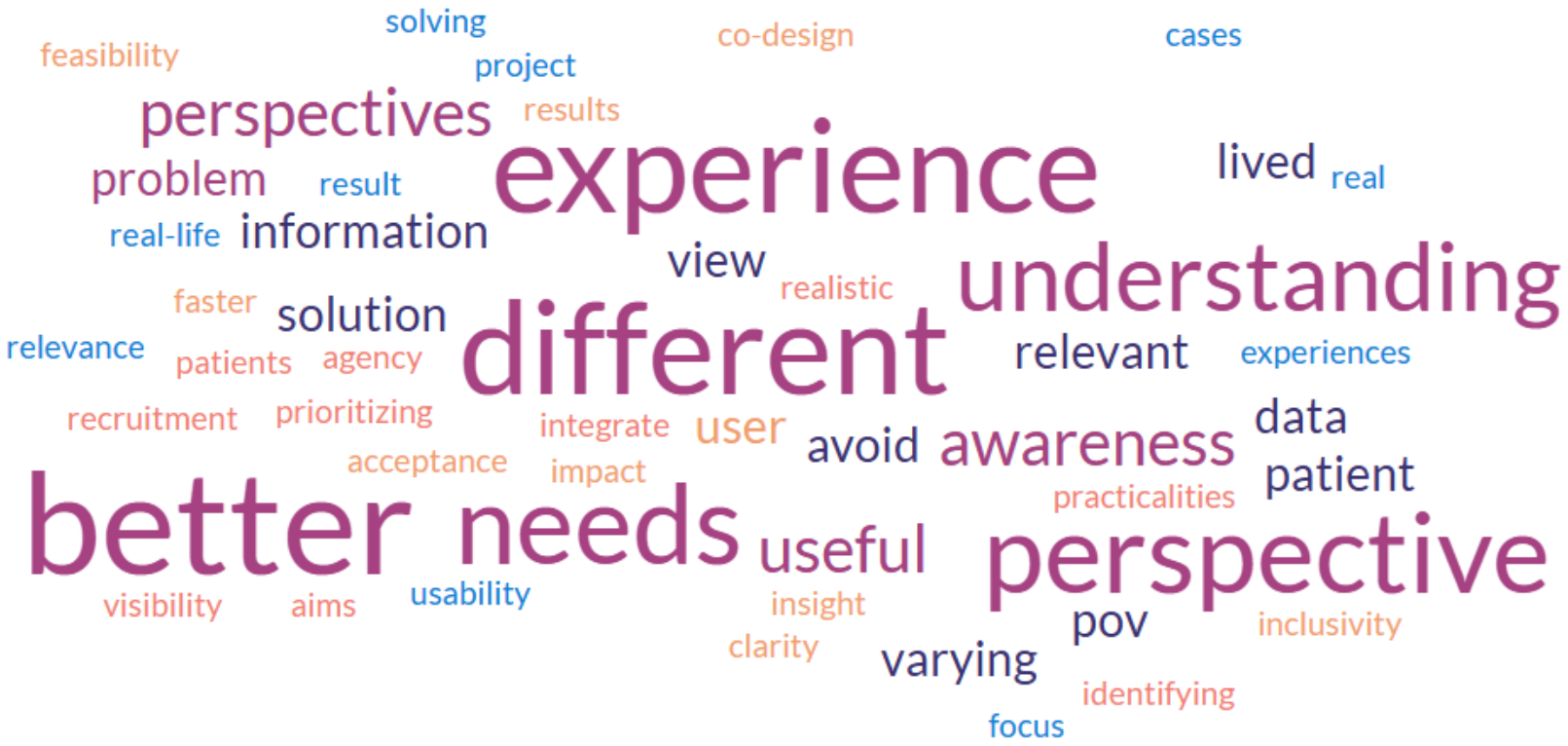

Figure 47 Vevox Word Cloud Responses for the prompt: What benefits might there be to involving the public/patients in research?

Figure 48 Vevox Word Cloud Responses for the prompt: What benefits might there be to involving the public/patients in biomedical engineering research?

6.7 Discussion and Reflection

This chapter presented the dissemination activities developed to (1) raise hand OA awareness in public spaces, (2) disseminate project outcomes and (3) increase public involvement resources and awareness amongst biomechanical engineering academics and students. Developing multiple activities for different target groups, while challenging to manage at times, was an interesting opportunity for collaboration and co-delivery. The overall impact of undertaking these activities (Figure 49) can be categorised into five main groups: awareness, engagement, education, professional development and future research. These align with what was projected as success measures in the Logic Model presented in section 6.3.3.

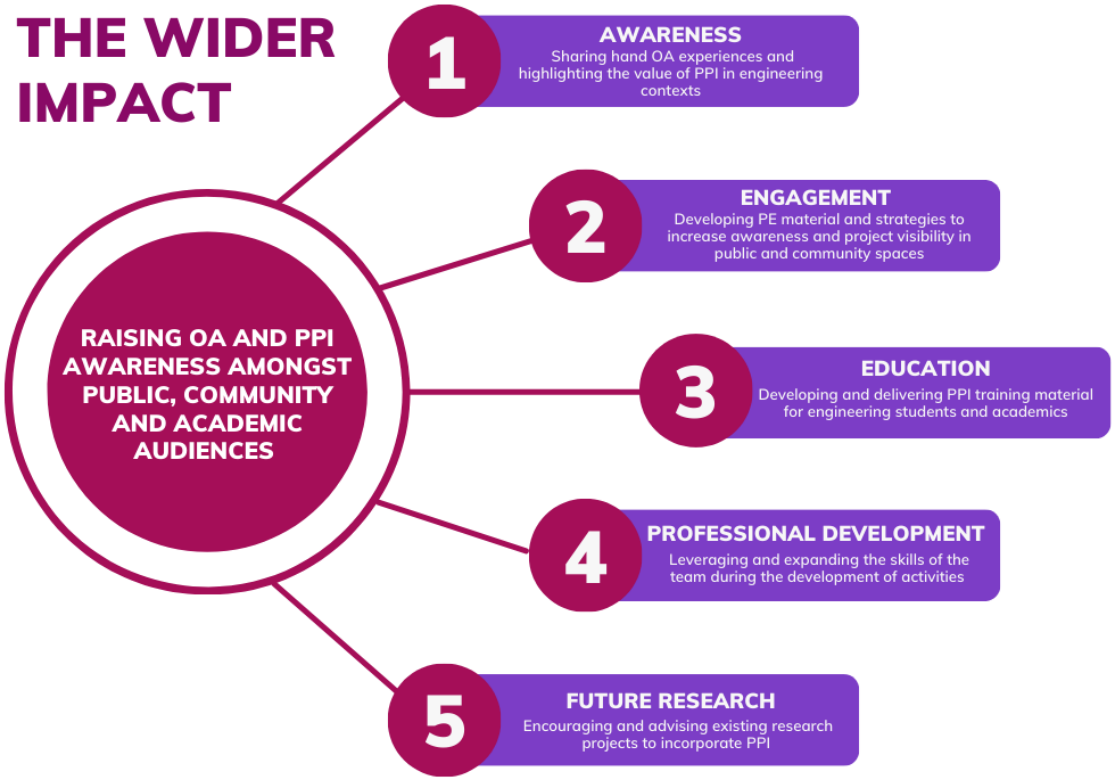

Figure 49 Wider impact of PPIE activities developed to raise awareness of hand OA and the value of PPI in engineering spaces.

There has been a growing commitment to PE in research [283]–[285] as it plays a core role in understanding the impact and future of research. Professor Alan Thrope, who in 2010 was chair of the Research Councils UK, believed that "*public engagement should be a part of every skilled researcher's portfolio*" [286]. PE has also been described as a way to develop mutually supportive relationships between research and society as it can create opportunities for the public to discuss, create and be involved in research [285]. In a research article, Tran Dong Thai

et al. [287] explored the views and needs of local researchers in Southeast Asia with regard to practising PE. From these surveys, they found that while researchers acknowledge PE as an important practice, they attribute the main barriers to facilitating PE to be time, personal perceptions, lack of capacity and lack of support. Thus, Tran Dong Thai *et al.* suggest that training, opportunities to conduct PE and, diverse communication methods to suit researchers' personal styles should be made available to encourage PE [287]. Fortunately, the UoS's dedicated PE team hosts several training sessions and support throughout the year for researchers. For instance, it was PERu's Development Fund that facilitated the piloting of our engagement activities, providing funding and exhibiting opportunities.

The educational material developed allowed for an insight into the understanding and dedication of public involvement within an engineering cohort. Again, while the number of attendees could be larger, it produced a training resource that can be used after the project's completion. The impact of these efforts are particularly evident from the growing number of student projects that have incorporated public involvement since we began delivering the workshops, notably an official second-year group design project ('Wearable MedTech') in which meeting with patients is a key part of the students' design process.

Since research is not a cyclic process – rather parallel with multiple different tasks happening at the same time – it is important to mention the limitations posed on the data capture and evaluation of the PE activities. With these activities being developed alongside the biomechanical analysis efforts, the time and resources required to facilitate the PE activities did not always align with those available. Therefore, while the data capture is limited, it is considered as a byproduct of handling the competing demands of the doctoral research project. For instance, the capacity of a doctoral research student differs from a research group with several members of the team dedicated to PE. To this end, it is recommended to scale PE activities according to the project's capacity to ensure enough time is given to fully assess its impact. Nevertheless, while it was a significant work load to juggle, the experience fostered a stronger dedication toward PPIE.

The primary goal of PE is to share findings or concepts with the general public; however, its two-way learning approach means that it still plays a significant role in generating new ideas and bringing in fresh perspectives that might not emerge from solely interacting with the academic community. To this end, working with people with similar experiences to those intended to be engaged can enhance dissemination material and improve research impact. The combination of PPI and PE has been widely discussed in published literature. For instance, Holmes *et al.* [124]

explored the potential benefits of combining the two approaches in their Manchester University NHS Trust organisation. They propose a cycle of practice that can be both research-led, which involves responding to the demands of the research sector to engage/involve the public, and community-led (or demand-led) ,which concerns listening and responding to the public's expectations and thoughts about health-related research. [124]

Due to the occupational skills required (i.e. experimentation, modelling, manufacturing etc.), there may be a stage of quantitative-based research projects that will be completed without the public's contribution. To manage expectations, ensure transparency and facilitate meaningful PPI opportunities, it is important to discuss with contributors: (1) the types of research activities being conducted, (2) the roles and intended purpose of PPI, and (3) contributor's preferred level of involvement. For instance, as outlined in the Terms of Reference, contributors took on an advisory role during the biomechanical analysis stages of the research cycle, trusting my abilities to conduct the work with their considerations in mind but not hesitating to ask questions and provide feedback during meetings. That said, while they did not conduct the biomechanical analysis, they played a key role in supporting critical thinking, informing technical workflow and disseminating its outcomes. Despite the constraints posed by leveraging biomechanical data collected prior to the project's start, introducing PE into the project provided additional collaborative and co-productive opportunities. Contributors also communicated that these opportunities aligned more with their interests and expertise. Working with our contributors to develop PE material and deliver educational workshops also helped to drive our message about the value of PPI partnerships and aligns well with the recommendation by Jackson *et al.* [178] about having contributors copresent results at conferences, engage with the wider public and co-appear in other dissemination media as a method of power-sharing and avoiding tokenistic box-ticking exercises.

6.8 Chapter Summary

Educational and dissemination materials for both public and academic audiences were developed to raise hand OA and PPI awareness and share project outcomes. While PPI and PE isn't mandatory within engineering educational spaces, this chapters highlights the efforts made to engage a wide range of people *throughout* the research process. This approach allowed progress to be shared at increasing levels of completion, inviting feedback and encouraging two-way nature of PPIE. The subsequent chapter aims to reflect on the overall process of integrating long-term PPI into a biomechanical-engineering-themed doctoral research project.

Chapter 7 A Critical Reflection of the Research Approach

7.1 Overview

This doctoral research project was conceptualised to leverage an existing dataset of finger kinematics, including computed tomography (CT) and magnetic resonance (MR) imaging of ten consenting participants, free from hand or wrist disease or injury [4]. It had not been decided by those who collected the datasets how they would be used (i.e. type of model, user and accessibility). Suggestions such as evaluating treatment options and rehabilitation strategies were proposed by academic members of the interdisciplinary research team, however, a public perspective was absent. Furthermore, preliminary patient and public involvement (PPI) activities highlighted the limited incorporation of the public perspective in biomechanical engineering, despite PPI becoming increasingly present in other research fields. To address the proposed educational and practical barriers associated with integrating PPI in engineering research, this project adopted an experiential approach by embedding public involvement throughout the research process.

Chapters 4 – 6 presented the actions taken to acknowledge the contributor-recommended research priorities identified at the project's early stages (see Chapter 3). These research priorities governed the decision-making process, informing the project's design, development and dissemination. As a result, this chapter aims to (1) reflect on the overall research process, exploring the associated PPI impacts, outcomes and limitations and, (2) share a set of guiding values for integrating PPI in research based on the lessons learned from this experience.

A portion of the content in this chapter has been published as:

T. A. Munyebvu, G. Lillywhite, N. May, C.B. Burson-Thomas, C. McGrath, C.D. Metcalf, M. Browne, & A. S. Dickinson. "How would you handle this?" The impact of embedding early patient and public involvement in a biomechanical computational engineering doctoral research project, Research Involvement and Engagement., doi: https://doi.org/10.1186/s40900-025-00694-3

7.2 Introduction

There has been increased recognition for including PPI in the research process by major healthcare research bodies such as the National Institute for Health and Care Research (NIHR) and Health Research Authority (HRA) [15], [142], [288]. Several funding bodies also acknowledge the importance of PPI in research, requiring evidence of PPI in grant applications [289], [290]. For instance, Health Data Research (HDR) UK's funding call requires proposals to demonstrate that patient and public involvement and engagement (PPIE) is an integral part of the proposed work. To aid researchers, HDR UK supply guidance on how to embed PPI in research funding applications [291]. While the benefits and significance of PPI has been advocated for in healthcare research, the variability and diversity of PPI evidence can make it difficult to generalise the evidence base onto a specific case [292] .

The specific barriers associated with integrating PPI in doctoral research has been discussed in literature to include: limited PPI experience, strict time and financial constraints, predetermined research projects with limited potential for PPI influence, dependence on supervisor's PPI experience, access to training, and the ability to engage with patients or the public with relevant expertise [191], [293], [294]. Smith *et al.* [295] highlight that despite the barriers, there are several papers which report on PPI in doctoral research [17], [163], [293], [296]–[299] however, they are limited, especially those discussing how to operationalise PPI effectively.

The aforementioned barriers on incorporating PPI in doctoral research pose an even greater challenge in research fields with a limited PPI infrastructure. To this end, this thesis proposed two additional barriers for integrating PPI that apply to fields such as engineering which largely focuses on quantitative methods. These include:

- an educational barrier; as researchers may not be aware of what public involvement requires, how it can benefit their work, how to support a diverse range of public members and the difference between public involvement and formal qualitative research; and
- a practical barrier; as quantitative methods tend to favour objectivity and replicability whereas public involvement in decision-making and research exhibits an evolutionary behaviour which cannot be predicted.

To address the educational and practical barriers associated with integrating public involvement in engineering research, this thesis adopted an experiential approach and embedded public involvement throughout the research process. This chapter aims to (1) reflect on the overall research process, exploring the associated PPI impacts, outcomes and limitations and, (2) share a set of guiding values for integrating PPI in research based on the lessons learned from this experience.

7.3 Approach Design

As there has been a heavy emphasis on the research *process*, critical reflection was selected as the most appropriate method to report the PPI included in this project. Critical reflection works to examine practice, challenge assumptions, consider context and generate new knowledge from experience. It has been used in a range of fields, including nursing, social care and education, to foster learning and improve policy [300]–[303]. As a result, this chapter was written to loosely follow the long-form Guidance for Reporting Involvement of Patients and the Public (GRIPP2-LF) checklist. This checklist was developed by Staniszewska *et al.* [161] to improve the quality, transparency and consistency of PPI reporting. A full checklist can be found in Appendix E.

While Chapter 3 served as a precursor to understanding how public involvement was initially integrated and informed the project's structure, this chapter considers the PPI approach adopted *throughout* the research process. As this is a first-hand account of the experience, a combination of 'I' and 'we' first-person voices are used to facilitate personal/critical reflection.

7.3.1 People Involved

Three members of the public ('public contributors') were consulted within the first six months of the project. All three were female, over fifty years old, and currently living with either clinically confirmed or suspected OA in their hands. They all volunteered to be part of this project and had no previous experience with PPI. They were recruited through the Saints Foundation - a charitable organisation run by a local football club [200]. Following the initial consultations, whereby three research priorities were determined based on the OA lived-experience, two of the three contributors extended their involvement and remained on the project until its completion. Public contributors were offered and fully reimbursed for their time and any expenses related to this project. One-time encounters were also made with various members of the public throughout the project but not on the same level of contribution as the two contributors described.

7.3.2 Stages and Nature of Involvement

After the research priorities were determined, the contributors continued their involvement throughout the various stages of the research process. They mainly took an advisory role however; their roles and preferred level of involvement was always discussed, evaluated and respected. As a result the PPI approach alternated between consultative, collaborative and co-productive, depending on the nature of the activity and their preferred level of involvement (Table 26).

