University of Southern Queensland

Faculty of Health, Engineering and Sciences

Conceptual Design of a Total Wrist Arthroplasty

A dissertation submitted by

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ABSTRACT

Total wrist arthroplasty surgery is often performed on patients suffering late stage pancarpal rheumatoid arthritis for the purpose of maintaining functionality. Current wrist arthroplasty on the market have a high rate of failure due to various complications such as component loosening, fracturing and dislocation. This dissertation aims to overcome these complications through the conceptual design of a total wrist arthroplasty. The engineering design process consisted of; identification of a need, definition of the problem/specifications, search for existing solutions and developing designs (Draper 2009). This research will be utilised to determine a working design for the wrist arthroplasty which will be further developed to a marketable product.

University of Southern Queensland

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Limitations of Use

CANDIDATES CERTIFICATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Paul Johnstone

[redacted]

Paul Timothy Johnstone [redacted] 11th October 2017

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TABLE OF CONTENTS

CONTENTS	PAGE
ABSTRACT	5
LIMITATIONS OF USE	7
CANDIDATES CERTIFICATION	9
ACKNOWLEDGEMENTS	11
TABLE OF CONTENTS	13
LIST OF FIGURES	17
LIST OF TABLES	20
ABBREVIATIONS	23
CHAPTER 1 – INTRODUCTION	
1.1 Outline of the study	25
1.2 Introduction	25
1.3 The problem	26
1.4 Research Questions	26
1.5 Research Objectives	27
1.6 Chapter List	27
1.7 Conclusions	29
CHAPTER 2 – RESEARCH DESIGN AND METHODOLOGY	
2.1 Introduction	30
2.2 Dissertation Methodology	30
2.2 Dissertation Methodology	33
CHAPTER 3 – IDENTIFY NEED FOR TOTAL WRIST ARTHROPLASTY	
3.1 Introduction	38
3.2 Cause of Wrist Failure	
3.21 Introduction	39
3.22 Osteoarthritis	39
3.23 Post Traumatic Arthritis	40
3.24 Kienbocks disease	41
3.25 Scapholunate Advanced Collapse	42