Table 26 Summary of PPI influence, impact and outcomes

Research Stage	Approach	Contributor role/influence	Impacts and Outcomes
Identifying the research problem	Consultation: *PPI group meetings*	Highlighted the importance of acknowledging the public contributor insights in all stages of the project as well as at the beginning.	Improved understanding of hand OA lived-experience. Project aim and structure redefined. Further validation of the scope for more active PPI in engineering. Agreement to extend our partnership throughout the research process.
Project design	Consultation and Collaboration: *PPI group meetings, group email discussions, review of early-stage discussion notes*	Summarised key lived experience factors to facilitate project restructure. Reviewed and agreed to suggested PPI activities within the study.	Three core research priorities to drive the project workflow were identified. These included: patient variability, joint instability and raising hand OA awareness. Contributors accepted invitation to sit on the project's multidisciplinary steering committee.
Commissioning: Internal funding for public engagement activity	Consultation and Collaboration: *PPI group meetings, steering group meetings, group email discussions, review and approval of funding applications via email*	Became co-applicants on the funding call. Reviewed and agreed on suggested PPI activities within the study	Funding approved by Public Engagement with Research unit
Designing, managing and undertaking: Statistical Shape Modelling	Consultation: *PPI group meetings, group email discussions, steering group meetings, attending modelling and data collection demonstration*	Highlighted the importance of considering how products or interventions may perform on different hand and finger shapes and sizes (i.e. "one size does not fit all,"). Feedback and interpretation given during model generation	Supported researcher's critical thinking and approach to analysis: Guided data processing workflow (characterise the datasets before generating a dynamic model), purpose and usability (datasets publicly available with instructions of use - https://github.com/abel-research/OpenHands)
Designing, managing and undertaking: Kinematic Analysis	Consultation: *PPI group meetings, steering group meetings, attending modelling and data processing demonstrations*	Highlighted joint instability as a major challenge associated with OA, likening it to a significant loss of function compared to what they would consider their ordinary level. Feedback and interpretation given during workflow design	Supported researcher's critical thinking and approach to analysis: The emphasis on function impacted the decision to combine the morphological data with associated kinematic data collected to further characterize the population in a joint instability context

Research Stage	Approach	Contributor role/influence	Impacts and Outcomes
Designing, managing and undertaking: Public Engagement	Collaboration and Co-production: *PPI group meetings, steering group meetings, public engagement project meetings*	Highlighted a need to raise awareness of the hand OA lived experience within both the public and research community. Attended meetings with student interns, guiding their work and enhancing their professional development. Co-created and reviewed content for website and infographic. Social media written content was reviewed to improve language for readability and accessibility. Suggested events to attend and target audiences to engage	A published website (https://handlethis.org/) and accompanying infographic sharing the contributor's lived experience with OA, delivery of PPI training material for engineering students, promotion of PPI within student, university-wide and community spaces and supporting student education and professional development.
Dissemination and implementation: Project outcomes	Collaboration and Co-production: *PPI group meetings, group email discussion, reviewing documentation, presenting and teaching*	Co-designed and co-delivered dissemination material for target audiences Co-authored conference and journal papers, co-delivered training and co-presented at internal/external events	Dissemination of project outcomes and promotion of PPI within student, university-wide and community spaces, inspiring public members to get involved in research and encouraging researchers to create more PPI opportunities for public members
Evaluating impact	Collaboration: *PPI group meetings, group email discussions*	Offered reflections on overall PPI approach within the study	Recommendations for future work were devised based on views and feedback given in end-of-project reflective interviews.

7.4 Capture or measurement of PPI Impact

7.4.1 Qualitative evidence of impact

7.4.1.1 Purpose

Qualitative methods have been cited to complement PPI as a means of exploring contributors' experiences [167]. According to Arumugam *et al*. [167], qualitative research methods like in-depth interviews, focus group discussions, and contributor observations can be utilized to investigate patient experiences with PPI, which can help support and promote their involvement in research. Conversations with public contributors throughout the research process are often captured informally using meeting notes as proof of the discussion and not necessarily for analysis. So far, blog posts, interactive discussion notes, impact logs, logic models, co-produced dissemination material and PPI statements have been referenced to demonstrate efforts made to measure PPI impact during this project. The additional use of semi-structured interviews allowed for further capturing the experiences and perspectives of project contributors, collaborators and supporters.

Narrative research is a qualitative research method often adopted in the field of health sciences to utilize 'storytelling' as a method of communicating an individual's experience to a larger audience [304], [305]. A narrative approach acknowledges human experiences and allows individuals to share their perspectives of an event without externally imposed constraints [306]. The purpose of such an approach is not necessarily to acquire truth or fact but instead, meaning. This approach complements the motivations behind PPI, which aims to value the meanings of individuals' experiences rather than use them as objective, decontextualised truths [185].

7.4.1.2 Design

The semi-structured interviews loosely followed (i.e. taking a more narrative approach) the robust interview study conducted by Hoven *et al*. [186] which explores the experiences of patient research partners and researchers involved in long-term co-creative research collaboration. The interview was organised into two sections: the first section involved more general questions about the role of PPI in engineering spaces, and the second section was more specific about the individuals' experience with this project.

7.4.1.2.1 Participants

The interview inclusion criteria included people who have worked with, collaborated or supported the doctoral researcher at least once during the project (October 2020 – October 2024). Of the seven participants (Table 27), two of them are public contributors (PPI1 and PPI2) who were involved throughout the project, two academic supervisors (SP1 and SP2), two internal academic collaborators (AC1 and AC2) and an external PPI collaborator (EX1).

Table 27 Interviewees and their role in the project

Pseudonyms	Role in the project
PPI1, PPI2	Public contributors: Members of the public living with hand OA involved in the project. This is the first research project they have been involved in.
SP1, SP2	Project Supervisors: Providing project support and guidance. Both supervisors work in the biomedical engineering field and prior to this project, were relatively new to PPIE.
AC1, AC2	Academic Support: Providing support, guidance and platforms for engaging with undergraduate teaching modules. Both academics work in the biomedical engineering field and were relatively new to PPIE at the start of the project.
EX1	External PPI Support: Providing support and guidance on the PPI aspect of the project, particularly at the beginning. They have extensive background in facilitating PPI in research and is currently working for a research body in a PPI-focused role.

7.4.1.2.2 Data collection

Semi-structured, video and audio-recorded, interviews took place on Microsoft Teams (Microsoft, United States of America). To ensure members could speak freely of their views, the interviews were conducted by a third party (i.e. a student intern who had no prior relationship with the participants) rather than myself as the project researcher. An interview guide (Table 28) was provided to the student intern and can be found in Appendix E.

The interviews were carried out at the end of the project, between July and September 2024. On average, they were 29 min long and were transcribed verbatim. Written (consent forms) and verbal consent (at the start of the interview) were obtained from participants to both record and transcribe the interviews. Ethical approval to conduct, record and store these interviews was granted by the UoS (ERGO94040). The audio/video recording was deleted immediately after the interview transcription was approved by the participant.

By nature of a thesis, the narrative has largely been told from the researcher's perspective. This is useful for depicting the overall PPI influence on the project as it was undertaken, however, it is also recognised that this limits the insights from additional perspectives. To address this,

reflective interviews were conducted to provide a forum for those involved in the project to express their views and experiences. However, it became evident that any analysis of this data should be a focused study rather than merely a component of the GRIPP framework in use. Therefore, given the structure of the thesis as well as time/resource restraints, there was insufficient opportunity to conduct a meaningful content analysis beyond the reflections provided using the GRIPP2 framework. Consequently, at this stage, the reflective interviews are presented as record of impact, with extracts/quotes from the transcripts embedded throughout the subsequent sections to complement the reported impacts, outcomes and reflections. Full transcripts will be made available upon reasonable request to facilitate further analysis.

Table 28 Interview guide for semi-structured interviews with individuals involved in the project

	General	**Project-Specific**
Questions	• When did you first learn about PPI? • What role do you believe PPI plays in research? • Have you heard/seen PPI embedded in a project such as this one? • What do you think is particularly positive or beneficial with embedding PPI in a field like this and why? • What do you think could be challenging about this approach and why?	• Were you involved in/ engaged by/ Did you support this project? If so, how? • Why did you get involved in/engaged by/support this project? • What do you think works with how you were involved in/engage by/support this project? • Why do you think it works? • What could work better or be done differently?

7.4.2 Quantitative evidence of impact

The quantitative evidence of PPI across the entire project was based on keeping a log of the amount and nature of the public contributor's involvement. These metrics include:

- The number of contributors involved and retained throughout the project
- The approximate hours of involvement
- The types of PPI activities included
- The number of students engaged as a result of the project
- The number of training workshops conducted
- The number of dissemination activities attended

7.5 Results and Discussion

7.5.1 Definition

The PPI definitions stated earlier in the thesis (see Chapter 3) remain appropriate. 'Public contributor' was used to describe the members of the public, living with hand OA, involved in this project. These contributors had a permanent presence throughout the project compared to individuals engaged on a short-term basis (i.e. at events). 'PPI' or 'public involvement' has been used to describe the public contributors' involvement in the project and throughout the research process. The term 'PPIE' is the collective term used when both public involvement and engagement were present. This is most notably used in Chapter 6 where PE and dissemination are the central talking points. In this case, the PPI informed the PE. Overall, this doctoral research project can be referred to as a PPI-driven project because it was the public's expertise and feedback that informed project decisions, influenced the project's structure and supported critical thinking.

7.5.2 Impacts and Outcomes

The two permanent public contributors were involved at all possible and appropriate (i.e. at their preferred level) stages of this biomechanical engineering doctoral research project. Their involvement notably influenced and supported my critical thinking and research approach, encouraging a new perspective and attitude toward the involvement of public members in engineering and quantitative methodological research.

> *"I imagine that this, for [the researcher's] PhD as an early career researcher, having a group of people who are fully supportive of what you're doing and behind you all the way is a really positive thing. I definitely felt the same in my PhD. It was, can be quite isolating so actually having a real force of people behind you going: 'no, this is really worthwhile. Keep going. We want to help you each way', you know, it has a really positive effect, I think, on you as an academic."*
> *EX1, External PPI Support*

The contributor's involvement and lived-experience expertise informed three research priorities which shaped the project's structure. To this end, a heavier PPI investment than initially planned was made. This steered the use of the available datasets and disseminate project findings accordingly. Their influence guided the technical workflow, providing context to research efforts

and supporting decision-making. For instance, the prioritisation of a statistical shape model over a musculoskeletal model came from PPI influence which in turn helped in further characterising the datasets in a joint instability context; an approach uncommon in hand biomechanical studies compared to knee joint biomechanics. For the public contributors, this project opened up new opportunities to have a say in research. This enabled them to use their skills and expertise to shape research decisions, incite attitude shifts towards PPI within academic spaces and share their PPI experience to encourage other members of the public to get involved.

> *"I think our experience with lived experience as opposed to engineering experience helped and it made the change her [the researcher's] mind, I think, in some respects, as the way she was going to do her PhD, and she included more PPI which she hadn't thought of doing at the beginning."*
>
> *PPI1, Public Contributor*

The impacts of the PPI approach adopted throughout the research project can be summarised as follows:

1. **Establishing and developing meaningful PPI relationships**
    a. An active and supportive partnership with two public contributors was established and maintained throughout the project.
    b. Frequent PPI meetings were organised with public contributors to provide project updates, give feedback and discuss ongoing decisions to be made.
    c. Public contributors were invited to take, and subsequently accepted, roles of equal standing to supporting academics in the Project Steering Group.
    d. Main changes/benefits for the doctoral researcher: A new perspective and attitude toward the involvement of public members in engineering/quantitative methodological research; leading to the restructure of the project based on PPI recommendations and advocacy for a PPI approach which supports mutual-learning (often underrepresented in engineering compared to clinical and healthcare research).
    e. Main changes/benefits for the public contributors: New opportunities to get involved in research relating to their lived-experience, contributing to research methods and attitude shifts to research within the department of mechanical engineering at the University of Southampton; working with researchers to encourage others to work with members of the public in similar ways.
2. **Providing a case study for a PPI-driven biomechanical engineering project**

a. A project plan was designed to address contributor-recommended research priorities. These centred on using:
    i. Computational methods to assess bone joint shape and motion trends between participant datasets to define levels of variability and joint instability.
    ii. Public engagement to raise awareness of hand OA and the value of PPI by conducting workshops and developing digital and physical resources.
b. Additional considerations were made to (1) address the representativeness and useability of computational modelling outcomes by making our work accessible to potential end-users and inviting collaborators to contribute to them and; (2) engage with community groups and the biomedical engineering community, in particular early-stage engineers, to raise OA awareness and encourage active PPI practice.
c. This project plan was continuously reviewed during Steering Group meetings, and a stakeholder map was created to outline the influence and interest of those involved or engaged during the project.

3. Creating a PPIE network

a. Our support network expanded to include additional individuals who advocate for a PPI approach to engineering research. We also expanded our public network to include more voices (lived and non-lived experience) for current and future involvement and engagement opportunities.
b. 'PPIE for Engineering' training material for early-stage biomedical engineering students was delivered to encourage the consideration and inclusion of the public's voice in their work. We also hosted opportunities for students to consult with us on best practice for embedding PPI in their largely quantitative analysis-based projects.
c. Establishment of a consistent presence at local events to share our progress and invite members of the public to join the network.

7.5.3 Process Reflection

7.5.3.1 Developing Meaningful Partnerships

This thesis presents the impacts and outcomes of integrating PPI in a biomechanical engineering project. While it was rewarding to have clear evidence of PPI's impact once an outcome was realised, it was the public-researcher partnership, cultivated from mutual respect and trust, that drove the project's successes. The contributors were engaged and stood by this project until its completion, which again is a testament to the strong working relationship built as well as their passionate and hardworking nature. While PPI is fairly limited in engineering, the contributors and I were intrigued to discover how our respective expertise could impact the project. This two-way exchange facilitated opportunities (1) for public contributors to learn about the research being done and have a say in the impact of their input and (2) for myself to explore new approaches to research and improve research quality and relevance through additional insights. PPI also supported our personal and professional development by honing new skills, increasing confidence and fostering relationships. This example of reciprocal relationship has been frequently highlighted in the literature as an enabler of successful PPI in research [307]–[309].

> *"I think you can really see the clear benefit of doing that [including PPI in engineering], like there is a tangible thing at the end that comes out which you can see is directly influenced by the patient and you know that you're designing something that is actually going to work in practice and takes into account the important outcomes for the patients. So we know in osteoarthritis, arthritis, there are probably a lot of different outcomes that you could try and address through some sort of technology. But unless you live with the condition, you're not going to know, are you, what outcomes are really important to affect your everyday life. So involving patients in this process will make sure that you have something that is going to work and is of benefit to people at the end."*
>
> *EX1, External PPI Support*

In their proposed framework, Wilson *et al.* [308] describe building reciprocal relationships to involve: equal partnership, all stakeholders knowing their respective roles, a co-learning process, and continuous reassessment and feedback. I believe the strong level of communication between us facilitated these factors as well as fostered an open and honest

environment, enhancing the quality of the PPI and how it influenced the project. For example, feedback from contributors was consistently sought and provided, ensuring contributors were heard and felt part of the project. Even when I did not explain something clearly or it was not evident how I had acted on their suggestions, it was confidently brought to my attention and discussed as a group. In addition, I made sure to continuously check-in with everyone regarding their roles and preferred levels of involvement, which, similarly, contributors were open to discuss. Comprehensive notes were kept as a record of meetings and regular correspondence was upheld to ensure everyone remained informed about upcoming meetings/events, outstanding tasks and project progress.

> *"[The researcher] spoke plain English to us. She didn't try and, you know, sort of dazzle us with all the fancy words that we wouldn't have understood but if she did use the word that we didn't understand, we just said "hang on a minute. What does that mean?" Yeah. And she was quite forthcoming in being able to explain it in plain English that we could understand."*
> *PPI1, Public Contributor*

While there were some constraints placed upon the contributor's influence regarding the existence of pre-collected data, there were opportunities for co-design, co-delivery and co-authorship made during this project. By working with contributors to develop material, it ensured that they could speak on their own experiences and contributions toward the project. This links well with the recommendation by Jackson *et al.* [178] about having contributors copresent results at conferences, engage with the wider public and co-appear in other dissemination media as a method of power-sharing, avoiding tokenistic attitudes, and showing the value of someone's input. Opportunities for co-delivery and co-authorship were most notably demonstrated during the dissemination stage while regular PPI and Steering Group meetings facilitated consultation/collaboration during the other stages. This approach upheld accountability by providing a collective forum to explore if and how, PPI suggestions were considered. As a result, this thesis proposes that both PPI, for mutual learning and project governance, and PE, for facilitating two-way conversation and improving research accessibility, is included in a research project. This is particularly notable for a quantitative research project where due to time and the occupational skills required to perform certain tasks (i.e. programming, experimentation), there will be periods of PPI inactivity (i.e. periods between meetings with public contributors). By being transparent about any constraints, communicating with contributors about their preferred level of involvement and creating a diverse range of PPIE activities for contributors to get involved in throughout the project, I was able to manage

expectations and ensure that I was not making assumptions on anyone's abilities or interests, nor was I speaking on behalf of anyone.

> *"Patient-public involvement is very important, as I've said because you are dealing directly to the patients who suffered osteoarthritis."*
> *PPI2, Public Contributor*

7.5.3.2 Learning by doing

At the start of our partnership, both the contributors and I were new to long-term PPI. In addition, there were limited examples and case studies within the computational biomechanics field to look to. Therefore, it was a case of learning on the job. In particular, the contributor's patience was greatly appreciated as I navigated the managerial aspects of PPI, particularly at the beginning of the project. These included financial management, funding applications, record-keeping and activity coordination.

> *"After a few initial hiccups and obviously, you know, once we got going sort of thing and then we ironed out the few problems that we might have had, which I can't even remember what they might have been. But we did have obviously a couple initially that we sort of thought, you know, "oh that's not any good, let's try it this way." I think once we sort of ironed it all out, it all went really smoothly."*
> *PP1, Public Contributor*

Facilitating the PPI and conducting the research required strong task management skills. Although there exists published literature on PPI in doctoral research [17], [163], [293], [296]–[299], they have been reported as limited [295], especially with regards to how to operationalise PPI effectively. Conducting PPI in a doctoral research project differs from larger scale project whereby there is often a dedicated PPI staff member to manage and support PPI activities. Doctoral researchers are often new to PPI or have limited experience and are bound by strict time and financial constraints [293]. For instance, as highlighted by Pearson *et al.* [191] doctoral research students often respond to a research call from a funding body or university where the research subject, questions and study design have already been determined. This may introduce barriers, since funding for PPI activities may not have been costed-in, and limit PPI influence. Other barriers of PPI integration include supervisors with limited experience of PPI, access to training and the ability to engage with patients or the public with relevant expertise [191], [294].

Without case-studies of how PPI has been integrated into quantitative research fields such as computational biomechanics, it was initially challenging to develop the PPI strategy. Ultimately, I gathered guidance from multiple sources (i.e. see sections 2.4.4 and 2.4.5) and sought out shadowing opportunities from colleagues working in research fields where PPI was well-established. The strength of our public-researcher partnership also helped to navigate periods of uncertainty. For instance, regular meetings with public contributors ensured that activities and goals remained on track as they became a forum to discuss project progress and give feedback. During these periods of PPI inactivity, contributors trusted that I would reach out to them when ready. Again, this originates from the mutual respect between us and the dedication to maintaining transparency and upholding accountability.

> *"And I would always say like have an open conversation with the public contributors as well, which again, I do feel like [the researcher] has done amazingly throughout but, um, because there are things you might think, oh, they might be quite interested that and then they'll turn around and be like, "no, no interest in doing that, thanks." So it's, I don't think we, you know, necessarily should assume what stages of the research and stuff people want to be involved in because it might not be the same for everyone."*
> *EX1, External PPI Support*

By extending our partnership beyond the initial project design stages, it was my responsibility to manage expectations and make it clear where and how the methods selected and the efforts made between meetings (i.e. programming, data analysis, event organisation etc.) aimed to address the research priorities that the contributors recommended. For instance, while a statistical model could have been created without their involvement, their involvement provided context and informed research decisions– i.e. why was it that I was doing what I was doing and how is it useful? In addition, as the research developed, it became increasing important to check in with contributors on their preferred level of involvement and acknowledge that the levels of involvement will fluctuate. For example, contributors preferred to take a more advisory role when developing the computational modelling aspects of the project than the PE aspects. Whether dissemination is more collaborative in nature than the analysis of biomechanical data, is a potential topic for further investigation into the cultural status of PPI in quantitative-based research fields. This links to the speculation made by Boote *et al.* [139], stating that the limited evidence of PPI in quantitative research may be due to researchers finding it easier to involve the public in qualitative research and the public being more comfortable with collecting and interpreting qualitative data than statistical data from quantitative research designs [139]. Nevertheless, this experience champions involving members of the public throughout a

quantitative research project, at the very least, to ensure that research tools employed and the questions being investigated are purposeful and relevant.

> *"The real value is making sure we are directing the research to answer a real proper question, that is really relevant to people with the condition and that the nuances of the technology development or the way we're doing the technology development actually meets their needs, that's more important than just doing it to get funding. I guess that's when you when you end up being at risk of tokenism."*
> *SP1, Supervisor*

7.5.3.3 Bridging the Gap

> *"Making that link between the scientific research and the PPI, well, that is and continues to be a challenge."*
> *SP2, Supervisor*

The nature by which the engineering research process largely focuses on measurement and quantification, impacts its compatibility with PPI which is evolutionary and unpredictable. As highlighted by Turk *et al*. [310] in a University of Oxford PPI guide intended for researchers who are interested in involvement, PPI may lead to a change of culture that assists other changes in culture which may never be directly attributed to the initial involvement. However, given the nature of how a PhD is assessed, measuring performance before impact is realised can oversimplify the considerable 'behind-the-scenes' efforts made to facilitate high-quality PPI. This links to a study by Papoulias and Brady [311] , who conducted 21 semi-structured interviews with individuals holding NIHR-funded formal PPI roles across England. In this study, they present the theme of 'the production of invisible labour'. Under this theme, participants emphasised the invisibility of the administrative and relational labour specific to public involvement. Some argued that key foundational aspects of involvement, such as the process of relationship building, do not lend themselves to recognition as a performance indicator. In other words, it cannot be "measured". This emphasises Staley and Barron's [183] argument of the harmful effects of conceptualising public involvement as an 'intervention' to be evaluated the same way that treatment is, rather than viewing it as a means for building relationships and facilitating two-way learning.

> *"But trying to kind of fit PPI into a scientific PhD is not easy because you can see that it's having an effect but how do you demonstrate that? How do you? Because you can't*

do the counterfactual, she [the researcher] can't do 'here's my PhD if I hadn't talked to people', there's only one [of her] in the world…they [quantitative and PPI approaches] are so far apart methodologically, it means it's really hard to bridge them really."

AC1, Academic Support

The ultimate goal of this thesis was to explore the ways in which a quantitative-based research project could be designed, conducted and disseminated to address contributor-recommended priorities for hand joint research. While this was an exploratory process, it was challenging to unite the technical methods and the PPI outcomes. Despite the best intentions to bridge that gap, it is recognised that any presenting disconnect may represent a finding in itself. The engineering research infrastructure may not yet be compatible with such an approach. Quantitative methods tend to favour objectivity and replicability whereas public involvement in decision-making and research exhibits an evolutionary behaviour which cannot be predicted. In addition, as discussed, PPI can have an impact on the contextual aspects of research, such as depth of partnerships, ethical conduct and project management which are not often the key talking points within research publications and conferences. The perceived disconnect between the 'technical' and 'PPI' chapters, however, does present the opportunity for more rigorous exploration of the views and role of PPI in engineering and other quantitative-based research fields where PPI is limited. This could also aid in improving the PPI practice in these fields because as stated by Ocloo and Matthews [176], the barriers to incorporating PPI into research are tied to limited understanding and exposure.

"And I think that [PPI] necessary because you need our input so that you can get the whole idea of what happened … when you go into the engineering part and you're making something for our use."
PPI1, Public Contributor

"I think it [PPI] should be included as part of the [engineering] training… It would widen the students' views because at the moment when I've been involved with some of the students projects that they've been doing and given our input, they seem to be focused just on that particular problem. And they're not thinking [about] how it will affect the end product user. So they need that public involvement so that they can widen their views and say 'oh well actually that's not gonna work because the product, you know, the public person says that's not gonna work and we need to widen our views on how to do it'."
PPI1, Public Contributor

7.5.4 Limitations

The small number of contributors meant it was difficult to manage bias. It is recognised that even with providing spaces for anonymity, with only two contributors, the chances of identifying the author of any feedback was more likely than with a larger group. To address this potential issue, we encouraged open discussions. Additionally, as the researcher, I tried to remain aware of potential power imbalances and facilitated opportunities for feedback by regularly checking in on this potential issue with everyone involved. Throughout the project, we made efforts to encourage more members of the public to join our group. Three additional individuals participated in one or two meetings, but we faced challenges in maintaining consistent attendance outside the two existing and permanent contributors. This is recognised as a concern, especially in an equality, diversity and inclusion context. Although disheartening, recruiting contributors is a common challenge within PPI [290]. Considering the limited PPI in this field, we believe our partnership both in its establishment and depth, represents a promising beginning. While the quality of the partnerships formed between researchers and the public are considered to significantly influence the effectiveness of PPI [20], the enhanced robustness that a larger and more diverse group could provide, particularly in terms of transferability to the wider populations of individuals with hand OA, is acknowledged and encouraged for future studies.

By nature of a thesis, the narrative has largely been told from the researcher's perspective. This is useful for depicting the overall influence this had on the project as it was undertaken however, it is also recognised that this limits the insights from additional perspectives. To supplement the reporting of PPI impact, a series of methods were employed to capture PPI impact and are referenced in the GRIPP2-LF checklist in Appendix E . While content analysis on reflective interviews was not performed, limiting the contributor's perspective on the overall process, there is opportunity for future analysis, if feasible. For instance, there remains scope to further explore the status of PPI in engineering on a 'cultural' and 'societal' level. Qualitative research methods may also be useful for investigating the reasons 'why' PPI may remain limited in quantitative-heavy research spaces. The outcomes from this project could present as a practical case study with the additional perspectives, particularly from the contributors involved, to gain deeper insight. To facilitate this, full transcripts will be made available upon reasonable request.

7.6 PPI Learnings and Recommendations

The following section presents eight recommendations for researchers new to PPI and seeking guidance. They derive from four years of experience of working with members of the public on a biomechanical engineering research project. These recommendations act as guiding values that ensure that everyone feels included, respected and supported. While these learnings can be considered in any research field, they originate from the core outlooks and actions taken to build meaningful partnerships and encourage collaboration in a largely quantitative-based research space.

7.6.1 Respecting the range of expertise within the team

> *"For me, public involvement is important because you are getting all the information directly, not from books, journals, or other research but from the patients with OA pain of the hands."*
>
> *– Public contributor* [202]

Something that connects us all is that we each have a life story to tell; one that comes with experience and expertise. Sharing life stories and experiences lends itself well to PPI and developing partnerships, because stories can inspire, empower, build empathy and educate, facilitating that element of PPI which encourages mutual learning [312]. It helps to establish connections between both people and ideas. We can learn facts from published literature or technical information from fellow researchers, but there are also things we can learn from the public – perspectives and experiences that researchers often do not have and yet are often overlooked. PPI encourages focus on these areas and complements the resultant design, development and dissemination of the research. Listening and valuing the public's expertise and the courage it takes to tells one's life story for the sake of research is crucial in developing purposeful research and accessible outputs.

> *"Most scientists/engineers/academics/clinicians developing treatments for arthritis don't have it. As a result, they can't fully empathise, they can't 'feel' what it's like to live with arthritis – they need people with arthritis in the team to help all those involved in the project fully understand the condition."*
>
> *– Supporting Academic* [202]

7.6.2 Starting Early

> *"[The researchers] … who were running these sessions were quite surprised by some of the things that are affected by arthritis and what we have to do to overcome it. Simple things we take for granted like sewing, writing a letter, opening those childproof caps, or trying to. Even gripping a bread knife or picking something up, when we are in the throes of a flare-up can be nigh on impossible."*
>
> *– Public contributor talking about the researchers* [202]

As a project timeline progresses and research methods have been established, people are more reluctant to make changes, so we suggest involving members of the public at the earliest stage possible. A question we were often asked throughout the project by engineers, was "How does PPI make a difference?" Here, we would invite people to look at PPI as something you *do* rather than something you measure. Listening to someone's experience can help to improve your understanding of a condition or a consensus of a research tool in an area you are working in, increasing the awareness of the societal impact of the research. Engineers often work together to develop research tools and thus, PPI can remove the barrier between them and the public, broadening the possible project outputs. PPI is evolutionary and thus difficult to predict how it will impact a project, therefore, leaving room to enact change by starting early is important.

7.6.3 Training/Planning

> *"PPI group was not only interesting but very informative especially in the way that [the researcher] took notes and put them on the Jamboard. She was so very organised and her excellent technical skills with the computer meant that any points we made in our discussion were quickly put on the screen."*
>
> *– Public contributor* [202]

Barriers to implementing PPI in research are frequently attributed to a lack of understanding [176]. Planning is crucial for the smooth running of PPI activities and communicating with public contributors during a long-term project. Understanding the difference between involvement, engagement and participation is also important in helping to distinguish your intentions. While most useful when starting, we also stress the importance of seeking out guidance and reading up on relevant frameworks throughout the project. We commonly used: The GRIPP2 checklist [161], the UK Standards for Public Involvement [15], and the NIHR briefing notes [142] for PPI

guidance, and documentation from the National Co-ordinating Centre for Public Engagement (NCCPE) [313] for engagement guidance. We also advocate for learning on the job, therefore if there is a fellow researcher integrating PPI in their work, reach out to them for advice or an opportunity to shadow them to learn more about what it takes to involve members of the public in a research project and engage with different community groups.

7.6.4 Establishing Partnership/Project Governance

> *"These sessions weren't about taking information from contributors; there was a mutual exchange of experience and mutual respect for everyone involved."*
>
> *– Postgraduate Researcher* [202]

"Nothing about me, without me" - the core principle of patient-centred care and decision-making embodied by various patient advocacy groups such as Patient Research Exchange and The Patient Association [314] - perfectly summarises the rationale behind establishing a working partnership with members of the public. Public contributors are members of the research team, steering the project and governing its outcomes. You are a team. Their perspective is just as valuable for shaping the purpose and outcomes of the technical work and therefore, they should be consulted and treated the same respect as a technical specialist or fellow researcher. How you value people's input and time, plan meetings, communicate outside of meetings, and reward their efforts will contribute to the type of partnership cultivated. Avoiding tokenism, sharing power, and creating more equity in the decision-making process is easier when we move away from a transactional approach of working with the public to a reciprocal one. PPI can influence all stages of the research cycle; so when in doubt, ask the contributors how they would like to be involved and if their expectations are being fulfilled.

7.6.5 Commitment

> *"[PPI] showed me that engineering continues to be technology-driven rather than patient-led. How can we expect people to use the technology we design if we haven't considered their perspectives or needs in the design process? One way to do that is by involving them at every stage possible."*
>
> *– Postgraduate Researcher* [202]

Dawson et al. [17] argue that public involvement is not a time-consuming and resource-intensive activity, stating that its success is highly dependent on the relationships cultivated

with the public contributors; in other words, it is dependent on one's commitment to PPI. In an engineering context, the PPI commitment entails dividing your efforts between conducting the project on a technical-level to cultivating a partnership with public contributors and engaging with different research communities. However, viewing PPI as part of the research process and something that drives the project's needs, rather than something extra to do, may help to map the required efforts and resources needed. As discussed by Canney and Bielefeldt [11], this demonstrates the power of recognising the "non-technical dimensions of engineering projects" whereby skills such as communication, budgeting, presenting to large audiences, managing expectations and note-taking, compliment the process. These skills are just as important as the technical skills it may take to conduct the project as they ensure the smooth running of multiple different activities, facilitate transparency with all stakeholders and help provide a clear projection of the project's expectations.

7.6.6 Flexibility

> *"I hope that we can continue to work together and share our experience with the wider community because it has been great to see how our partnership has evolved since we first met and how many more opportunities we can create to share our work and communicate to researchers the value of public involvement."*
>
> *– Postgraduate Researcher* [202]

Making sure contributors can be involved at every possible stage is ideal but listening and respecting their preferred level of contribution for different activities is just as important. Working together in this way means the project must take a more holistic approach where the needs of all, including the researcher, the public contributors, supporting academics, the public and the research community, must be managed. To this end, it is important to diversify your communication approaches for each group. For instance, it's important to ask the public whether the method that the project outputs have been presented resonates with them and reflects any previous contributions and if not, go back to the drawing board and think of new ways to do it. Managing expectations is reliant on strong communication, transparency and accountability. PPI is evolutionary and as noted by Hewlett et al. [170], it is complementary to scientific research, whereby the public's perspective (often not available to most researchers) complements researchers' analytical skills and scientific perspective. Being open, adapting to PPI outcomes and developing meaningful relationships with the public is incredibly beneficial as it may lead to new and unforeseen solutions or research outlooks. Lastly, it is important to

see mistakes and misunderstandings as acceptable parts of the process. If you are honest with contributors, they will be honest with you. It may not be initially clear how to incorporate the contributor insights in the project design but embracing that partnership you established and being authentic and flexible will help. As discussed by Staley and Barron [183], learning is a PPI outcome.

7.6.7 Consistent Feedback

> *"Having input about our feelings towards arthritis and what we do to carry on normal life has felt like we are at last being listened to as well. I hope that more input from the patients will be taken into account as well in the future."*
>
> *– Public contributor* [202]

Feeding back to public contributors on acknowledgement, study progress, success and impact, is widely recognised as a common point of neglect by researchers conducting PPI [175], [307]. This feedback is crucial as it reinforces the concept of an equal partnership and eliminates the transactional nature of research. There are going to be areas of the research process that the researcher undertakes independently, especially in an engineering context where data collection may include experimentation and testing of research material. It is important that you keep communication active, keep a record of what was done and how PPI did or did not influence the work and provide contributors with this feedback even during the times where PPI is less evident. After having shared their story, contributors appreciate evidence of their words and views being taken into account but would also like transparency of where it was not. This can also inform their contribution to future work. One way consistent feedback can be facilitated is by creating a steering group and inviting contributors to be members alongside supporting staff and stakeholders. Regular steering group meetings can play a crucial role in fostering a reciprocal relationship by providing a regular platform to keep everyone informed about the progress of the project and allow the opportunity for everyone to give feedback and suggest changes.

7.6.8 Diversification of Efforts

The focus of quantitative-based projects revolves around data collection, processing and analysis. This project has shown how PPI encourages the clarification of the research question and prioritisation of research efforts with the consideration of an additional perspective, notably that of the lived-experience or service-user. Thus, PPI helps to determine the purpose of the

technical investigations adopted, shifting our attitude from designing a project around the technology to using the technology as a means to address the needs of the public contributors. This further emphasises how the technical (i.e. the computer programming, clinical or mechanical testing) and non-technical (i.e. developing working partnerships with the public or investing in interactive and accessible forms of steering a meeting) elements of a project can work side-by-side to define the research priorities, acknowledge the public's contributions, and at the very least make the research outputs more accessible.

7.7 Conclusion

This chapter was written in accordance with the GRIPP2-LF checklist to report and reflect on how PPI influenced the project as a whole. Developing a meaningful partnership between the public contributors allowed for the restructure of this doctoral research project, enabling a much heavier PPI influence than initially planned or published for a computational biomechanical engineering project. The contributor's long-term involvement highlighted how members of the public can help generate ideas and guide engineering workflow; leading to solutions that may never have surfaced without collaboration. This thesis encourages the inclusion of the public in the development of biomechanical engineering research because while it is inherently interdisciplinary, it often has limited representation of public perspectives and collaboration. By continuing to integrate PPI in quantitative research fields, the PPI infrastructure and evidence base can continue to grow and better support researchers interested in pursuing a similar path.

Chapter 8 Discussion and Discussion and Conclusion

8.1 Discussion

As widely discussed in literature, barriers to implementing PPI in research often originate from limited understanding. Researchers may be unfamiliar with what PPI entails, how to support public contributors, and the distinction between PPI activities and formal qualitative research. This thesis aimed to explore the integration of long-term public involvement into a biomechanical engineering doctoral research project with the research question guiding this thesis being: *can a quantitative-based research project be designed, conducted and disseminated to address PPI-reported priorities for hand joint research?* This thesis was never intended to "prove" the value of PPI. The contributors and I trusted in and championed our partnership from the beginning. Instead, this thesis was about taking action and exploring the ways in which PPI could be integrated and influence quantitative-based research, because while there has been encouragement from bodies such as the EPSRC [194], [195] and the Engineering Council [5], there is limited PPI infrastructure and evidence in the field. To this end, this thesis provides a first-hand account of exploring the ways in which PPI could be integrated into the research process of a largely quantitative-based research project. In short, the involvement of members of the public in this project guided the utilization and processing of the pre-existing datasets and inspired broader impacts beyond the computational modelling efforts. As a result, this research produced a combination of biomechanical findings and public-centred outcomes. From this experience, a set of learnings were produced, providing key recommendations for researchers new to PPI and seeking guidance.

Chapter 3 presented how the members of the public were initially involved and how this influenced the project's design. The early-stage PPI activities highlighted several lived-experience factors. With the time and resource constraints of a doctoral research project, we collaborated in identifying core priorities to consider during the processing of the datasets made available at the conception of the project. This, along with the enthusiasm from all parties to continue our working partnership, shifted the project's primary focus from mainly generating a computational model to exploring how the available datasets and supplementary resources could be leveraged to address the PPI-identified priorities of (1) *patient variability*, (2) j*oint instability* and (3) *raising hand OA awareness*. As a result, where appropriate and desired, the public contributors were involved at every and any stage. A mix of consultative and collaborative approaches were adopted to accomplish this. Considering the limited evidence base for PPI in

quantitative work, we used several existing frameworks and adapted our PPI strategies accordingly since they did not often reference PPI in the context of the quantitative elements of a research project.

Chapters 4 and 5 presented the characterisation of the provided datasets in the context of the contributor-reported priorities. This is an important outcome as while the data was collected before the contributors' involvement, their experience and interpretations filtered the options for data processing, analysis, interpretation and dissemination. This strengthens Pfannkuch and Wild's [188] argument that context knowledge is needed to do even the most purely technical role effectively. In these chapters, while I, as the researcher, processed the data and generated its outputs, I did this with the public contributors' considerations and interpretations in mind. Our collaboration provided focus, prioritising the understanding of the morphological properties of the training population *before* generating whole-scale models from techniques such as musculoskeletal modelling. The useability of the datasets was also another important aspect of the discussions with public contributors, facilitating the manner in which the datasets were processed and made available (e.g. including clear instructions embedded in any published code, signposting where these datasets are available to non-academic as well as academic users and highlighting how they may be useful in other research fields – such as hand-interfacing devices design). So while the co-production approach was limited by the use of an existing dataset and the occupational knowledge needed to perform the analysis, their involvement through the consultation approach offered a viewpoint that had previously been absent. This reinforced accountability, making sure that the actions taken were well-communicated and feedback, regarding whether contributors felt their suggestions had been considered, was sought.

Chapter 6 added an additional layer to the project by introducing PE, dissemination and teaching activities in parallel to the computational modelling studies. It is uncommon to see such a chapter embedded in a biomechanical engineering thesis however to address the recommendation from the public contributors to raise hand OA awareness during the project, it contributed a significant portion of the project's development and dissemination. Compared to the other technical chapters, this chapter presented efforts that arose from a more collaborative PPI approach whereby public contributors co-developed and delivered educational and dissemination materials for both public and academic audiences. Sharing research context, progress and output with stakeholders is a universal step of the process and thus, this thesis demonstrates how collaborating with the public to develop dissemination material is a key aspect of the research process and can be included even if the project is primarily quantitative in nature.

8.2 Key Contributions

This thesis is not the first engineering project to seek non-engineer expertise during the research process, however with the limited evidence of long-term public involvement in quantitative research studies, to the author's knowledge it is an exceptional case in computational biomechanics. The research process yielded the following contributions:

- Open-Source Statistical Shape Models: The first publicly available statistical shape models of the finger's skeletal anatomy generated from living participants which includes the removal of pose variation during imaging to maximise the observable size and shape variation from a small dataset, giving users options on the most appropriate model for their purpose where scale may not be a principal component of interest.
- Correlation between Shape and Kinematic Data: The development of a wavelet-based signal processing algorithm for the quantification of 'movement smoothness' within range of motion data. The indicated association between joint conformity and movement smoothness is logical, and should it be confirmed by further data analysis, this may provide insights into identifying individuals at risk of finger joint instability and thus inform physiotherapy and surgical interventions.
- Development of Engagement Resources: A website was dedicated to raising awareness of both hand OA and the project, using it and an accompanying social media campaign as an additional opportunity to recruit more public contributors, although unsuccessful. Attendance at public and community events also helped share our message, dedicating time to share the research outputs in a non-university setting.
- Establishing a presence in PPI-limited spaces: Dissemination material such as exhibitions, presentations and talks were delivered to public, community and academic groups to share the project's progress and research outputs to gain feedback and gauge interest but also to increase the visibility of PPI in engineering research.
- Targeted PPI Training Material: PPI training material was delivered to undergraduate engineering students to share the value of PPI in engineering studies despite limited education on the topic and encourage them to integrate it in their work.
- Key Learnings from the Integration of PPI: Critical reflection on the overall PPI process highlighted the key learnings and recommendations for researchers. It also provided an overview of the PPI influence and theoretical underpinnings for increased PPI activity in similar quantitative-based research spaces.

8.3 Outlook and Future Directions

Collaborative Modelling. The resultant finger model describes a small, homogeneous population, and assumptions cannot be made about how it represents individuals outside the training dataset. To this end, while the absence of datasets with OA characteristics may limit the immediate value of the open source deliverable and its ability to understand the effects of OA, it does provide a baseline which may provide a foundation for future comparison to OA models. In addition, this model can be supplemented with additional shape information [86], [90] , and if trained with additional CT images, the model may be of use for investigating further the apparent associations between joint conformity, that plays a role in stabilising the joint during movement, and movement smoothness, that may be descriptive of joint stability. Additional work is also necessary to validate the joint-level statistical shape model used to provide focus on the PIP joint morphology. Nonetheless, the SSM pipeline's ability to create both full bone and joint-specific models highlights its adaptability, reaffirming its value for publishing open-source; another decision affirmed by contributors and academics alike.

Qualitative Analysis: As this project was conducted by the researcher, the narrative was largely told from the researcher's perspective. While this was useful for depicting the experience alongside the synthesis of technical research outputs, it is recognised to have limited the qualitative insights of the additional perspectives captured. Nevertheless, there remains scope to further explore the status of PPI in engineering on a 'cultural' and 'societal' level. Qualitative research methods may be useful for investigating the reasons 'why' PPI may still be limited in these quantitative-heavy spaces. The outcomes from this project could present as a practical case study with the additional perspectives, particularly from the contributors involved, to gain deeper insight.

Diversity and Inclusion: Although the number of contributors was small, it allowed for meaningful and long-lasting partnerships to be developed which is often absent in biomechanical engineering studies of this nature. While the quality of the partnerships formed between researchers and the public are considered to significantly influence the effectiveness of PPI [17], the enhanced robustness that a larger and more diverse group could provide, particularly in terms of transferability to the wider populations of individuals with hand OA, is acknowledged and encouraged for future studies.

Improved PPI Education and Visibility: While this project aimed to integrate PPI as fully as possible, there were still noticeable barriers in bridging the gap between the engineering and PPI activities. For instance, the PPI impact on the modelling process was limited by the use of an existing dataset. Therefore, while areas of improvement exist in the PPI strategy adopted in this

thesis, if more researchers engage with this approach, a more comprehensive guidance for collaborating with members of the public in quantitative research settings can be developed. This may facilitate the involvement of the public at the earliest point of data collection and throughout its lifetime (i.e. from doctoral research to inter-institutional research).

8.4 Conclusion

Computational biomechanical modelling can rightfully be described as a technology-driven field. It is dependent on the data, the researcher's occupational skills and the software available. This thesis leveraged an existing dataset and developed public engagement material to investigate research priorities recommended by public contributors. These efforts demonstrate a case for how PPI can influence quantitative-heavy research fields, such as computational biomechanics. The quantitative and largely non-collaborative nature of computational modelling initially made it challenging to envision how PPI could be integrated, especially when compared to clinical studies during which, engaging with the public is a fundamental part of the process. However, the active and long-term public-researcher partnership developed throughout this project and built upon mutual trust, learning and respect, facilitated this.

Many practices in engineering design encompass the principles behind PPI, such as the Design Council's Double Diamond framework and human factors, and thus it is not believed that this project is the first to delve into seeking non-engineer expertise, instead it specifically focuses on the scope of PPI in the development of engineering research. As a result, this thesis acts as a case study, rather than a definitive blueprint, encouraging public involvement to become more conventional in primarily quantitative research fields, such as biomedical engineering where people are often the end-users of research outcomes. At its core, engineering applies scientific knowledge to address people's needs, and how better to understand those needs than to consult, collaborate and co-produce research with the public?

Appendix A Additional Documentation for Early-Stage Public Involvement Activities

A.1 Short-form guidance for reporting the involvement of patients and the public during early-stage consultations checklist

Table 29 Short-form GRIPP2 Checklist for Chapter 4 of Thesis titled: "Human and Biomechanical Considerations in Hand Joint Disease"

Section and topic	Description	Reported on page No.
1. Aim	Report the aim of PPI in the study	75
2. Methods	Provide a clear description of the methods used for PPI in the study	75–78
3. Study results	Outcomes—Report the results of PPI in the study, including both positive and negative outcomes	78–90
4. Discussion and conclusions	Outcomes—Comment on the extent to which PPI influenced the study overall. Describe positive and negative effects	83–92
5. Reflections/critical perspective	Comment critically on the study, reflecting on the things that went well and those that did not, so others can learn from this experience	90–92

A.2 Terms of reference for early-stage public involvement sessions

Date: January 2021

Purpose/role of the group

Project summary

Degeneration of hands and wrists presents a major socioeconomic problem and barrier to healthy ageing. In the UK, more than 1.5 million people have sought treatment for hand and wrist osteoarthritis (OA) which often affects joint movement and function; compromising the patient's daily life [1]. Musculoskeletal modelling is a useful tool for investigating the key mechanisms of the hand, how these mechanisms are affected by disease and what the impacts of treatment are [2]. Tinashe Munyebvu has recently started a PhD at the University of Southampton and is investigating how the incorporation of the patient's voice can influence the generation of musculoskeletal hand models capable of evaluating hand function and treatment options. This PhD project is in its early stages of development; therefore, using Patient and Public Involvement (PPI), this study aims to seek the involvement of members of the osteoarthritis community to help identify and prioritize the decisions made during the development of the musculoskeletal hand models.

How much influence will people be able to have?

This project is linked to, although not funded by, the EU project APRICOT. Therefore, it is possible that anonymized outputs from this project may be shared with APRICOT project partners. The EU Project, APRICOT aims to develop a radically new type of implant for the treatment of small joint arthritis. In this study, your influence will most likely be seen in the postgraduate research project rather than the larger APRICOT project. We hope to incorporate the experiences and voices of the members of the hand osteoarthritis community to inform the development and design of musculoskeletal hand models.

Aims and Objectives

- To enable members of the hand osteoarthritis community (the PPI contributors) to have an active partnership with researchers
- To discuss and outline the major issues associated with hand arthritis
- To explore the challenges associated with current hand arthritis treatments

- To discuss key areas of investigation that can be facilitated by computer-generated hand models (i.e., hand function, treatment evaluation etc.)

Membership

a) Members:

- Tinashe Munyebvu (Postgraduate Researcher, Faculty of Engineering and Physical Sciences)
- Dr Charles Burson-Thomas (Research Fellow, Faculty of Engineering and Physical Sciences) PPI contributors (members of the hand osteoarthritis community)

b) PPI contributors: Public contributors will receive expenses and reimbursement in line with the NIHR Southampton BRC payment policy for all activities relating to these consultations

c) Quorum: At least half of the group members should be present for a meeting to proceed otherwise that session will be rescheduled.

Postgraduate Researcher will send invites to members of the group and will be aided by Research Fellow. Guests are welcome to join by invitation from members of the group as and when the agenda dictates.

Sessions

We are hoping to conduct a total of four PPI sessions (one every two weeks). Each session will last no more than an hour and will be held online via video-conferencing software (Microsoft Teams).

What is expected from members of the public?

Provide an honest description of the challenges of living with hand osteoarthritis, based on personal experience. Contributors should be reassured that there is no 'right answer': we would like to listen to your experience and learn with curiosity. Also, we would expect that should two people have a different experience, they would not be questioned by each other regarding the validity of their descriptions – each participant's views will be respected by all.

What can participants expect from us?

Members of the public can expect us to be polite and honest, show proper consideration of their views, and show respect regarding their knowledge and experiences. We will also ensure we are sincere when describing the views of the people involved – we will never deliberately misrepresent anyone's views.

Anonymity, recording and sharing information

It is important that members can speak freely of their views. Sessions will not and should not be recorded using video/audio. Points discussed verbally during PPI sessions will be recorded by one of the investigators in the form of hand-written notes. These notes act as a written record of a meeting (minutes). They will be transcribed into digital notes after each session and sent via email to every present member of the corresponding meeting. When recording information or discussing any of the information publicly, there will be no attribution of comments or views of an individual. At any point during or after the PPI sessions, the PPI contributors will have the right to access, correct, and/or delete recorded information they feel does not represent what was discussed.

Personal data such as names and emails will not be shared with anyone outside the research team (Tina, Charlie and the supervisory team).

Group responsibilities

- An invite link for the Microsoft Teams meeting will be sent no later than two working days before the meeting (please do not share this link with anyone outside of the group)
- Group members are encouraged to inform Tinashe Munyebvu of any topics they would like raised before the next meeting
- Within the first ten minutes of the meeting, Tinashe Munyebvu will provide a summary of the project's progress including a summary of the previous meeting Following the project summary, the rest of the meeting will consist of talking around each point on the agenda
- Minutes of each meeting will be circulated and agreed by all those who attended the meeting
- Members may be contacted between sessions - contact between group members can be done via email unless agreed otherwise.

Review

The information in this terms of reference will be reviewed biweekly to ensure it is in line with current practice.

References

[1] Arthritis Research UK (2013), "OSTEOARTHRITIS IN GENERAL PRACTICE Data and perspectives," 2013.

[2] M. Mirakhorlo, J. M. A. Visser, B. A. A. X. Goislard de Monsabert, F. C. T. van der Helm, H. Maas, and H. E. J. Veeger, "Anatomical parameters for musculoskeletal modeling of the hand and wrist," Int. Biomech., vol. 3, no. 1, pp. 40–49, Jan. 2016, doi: 10.1080/23335432.2016.1191373

A.3 Impact logs for early-stage public involvement activities

Date	Outcome*	Impact**	Reflections/learning
03/02/2021	First session: introductions and insight with everyone's connections and why they wanted to get involved in this project. Public contributors were given a brief presentation on the PhD project and its current status. We got into a brief discussion about pain relief, age representation in OA research and the impact of joint instability of daily living. Meeting minutes were sent to everyone who took part for review.	As the first session, we prioritised getting to know each other and outlining the project and plan for their involvement. Though we didn't get into much discussion about the lived-experience, it was clear that everyone was keen to get involved and share their stories.	Public contributors were involved in previous PPI sessions; however this was pre-COVID19 pandemic/lockdown/social distancing. As these sessions took place during a lockdown, we were all adapting to this new way of engaging with people. We tried to use a university-favoured video conferencing software to host the call however it wasn't very compatible to those without university accounts. Therefore, we will use a more public-friendly application.
17/02/2021	The lived-experience discussions began we talked about the sorts of activities that involve hands, and which are important and/or impacted by hand OA, the usefulness of a computer model of the human hand (the backbone of the PhD), clinical consideration and age representation of hand OA.	Aspects of the hand OA lived-experience were discussed; including nutritional or weather factors that were unbeknownst to the researchers. Considerations for the computational modelling aspect of the project were discussed and noted. These included the applications (i.e. education, research, rehabilitation, surgery) for such a model and who would benefit the most from its outcomes. In addition, the data used for such computer models was discussed (not one size fits all). This was key consideration for the computational modelling. An invitation to the project Steering Group was extended to the public contributors.	We got into interesting conversations however since TM also had to record the minutes, the conversation could get affected at times when a pause was needed to write things down. Therefore, a more engaging way of recording the outcomes of the meetings was needed. In addition, we were all still getting to know each other so a more interactive way of capturing the discussion would be welcome.

03/03/2021	Continued the conversation of activities of daily living (ADLs) impacted by hand OA. These were listed and captured on the interactive whiteboard. We took the ADLs and tried to categorise the types of movements needed for them. For example, the ADLs that appeared most affected by hand OA were those that required small and repetitive. We talked about self-management techniques (adaptation). We also discussed joint instability. This session also focused on views on treatment and considerations for new implants. We discussed the conditions of OA joints and things that public contributors would need to take into consideration before signing up for an implant surgery. This included trust and transparency with the clinical team, anaesthetic preferences and preserving as much joint tissue as possible	There was an agreement that public awareness of hand OA appeared lower than for hip or knee OA. Public contributors thought it was important for the PhD to find ways to raise more awareness. Joint instability has frequently come up during discussion with the public (pilot study and this work). Pain and stiffness are usually (in media) highlighted in the literature as a major problem of OA rather than joint instability. Joint instability has a major impact of hand function and causes "lack of trust" in joints as mentioned by the public contributors. Again, this might be something we can address with the project. The last part of the session mostly focused on treatment considerations. This linked closely with the outcomes of the APRICOT project rather that the PhD however, their views and opinions on clinical translation of such a device sparked conversations of their involvement in the research process and what they would consider important before seeking out such treatment	The incorporation of Google Jamboard stimulated a much more active discussion. We covered a lot of topics, especially on the lived-experience, and there was a lot that we agreed needed more awareness both within in the public and research community. This was the first instance that we wondered if we could do that together, rather than isolating the PPI to these four project design consultations.
17/03/2021	We aimed to cover more on the treatment. We discussed their experience with diagnosis, treatment and rehabilitation. This led to more considerations on how researchers and clinicians could improve from a patient perspective. This led to another discussion on general awareness of hand OA and the lack of information in comparison to the hips and knees. We used the last few minutes of the session for APRICOT-related discussions; this included the benefits of early inventions and a multiple choice question to outline a preferred scenario for the "perfect" implant to treat hand OA.	As we discussed everyone's views on the clinical and surgical pathways for treatment, we got a better understanding of the needs public contributors wish to be addressed or improved. This paired with the need for more public information on hand OA once again highlighted their enthusiasm to share their experiences with the public and get the conversation started about hand OA.	TM used a blank interactive whiteboard the session before. The use of a custom whiteboard template this time around helped with reformatting after the meeting. It was now just a case of putting the post-it's in the right area. Our work together is only beginning. We are all fairly new to PPI, but it was clear that there was much more we could talk about and learn from each other; four meetings was not enough. We plan to schedule more.

Attendees to all sessions: TM (PhD Student), CBT (Academic Support), CP (Public contributor), GL (Public contributor) , NM (Public contributor)

*Outcome: Immediate, demonstrable change

**Impact: Sustained change, can be intended/unintended, positive/negative

A.4 Jamboards from early-stage public involvement activities

Figure 50 – Session 3 Interactive whiteboard created using Google Jamboard during the session (top) and formatted after the session with the contributor's input (bottom) to capture the discussions had during early-stage PPI meetings.

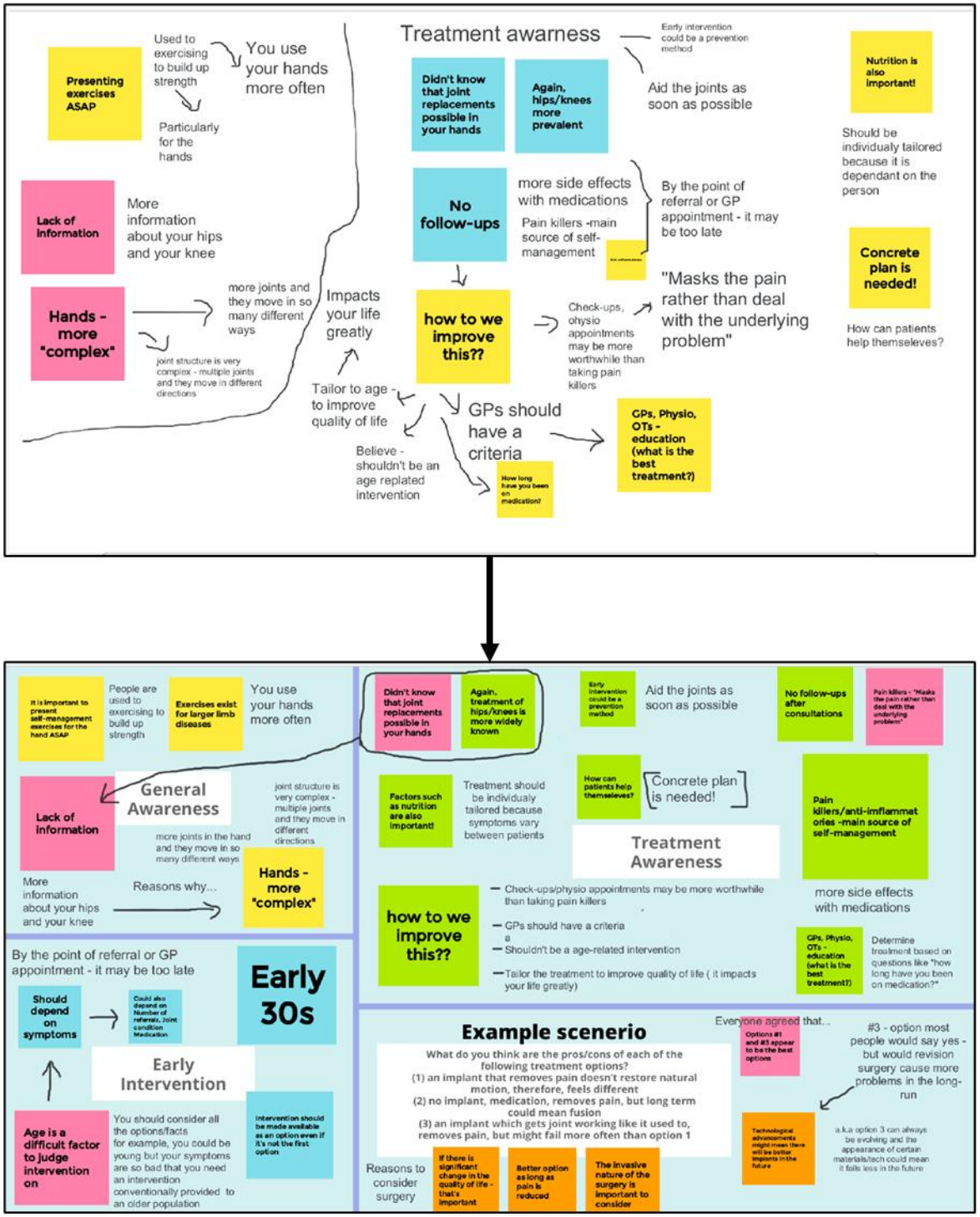

Figure 51 – Session 4 Interactive whiteboard created using Google Jamboard during the session (top) and formatted after the session with the contributor's input (bottom) to capture the discussions had during early-stage PPI meetings.

A.5 Terms of reference of project steering committee

Purpose/role of the group

The hand is one of the most complex structures in the human body. It can perform countless actions and thus, is a crucial part of our everyday lives. In 2013, more than 1.5 million people in the UK sought treatment for hand and wrist osteoarthritis (OA) which often affects joint movement and function; compromising the patient's daily life [1]. Developing a better biomechanical understanding of the hands is important to improve clinical assessment and treatment design for musculoskeletal disorders such as OA. [2], [3]. However, whilst hand joint disease has a major impact on people's confidence, independence and quality of life, biomechanical analysis of the hand and wrist joints remains at an early level of understanding compared to lower-limb joints. This makes the hand a relevant biomechanical case study to evaluate the impact of PPIE in engineering. Therefore, the hand has been chosen as the focus of such a public-focused project. The proposed steering group aims to gather those closely linked to this research to help identify, prioritize, and oversee the decisions and progress made.

Role description

The aims of the group are:

- To help identify, prioritise, and oversee the decisions made in this research project as well as suggest possible areas of improvement
- To establish an active partnership with PPI contributors; ensuring they are part of the decision-making process
- To support and provide Tina Munyebvu with professional development opportunities and insights throughout the PhD
- To work with Tina Munyebvu for the fulfilment these aims

Membership

a) Student: Tinashe Munyebvu (Postgraduate Researcher)

b) Members:

PhD supervisors:

- Professor. Cheryl Metcalf (Faculty of Health Sciences)
- Dr Alex Dickinson (Faculty of Engineering and Physical Sciences)
- Professor. Martin Browne (Faculty of Engineering and Physical Sciences)
- Professor. Markus Heller (Faculty of Engineering and Physical Sciences)

Project Partners:

- Dr Charles Burson-Thomas (Faculty of Engineering and Physical Sciences)
- Public Engagement Officer (Public Engagement with Research unit)
- Public contributors (Public members and members of the project's Contributor Advisory Group)

There is a range of different expertise within the group, reflecting the group's collaborative approach. Tina Munyebvu will be in charge of sending meeting invites. Guests are welcome to join by invitation from members of the group.

c) Public contributors will receive expenses and reimbursement in line with the NIHR Southampton BRC payment policy for all activities relating to the steering group.

d) Quorum: The steering group is quorate when at least half of the total number of members are present.

Meetings

What is the time commitment?

Meetings will be held quarterly each year up until September 2024. With the first meeting having taken place in April 2021. Meetings will be arranged by Tina Munyebvu. Due to the current restrictions, meetings will be held online via Zoom. An invite for the Zoom meeting will be sent no later than two working days before the meeting is to take place. Each meeting will likely last no more than an hour and a half. A 5-10-minute break will be offered at the halfway point.

Anonymity, recording and sharing information

It is important that members can speak freely of their views. Points discussed during meetings will be recorded by a member of the group. When recording information or discussing any of the information publicly, there will be no attribution of comments or views of an individual. All group members can review, change or delete any recorded information during or after the meetings.

Group responsibilities

- Group members are encouraged to inform Tina Munyebvu of any topics they would like raised before the next meeting
- Within the first forty-five minutes of the meeting, Tina Munyebvu will provide a summary of the project's progress including a summary of the previous meeting
- Following the project summary, the rest of the meeting will consist of talking around each point on the agenda

- Minutes of each meeting will be circulated and agreed by all steering group members who attended the meeting
- Members may be contacted between meetings for advice should the need arise.
- Contact between group members can be done via email unless agreed otherwise.
- Occasionally, sub-groups may be formed to work on specific issues as appropriate

Review

The information in this terms of reference will be reviewed quarterly to ensure it is in line with current practice.

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Appendix B Statistical Shape Modelling of Fingers

B.1 Visualisation of principal component for middle, ring and little finger

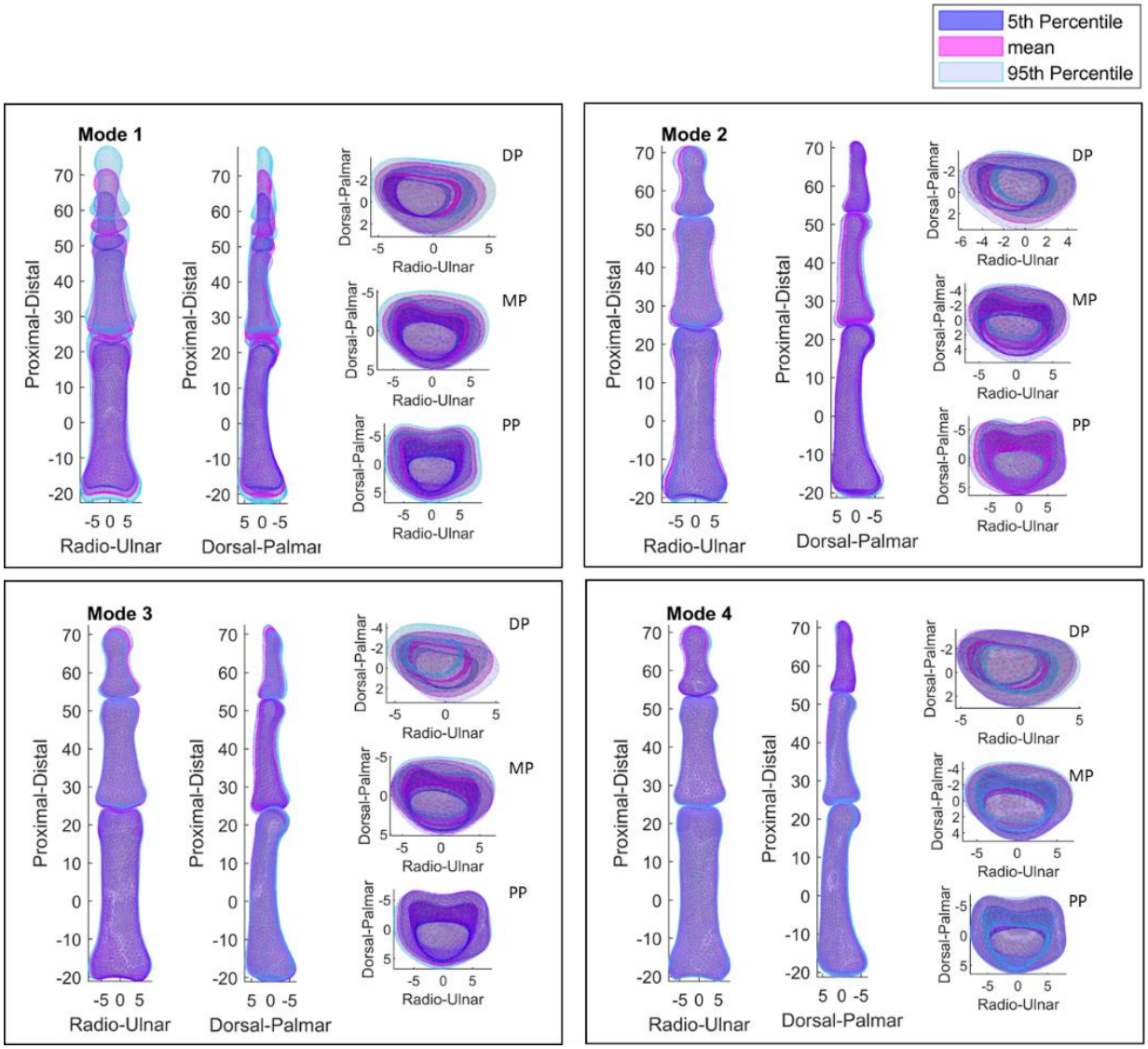

Figure 52 First, second, third and four principal component of middle finger statistical shape model (pose corrected and including scale effects)

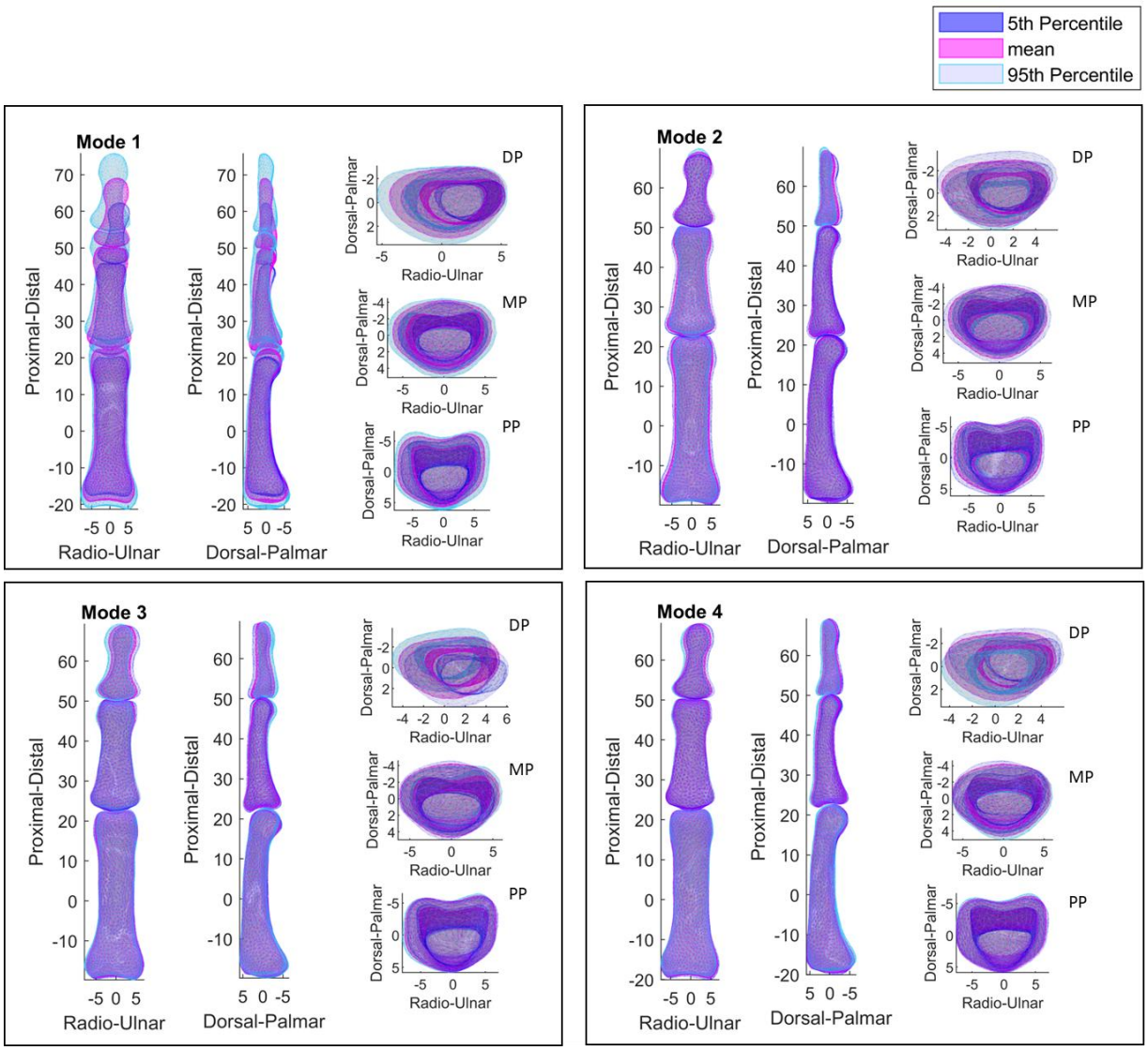

Figure 53 First, second, third and four principal component of ring finger statistical shape model (pose corrected and including scale effects)

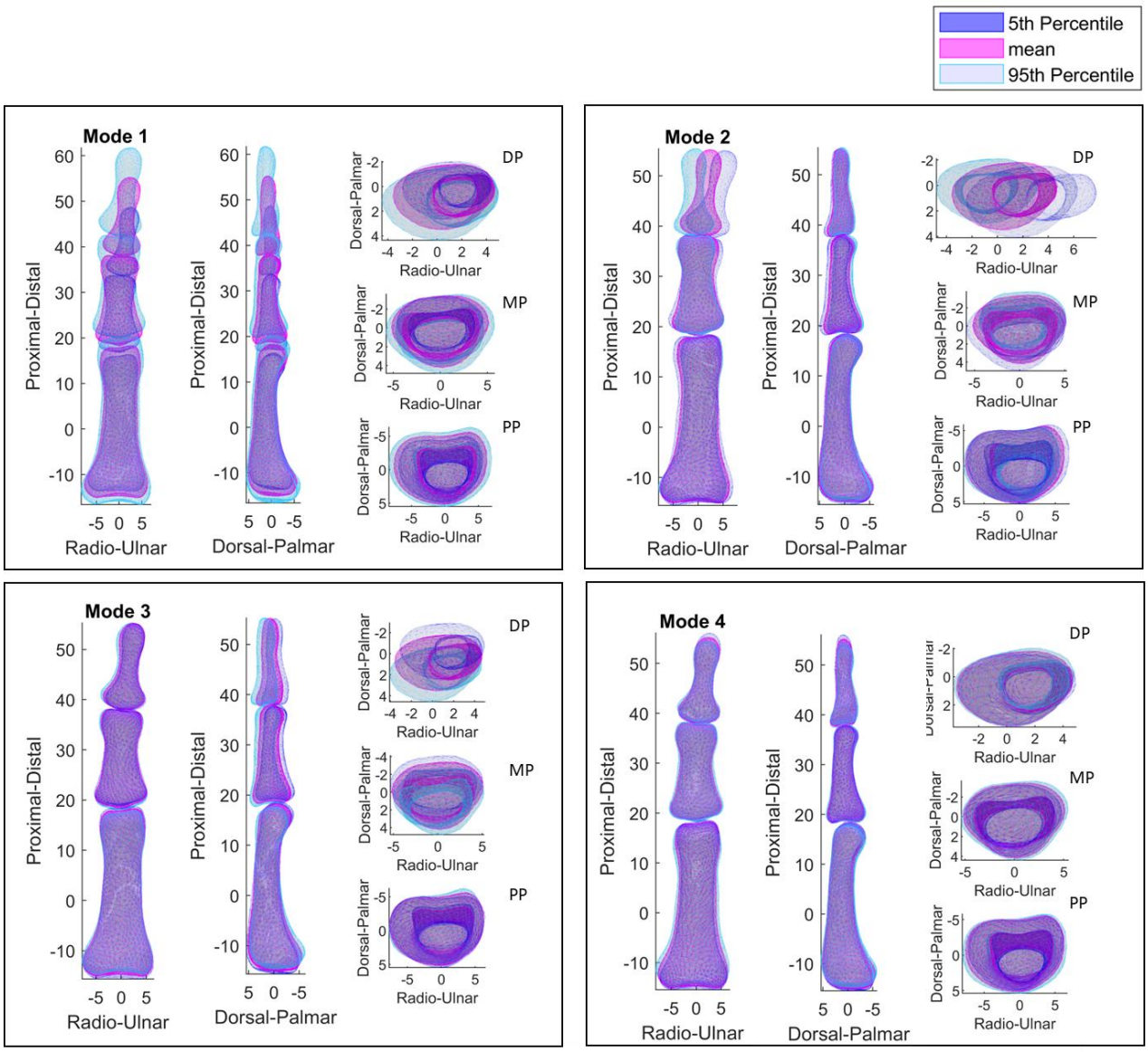

Figure 54 First, second, third and four principal component of Little finger statistical shape model (pose corrected and including scale effects)

Appendix C Signal Processing and Movement smoothness Indicator Data Analysis

C.1 Power spectral density of angular velocity signals before denoising

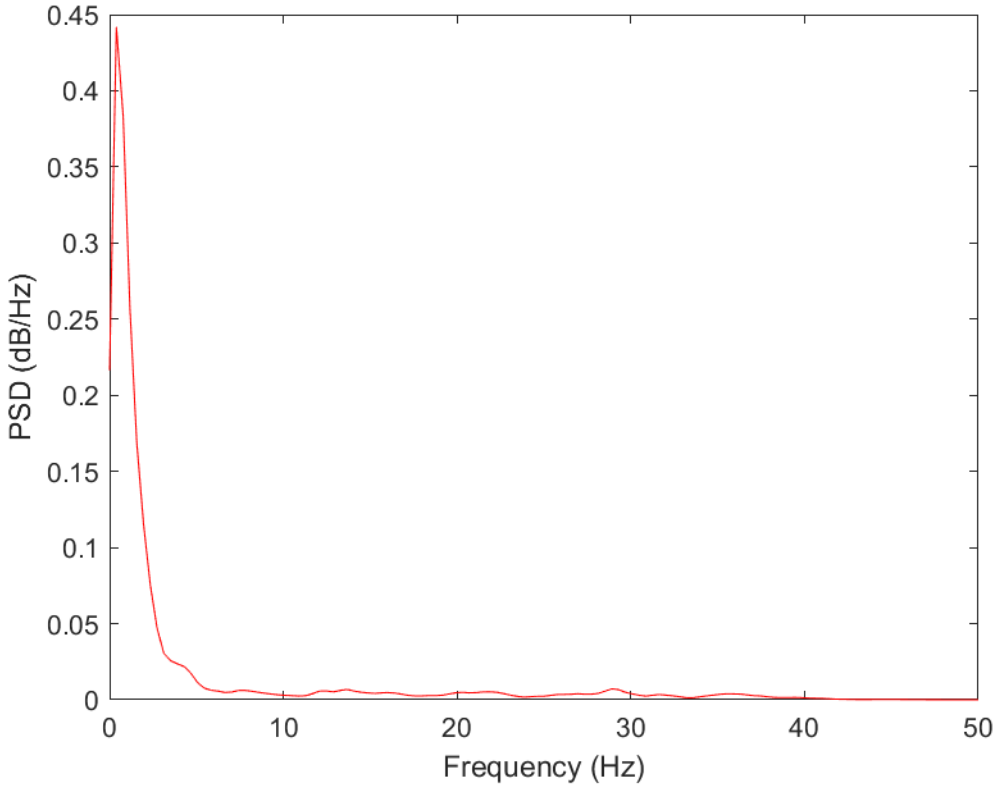

Figure 55 Power Spectral Density (PSD) of Participant 1's index finger tip-to-tip range of motion angular velocity signal (before denoising)

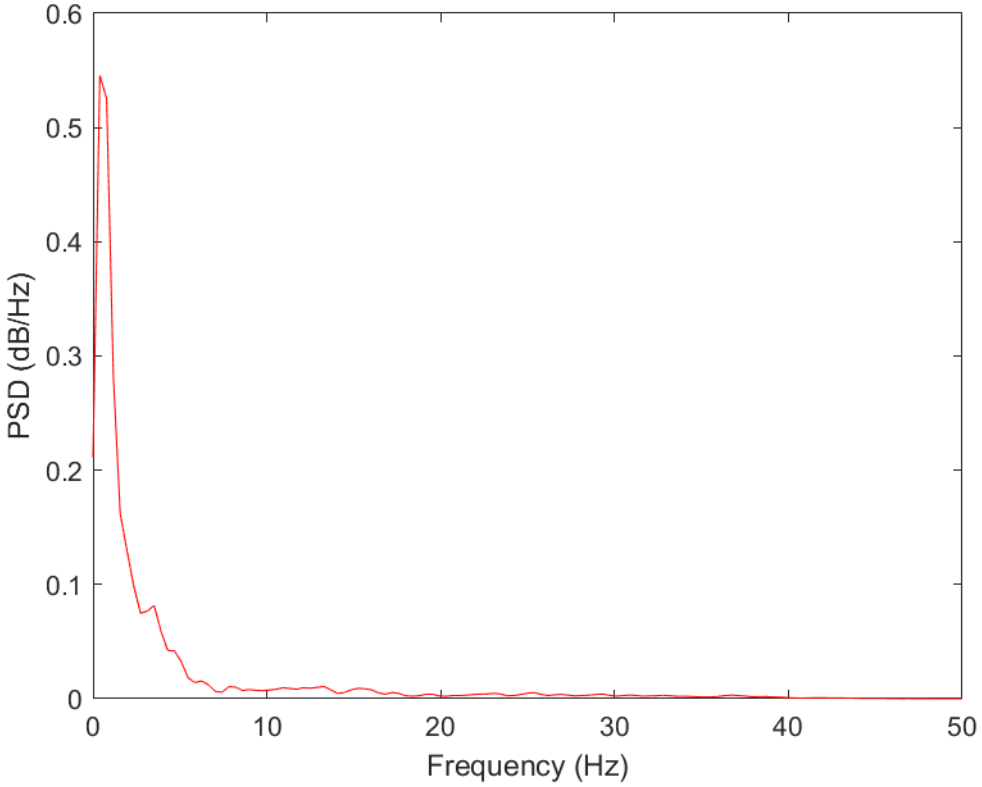

Figure 56 Power Spectral Density (PSD) of Participant 2's index finger tip-to-tip range of motion angular velocity signal (before denoising)

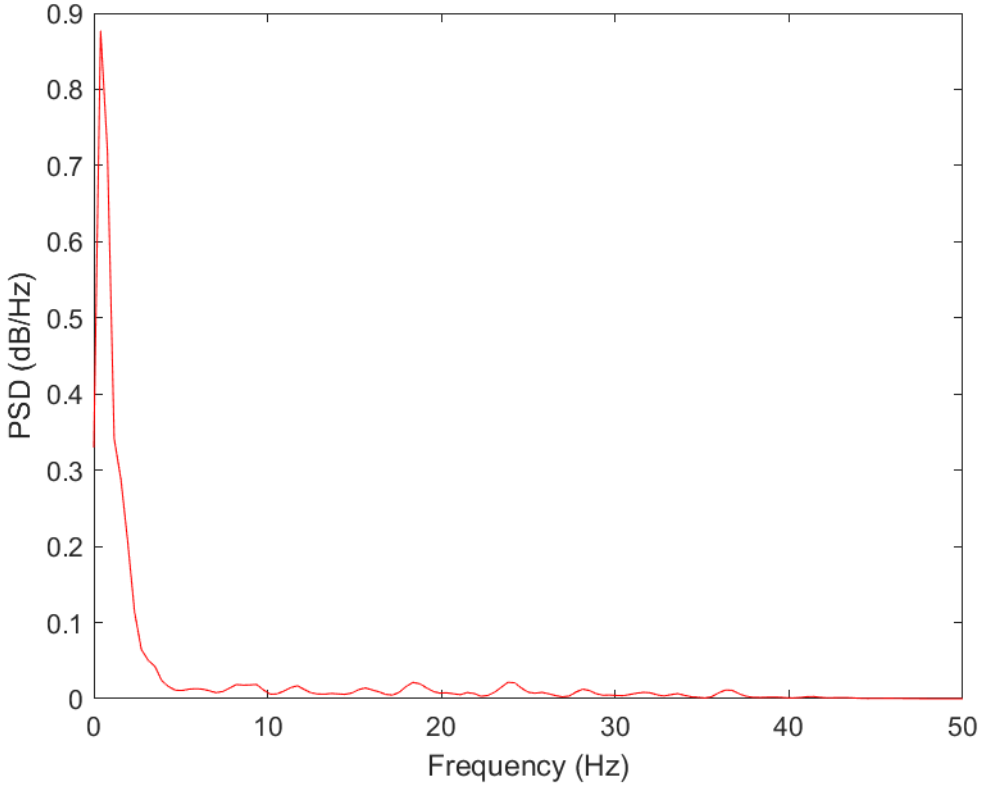

Figure 57 Power Spectral Density (PSD) of Participant 3's index finger tip-to-tip range of motion angular velocity signal (before denoising)

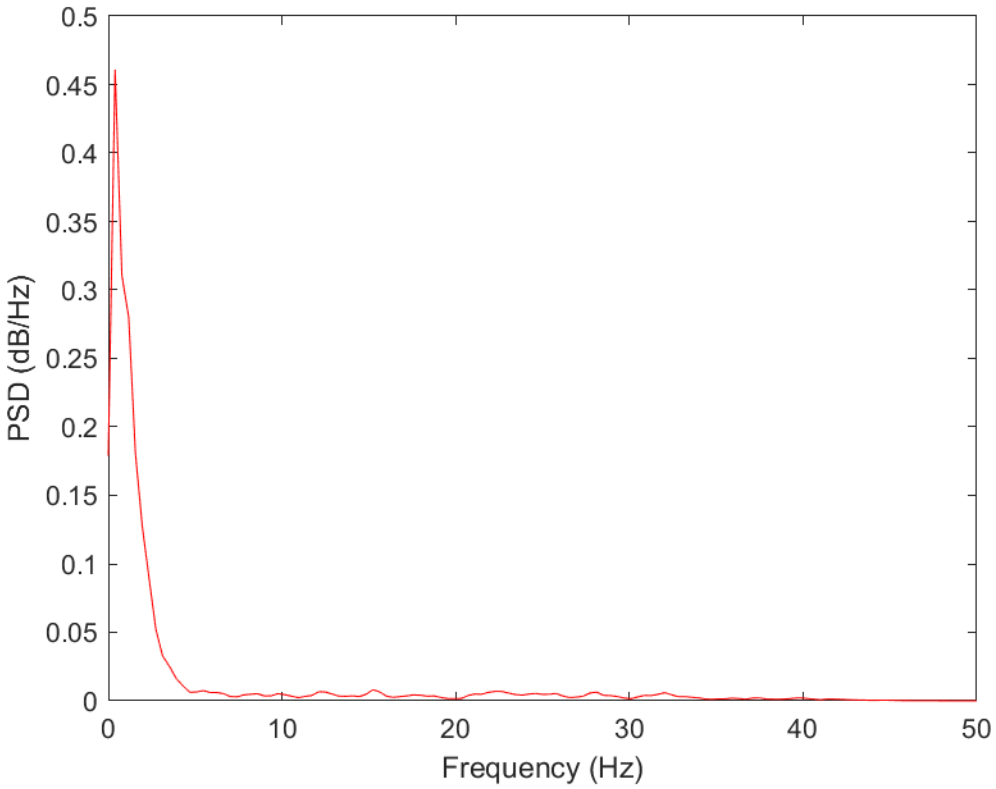

Figure 58 Power Spectral Density (PSD) of Participant 4's index finger tip-to-tip range of motion angular velocity signal (before denoising)

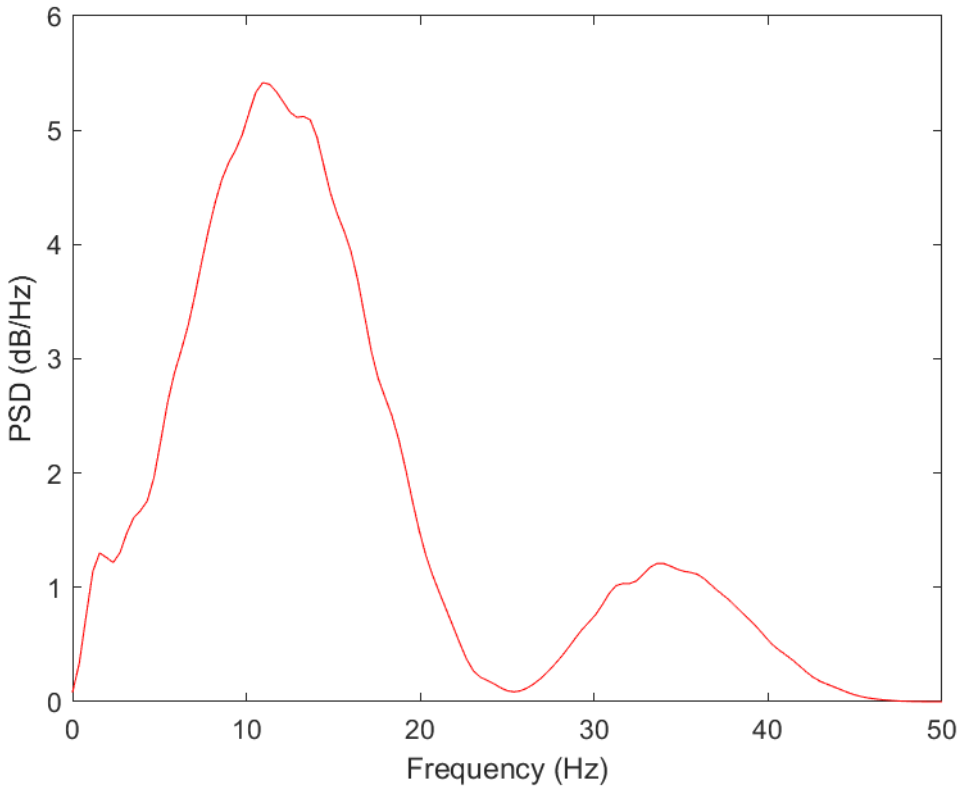

Figure 59 Power Spectral Density (PSD) of Participant 5's index finger tip-to-tip range of motion angular velocity signal (before denoising)

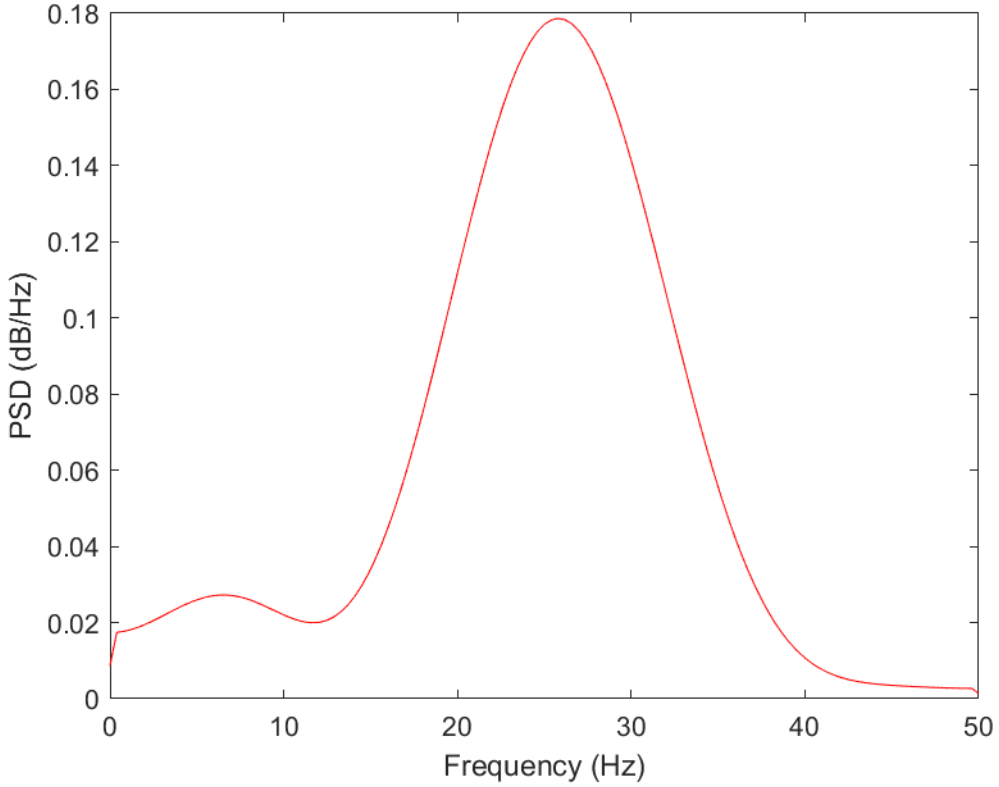

Figure 60 Power Spectral Density (PSD) of Participant 6's index finger tip-to-tip range of motion angular velocity signal (before denoising)

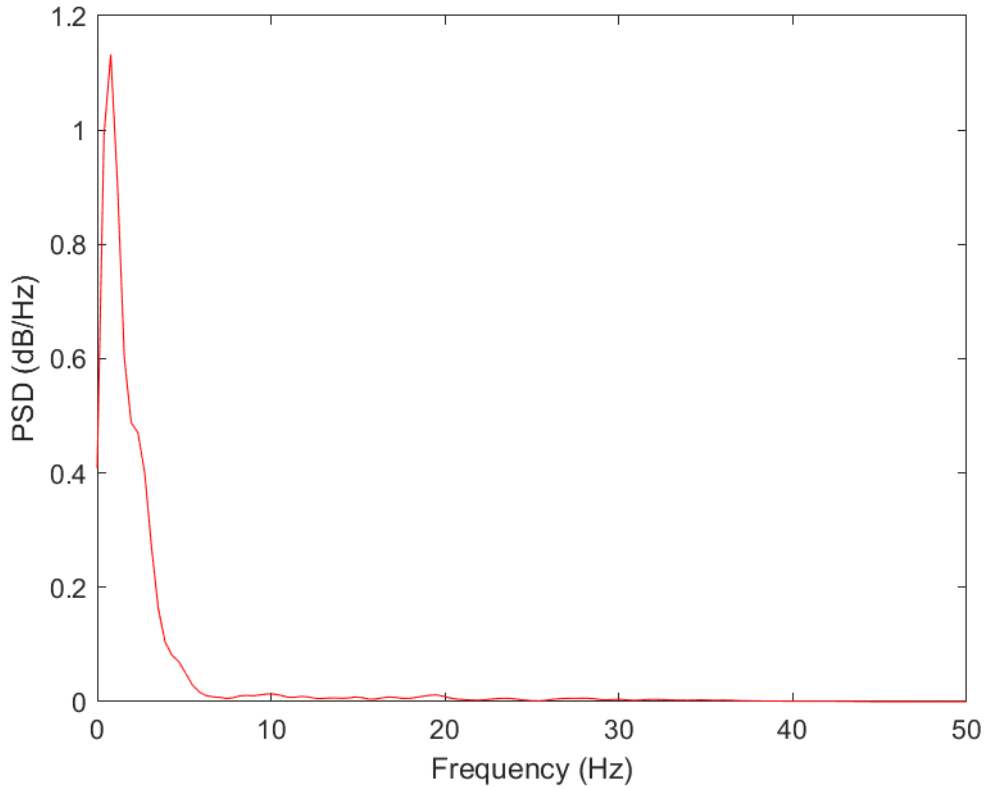

Figure 61 Power Spectral Density (PSD) of Participant 7's index finger tip-to-tip range of motion angular velocity signal (before denoising)

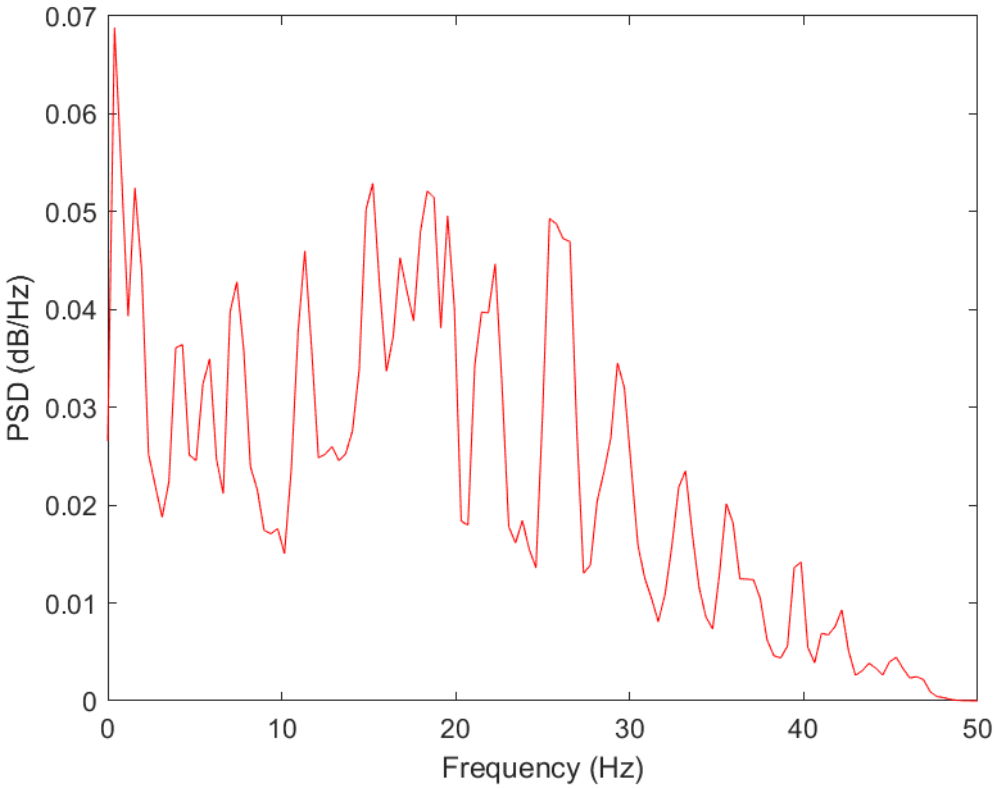

Figure 62 Power Spectral Density (PSD) of Participant 8's index finger tip-to-tip range of motion angular velocity signal (before denoising)

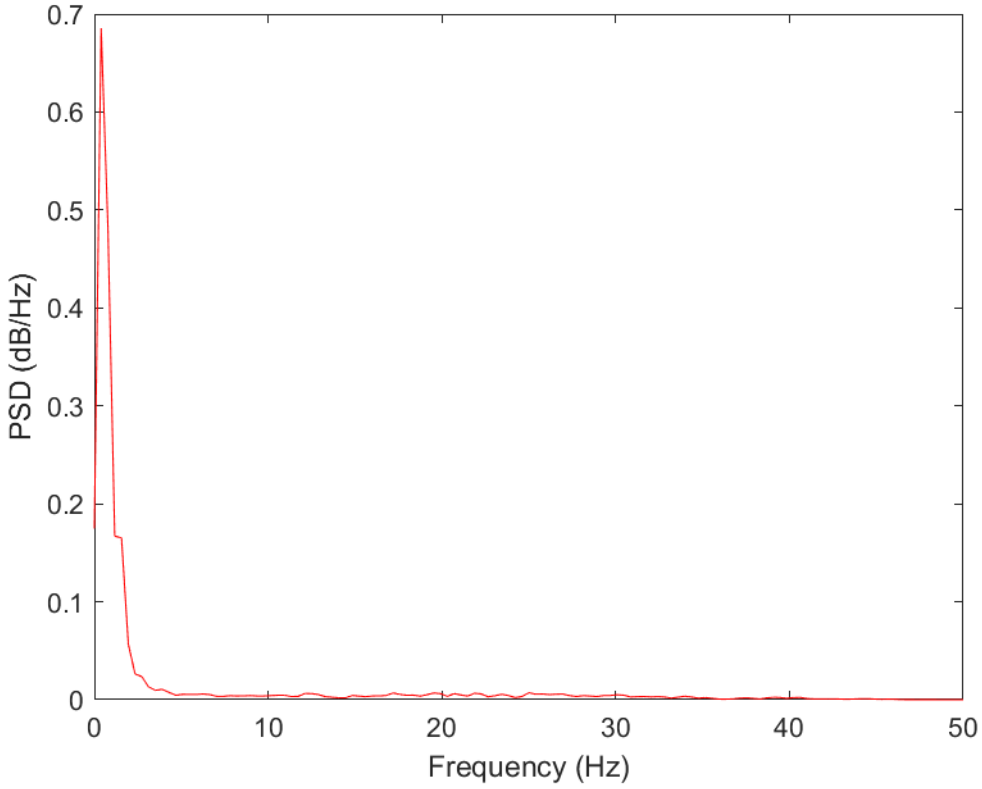

Figure 63 Power Spectral Density (PSD) of Participant 9's index finger tip-to-tip range of motion angular velocity signal (before denoising)

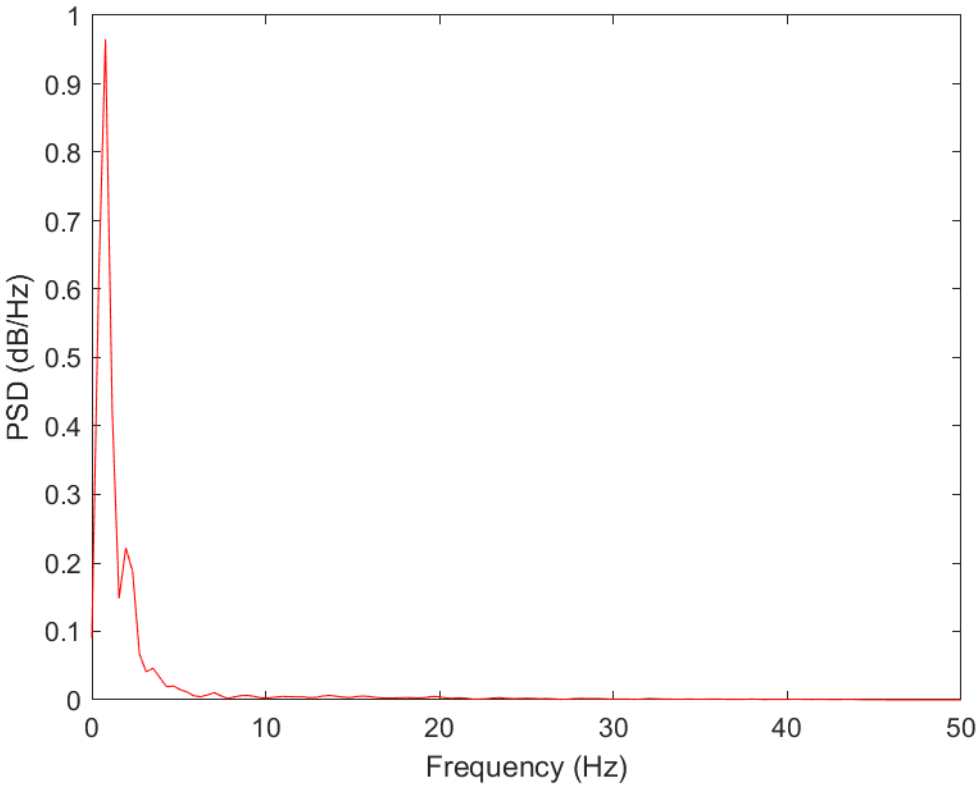

Figure 64 Power Spectral Density (PSD) of Participant 10's index finger tip-to-tip range of motion angular velocity signal (before denoising)

C.2 Signal Decomposition

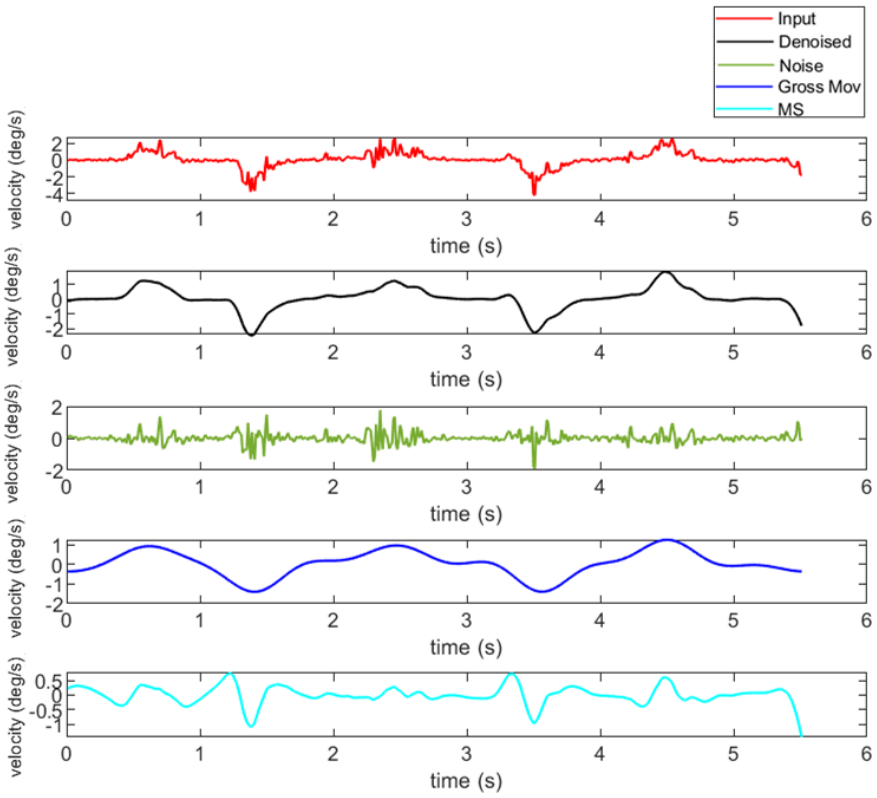

Figure 65 Participant 1's Signal Decomposition Results: Input signal (red) and resulting denoised signal (black) decomposed into noise (green), gross movement (dark blue) and movement smoothness (cyan)

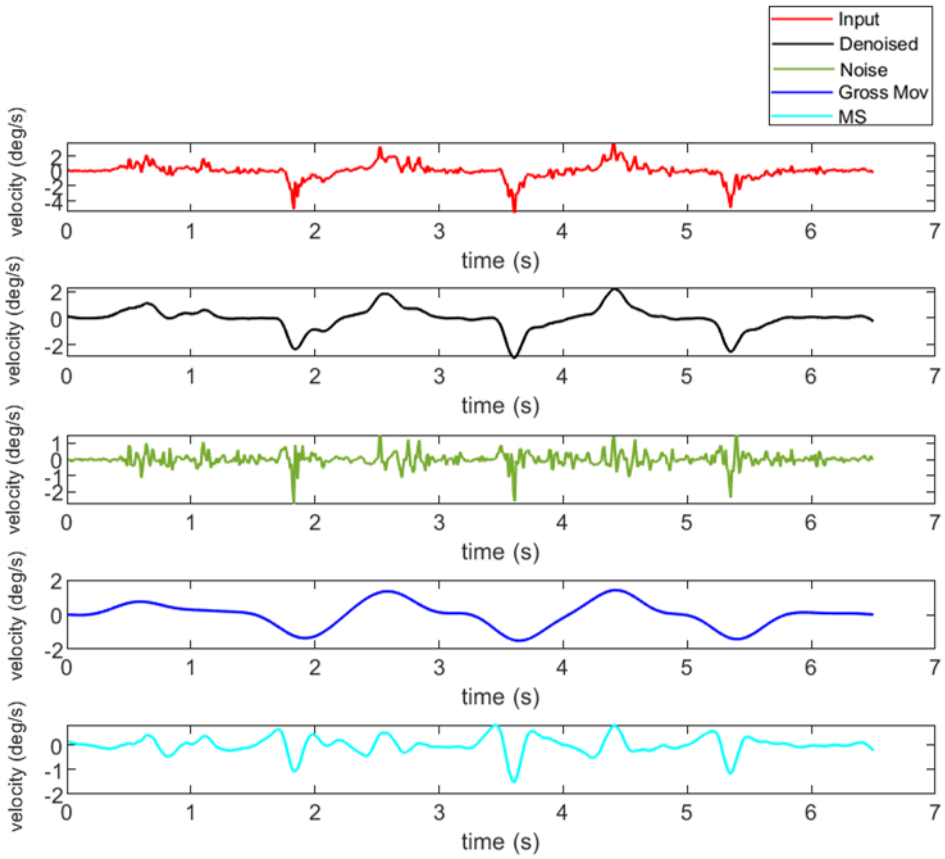

Figure 66 Participant 2's Signal Decomposition Results: Input signal (red) and resulting denoised signal (black) decomposed into noise (green), gross movement (dark blue) and movement smoothness (cyan)

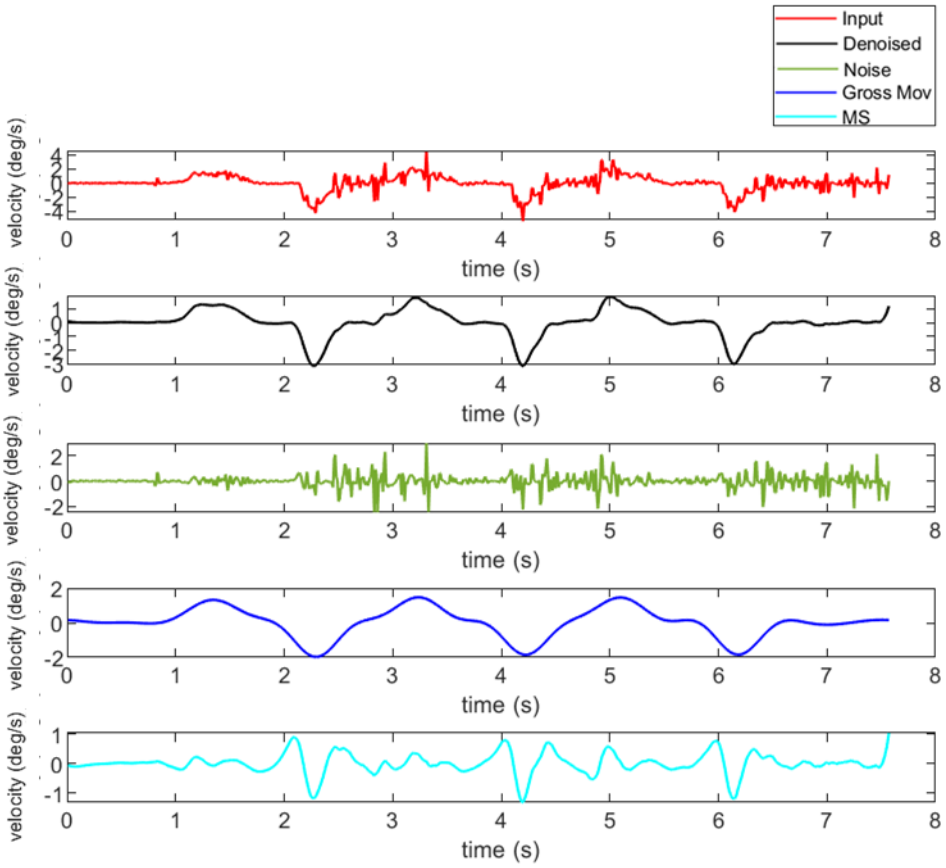

Figure 67 Participant 3's Signal Decomposition Results: Input signal (red) and resulting denoised signal (black) decomposed into noise (green), gross movement (dark blue) and movement smoothness (cyan)

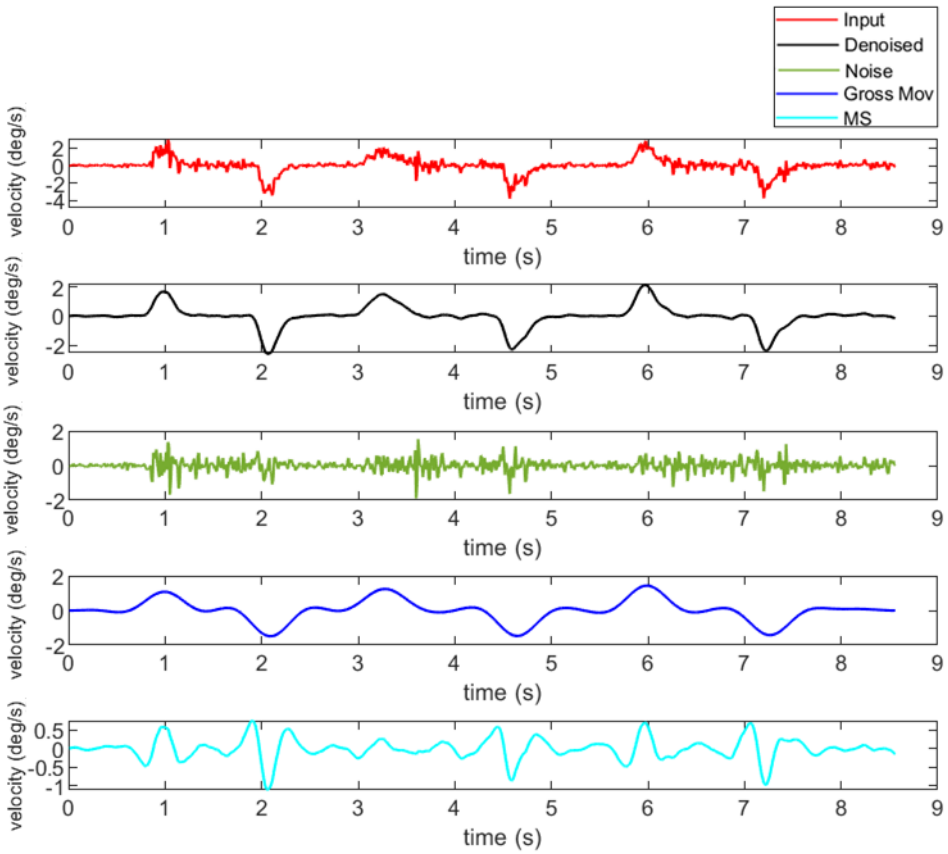

Figure 68 Participant 4's Signal Decomposition Results: Input signal (red) and resulting denoised signal (black) decomposed into noise (green), gross movement (dark blue) and movement smoothness (cyan)

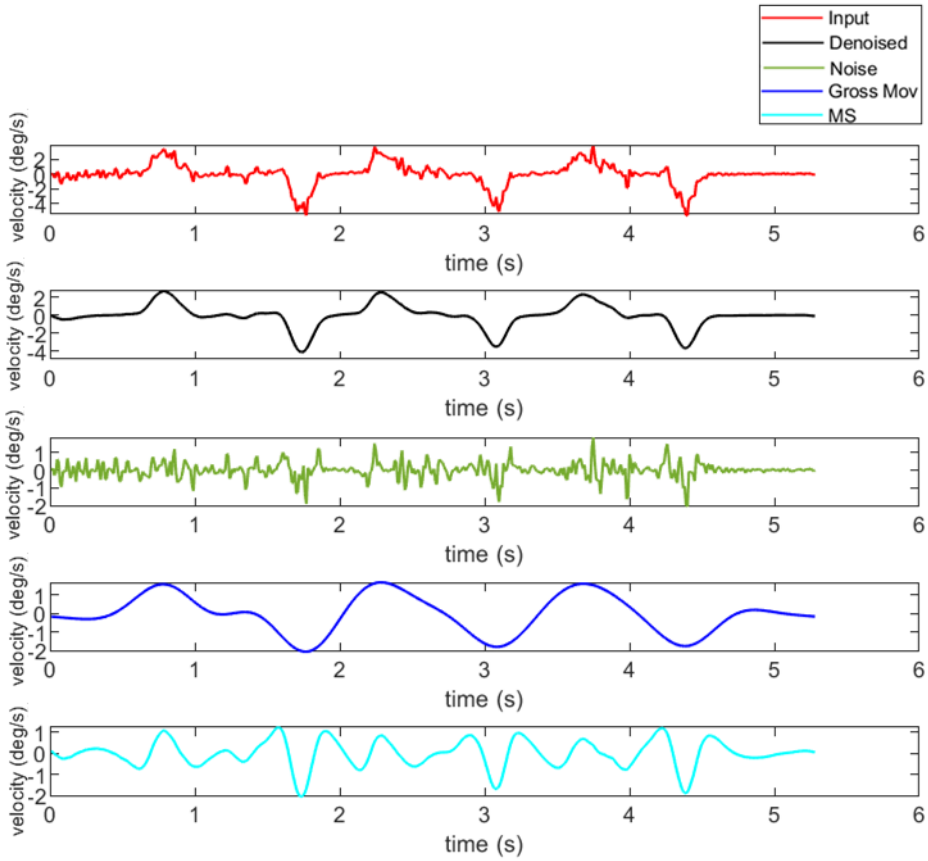

Figure 69 Participant 7's Signal Decomposition Results: Input signal (red) and resulting denoised signal (black) decomposed into noise (green), gross movement (dark blue) and movement smoothness (cyan)

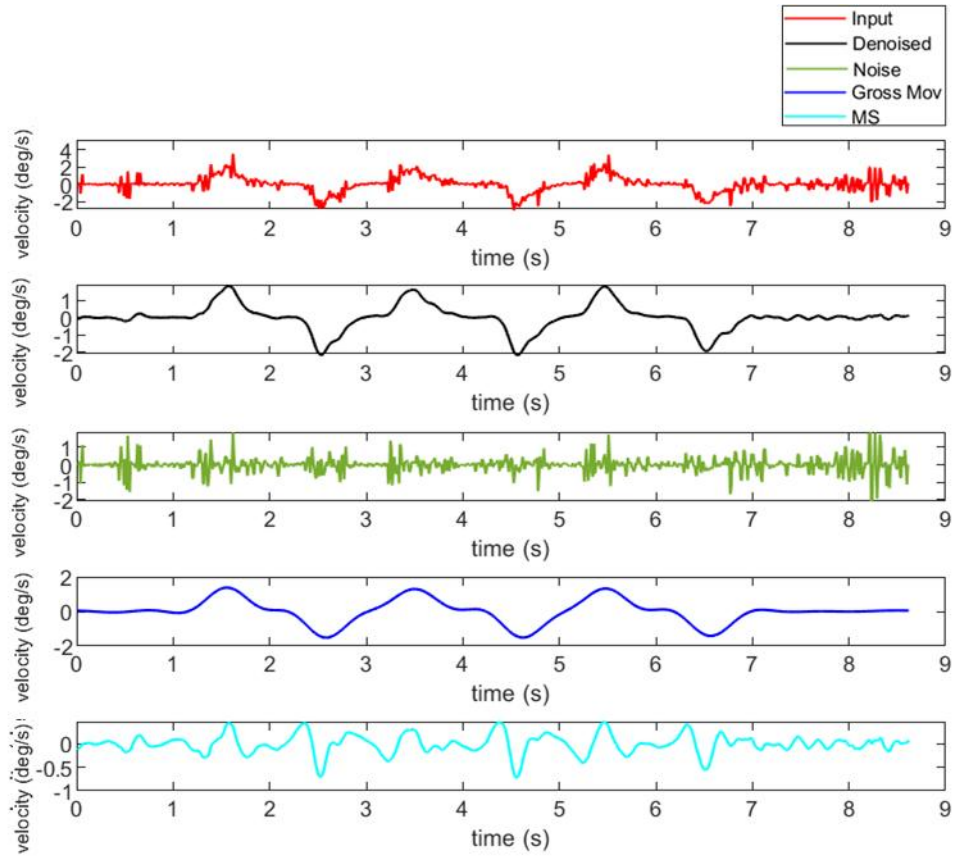

Figure 70 Participant 9's Signal Decomposition Results: Input signal (red) and resulting denoised signal (black) decomposed into noise (green), gross movement (dark blue) and movement smoothness (cyan)

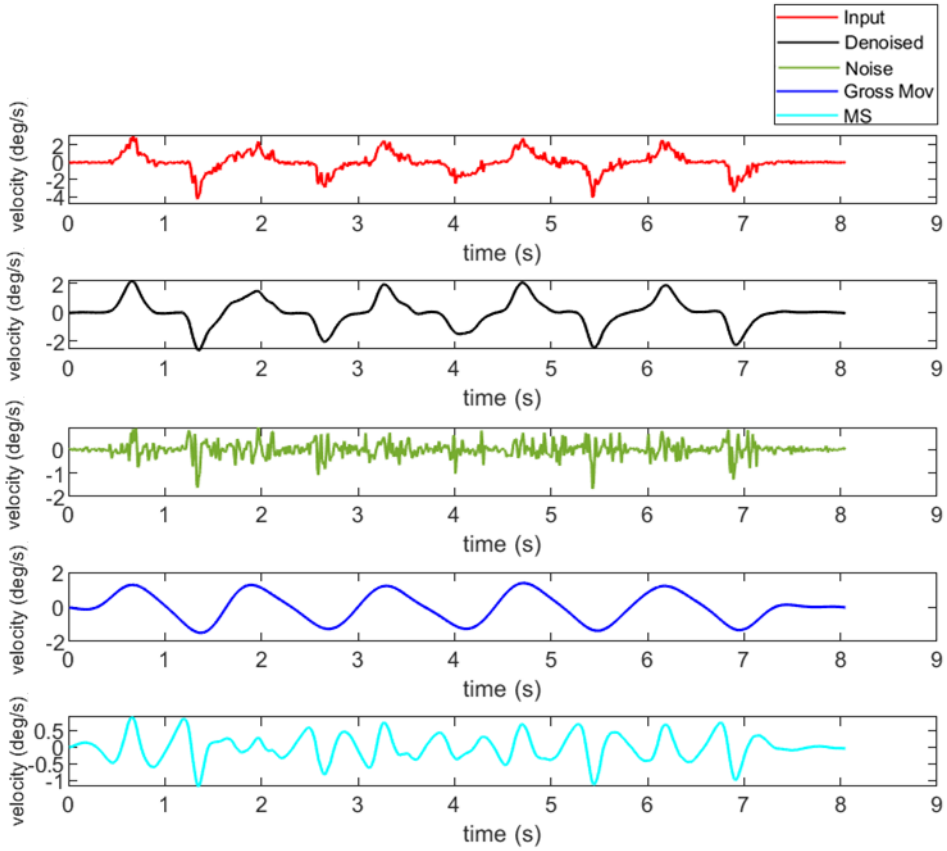

Figure 71 Participant 10's Signal Decomposition Results: Input signal (red) and resulting denoised signal (black) decomposed into noise (green), gross movement (dark blue) and movement smoothness (cyan)

Appendix D Additional Documentation for Public Engagement Activities

D.1 Short-form guidance for reporting involvement of patients and the public during public engagement activities checklist

Table 30 Short-form GRIPP2 Checklist for Chapter 7 of Thesis titled: "Human and Biomechanical Considerations in Hand Joint Disease"

Section and topic	Description	Reported on page No.
1. Aim	Report the aim of PPI in the study	145
2. Methods	Provide a clear description of the methods used for PPI in the study	146–149,160
3. Study results	Outcomes—Report the results of PPI in the study, including both positive and negative outcomes	149–163
4. Discussion and conclusions	Outcomes—Comment on the extent to which PPI influenced the study overall. Describe positive and negative effects	171–173
5. Reflections/critical perspective	Comment critically on the study, reflecting on the things that went well and those that did not, so others can learn from this experience	171–173

Appendix E Accompanying documentation for PPIE Reflections

E.1 Long-form guidance for reporting the involvement of patients and the public for entire project

Table 31 Long-form guidance for reporting the involvement of patients and the public for overall doctoral research project titled: "Human and Biomechanical Considerations in Hand Joint Disease"

Section and topic	Subsections	**Reported on page No.**
Section 1: Abstract	1a: Aim 1b: Methods 1c: Results 1d: Conclusions	2
Section 2: Background	2a: Definition 2b: Theoretical underpinnings 2c: Concepts and theory development	175
Section 3: Aims	N/A	176
Section 4: Methods	4a: Design 4b: People Involved 4c: Stages of Involvement 4d: Level or nature of involvement	176–180
Section 5: Capture or measurement of PPI impact	5a: Qualitative evidence of impact 5b: Quantitative evidence of impact 5c: Robustness of measure	180-182
Section 6: Economic assessment	N/A	N/A
Section 7: Results	7a: Outcomes of PPI 7b: Impacts of PPI 7c: Context of PPI 7d: Process of PPI 7e: Theoretical development 7f: Measurement 7g: Economic assessment	183-186
Section 8: Discussion and Conclusions	8a: Outcomes 8b: Impacts 8c: Definition 8d: Theoretical underpinnings 8e: Context 8f: Process 8g: Measurement and capture of PPI impact 8h: Economic assessment 8i: Reflections/critical perspective	186-198

E.2 Interview Guide used for PPI reflection interviews

Exploring the impact of PPIE in engineering spaces

1. Introduction

Patient and public involvement (PPI) refers to research being carried out 'with' or 'by' members of the public rather than 'to', 'about' or 'for' them [1]. PPI is about working in partnership with the public throughout the research process rather than viewing them as 'subjects'. This approach is highly encouraged in healthcare research. It is based on the fundamental principle that those who are affected by the outcomes or process of research have a right to influence the research project's aims, as well as how it is conducted [2]. As a discipline which bridges the gap between engineering and healthcare, biomedical engineering, at its best, is a field that also promotes the collaboration between researchers and non-researchers, such as health scientists, clinicians and policymakers, however, public members with lived experience are less frequently included as partners on these health research teams [3].

Barriers to implementing PPI in research often originate from a lack of understanding. Researchers may not know what it involves, how to support public contributors and the difference between PPI and formal qualitative research [4]. Therefore, there is scope for increasing the PPIE practice, education and thus the evidence base within biomedical engineering to help establish it as a common approach in the engineering research process. To this end, an engineering doctoral research project about hand biomechanics at the University of Southampton (undertaken by author TAM) was designed alongside members of the public ('PPI members') to have a PPIE focus with a computational modelling background. We hope to reflect on its potential impact in engineering spaces and thus, provide lessons learned and recommendations for engineers who want to be more proactive with PPI in their own work. To capture the learnings, we hope to reflect on the experiences of those involved, engaged and those who have supported this project in the form of semi-structured interviews.

2. Interview Aim

To explore the experience of those involved in, engaged by or supported a co-designed, public-centred and long-term biomechanical computational engineering PhD research project

3. Background to Biomechanical Engineering PhD Research Project

Hand osteoarthritis (OA) is the most common musculoskeletal joint condition, affecting millions of people in the ageing population worldwide [5]–[9]. OA in the hands is highly prevalent [10], [11]. As well as causing chronic pain, hand OA can have a significant impact on hand function,

limiting an individual's ability to perform everyday tasks. Often computational modelling methods are used in biomechanical engineering to assess conditions such as OA.

Ethical approval was granted for Secondary Data Analysis of an existing hand. The training dataset represented ten consenting participants (5F:5M, mean age 31yrs, range 27 – 37yrs), who were free from hand or wrist disease or injury and had been recruited for a finger motion capture and imaging study (IRAS Ref: 14/LO/1059) [12]. From these datasets, computer-generated models, such as musculoskeletal* (MSK) or statistical shape models** (SSMs) can be created to describe trends in the data. Therefore although the datasets available describe those free from known hand or wrist disease, it was important for us to include voices that represent the OA lived experience to better understand how these models can be used to support patients.

*MSK models: Computational models that can be generated from medical imaging and motion capture data. It is often used in biomechanical research to simulate and study the movement and forces acting on the MSK system of the human body during different activities.

**SSMs: Computational models that can be generated from medical imaging using computer visualisation tools. It is often used in biomechanical research to analyse and quantify the differences in the shapes of biological structures.

Early stage consultations with members of the public, living with hand OA, marked the beginning of a biomechanical engineering PhD project that would split its efforts between/into two methodological groups: (a) computational modelling and (b) public engagement to address/acknowledge the lived-experience factors discussed above, and wherever possible and appropriate, work closely with PPI Partners throughout the research process (i.e. the design, execution and dissemination.).

If you would like to read more about PPI please see: [1], [13]–[18]

If you would like to read more on Statistical Shape Modelling please see: [19]–[23]

4. During the Interview

You will be using Microsoft Teams to conduct and record interviews. I have emailed calendar invites for confirmed interviews.

At the beginning of the interview:

1. Enter the designated Microsoft Teams meeting for each interviewee (Section 6)

2. Once both you (the interview) and the interviewee have joined

3. Hit the record button and remind the interviewee that the meeting is being recorded for transcription purposes and ask if they are happy to proceed with this knowledge (they have already signed consent forms, but this is just so extra verbal consent at the start of the meeting)

4. Proceed with the Interview Questions (Section 5)

We would like to talk about two topics, with a few flexible questions for each. The first is quite general with regard to PPI in engineering spaces, whereas the second is more specific about their experiences with this project.

5. Interview Questions

Please ensure that all participants are asked the same questions, but feel free to adapt as necessary. Each interview is expected to last approximately 45 minutes to 1 hour, so please be mindful of the time. I recommend creating a brief opening of two to three lines to introduce the interview to the interviewee at the start of the recording.

For example: *Patient and Public Involvement has become a key component of a biomechanical engineering project conducted by Tinashe Munyebvu. Working with members of the public throughout the project has had an impact on Tinashe, the project itself and the people involved or engaged by it. These interviews are a way for us to gauge your experiences with this project as a member of that third group. We would like to talk to you about two topics, with flexibility for each. The first is quite general concerning public involvement in engineering research spaces, whereas the second is more specific about your experiences with this project.*

Questions to ask are as follows:

<u>Part 1: General questions about PPI in engineering spaces</u>

1. When did you first learn about Patient and Public Involvement?

2. What role do you believe PPI plays in research?

3. Have you heard/seen PPI embedded in a project such as this one?

4. What do you think is particularly positive or beneficial with embedding PPI in a field like this and why?

5. What do you think could be challenging about this approach and why?

<u>Part 2: Participant experience</u>

6. Were you involved in/ engaged by/ Did you support this project? If so, how?

7. Why did you get involved in/engaged by/support this project?

8. What do you think works with how you were involved in/engage by/support this project?

9. Why do you think it works?

10. What could work better or be done differently?

These interviews loosely follow the same interview guide as previously published literature that explores the experiences of patient research partners and researchers involved in long-term co-creative research collaboration [24].

6. Interviewees

We have confirmed seven interviews in total.

Pseudonyms	Role in the project
AC1, AC2	Academic Supports: Providing support, guidance and platforms for engaging with undergraduate teaching modules
EX1	External PPI Support: Providing support and guidance on the PPI aspect of the project, particularly at the beginning
SP1, SP2	Project Supervisors: Providing support and guidance (all aspects, PPI, engineering, etc.)
PPI1, PPI2	Public contributors: Members of the Public with hand OA lived experience involved in the project

7. References

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