TABLE OF CONTENTS

CONTENTS **PAGE**

3.26 Rheumatoid arthritis 44

3.27 Conclusion 46

3.3 Surgical Treatments.

3.31 Introduction 47

3.32 Selection of Surgical Procedure 48

3.33 Early Stage Arthritis Treatments

3.331 Ablative Treatment 53

3.332 Arthrodesis Treatment 56

3.34 Late Stage Arthritis Treatment

3.341 Arthrodesis Treatment 58

3.342 Total Wrist Arthroplasty 60

3.35 Conclusion 63

CHAPTER 4 – DETERMINING DESIGN PARAMETERS

4.1 Introduction 64

4.2 Research into Wrist 64

4.21 Anatomy of the Wrist

4.211 Bones of the Wrist 65

4.212 Joints of the Wrist 66

4.213 Ligaments of the Wrist 69

4.22 Biomechanics of Wrist

4.221 Introduction 75

4.222 Evolution of Wrist Theory. 76

4.223 Wrist Kinematics 83

4.224 Dart Throwers Motion 83

4.225 Relevant Information on Wrist for Design Parameters 84

4.3 Failure Analysis 85

4.4 Determining Design Parameters 122

CHAPTER 5 – Conceptual Design of a Total Wrist Arthroplasty

5.1 Introduction 128

5.2 Design Information 128

TABLE OF CONTENTS

CONTENTS **PAGE**

5.3 Concept Design 132

CHAPTER 6 – CONCLUSION

6.1 Introduction 139

6.2 Conclusions 139

6.3 Further Research and Recommendations 141

CHAPTER 7 – REFERENCES 143

CHAPTER 8 - APPENDICES

8.1 Ligaments of Wrist 149

8.2 Wrist Kinematic Theories 166

8.3 Literature Review 174

8.4 Project Specification 194

8.5 Progress Report 197

LIST OF FIGURES

Number	Title	Page
2.1	Design Process Steps	29
2.2	Systematic Literature Review Process	33
3.1	Wrist after Distal Radius Fracture	39
3.2	Wrist Suffering Kienböck's Disease	40
3.3	Wrist Suffering SNAC (level 3)	42
3.4	Decisional Flow Chart for Type of Surgery	47
3.5	Surgical Technique in Relation to Functional Requirements	48
3.6	Wrist after a Proximal Row Carpectomy	53
3.7	Incisions for Wrist Denervation	54
3.8	Wrist (SNAC 3) after Four-Corner Fusion (4CF)	56
3.9	Comparison of Wrist Motion for different surgeries	60
4.1	Bone Anatomy of the Wrist	64
4.2	Joints of the Wrist	65
4.3	Motions of the Human Wrist	74
4.4	Swanson Wrist Replacement	85
4.5	Original Volz Arthroplasty	89
4.6	Modified Volz Wrist Arthroplasty	90
4.7	Meuli I (Polyester Head)	93
4.8	Meuli II (Polyethylene Head)	94
4.9	Meuli III (Metal-on-UHMWPE Articulation)	94
4.10	Trispherical Wrist Arthroplasty	97
4.11	Guepar Wrist Arthroplasty	100
4.12	Biaxial Wrist Arthroplasty	102
4.13	Destot Wrist Arthroplasty	105
4.14	Anatomic Physiologic Wrist	107
4.15	Universal Wrist Arthroplasty	109
4.16	Universal Wrist Arthroplasty (second edition)	110
4.17	Universal 2 Wrist Arthroplasty System	112
4.18	Total Modular Wrist System (TMW)	115
4.19	Maestro Wrist Reconstructive System	117
4.20	Remotion Wrist Arthroplasty	119
5.1	Dimensions of Carpal Plate of Maestro Arthroplasty	128

LIST OF FIGURES

Number	Title	Page
5.2	Dimensions of Capitate stem of Maestro Arthroplasty	128
5.3	Dimensions of Convex Head of Maestro Arthroplasty	129
5.4	Ellipsoid	129
5.5	Dimensions of Radial Components of Maestro	130
5.6	Inclination of the Wrist	130
5.7	Dimensions of Fixation Screws for Maestro Arthroplasty	131
5.8	Sketches of Distal Carpal Plate	132
5.9	Creo Model of Distal Carpal Plate View 1	133
5.10	Creo Model of Distal Carpal Plate View 2	133
5.11	Sketches for Ellipsoid Convex Head	134
5.12	Creo Model of Convex Head View 1	135
5.13	Creo Model of Convex Head View 2	135
5.14	Sketches of Radial Component	136
5.15	Creo Model of Radial Component	136
5.16	Sketch of Fixation Screw	137
5.17	Creo Model of Fixation Screw	137
8.1	Palmer Radiocarpal Ligaments	149
8.2	Ulnocarpal Ligaments	154
8.3	Palmer Midcarpal Ligaments	156
8.4	Triangular Fibrocartilage Complex	160
8.5	Palmer Midcarpal Ligaments	164
8.6	Navarro 3 Column Theory	166
8.7	Link Theory	168
8.8	Modified Column Theory	169
8.9	Oval Ring Theory	171
8.10	Bone Anatomy of the Wrist	202
8.11	Motions of the Human Wrist	205
8.12	Systematic Literature Review Process	227
8.13	Progress schedule	234

LIST OF TABLES

Number	Title	Page
1.6	Chapters of Dissertation	26
2.1	Design parameters table	30
2.2	Different Methodologies for Literature Review	31
3.1	Range of Motion for TWA	60
4.1	Ligaments of the Wrist	68
4.2	Functions of Ligaments	70
4.3	Evolution of Wrist Kinematic Theories	75
4.4	Description of wrist kinematic theories	76
4.5	Results of Studies on Swanson Arthroplasty	86
4.6	Results of Studies on Volz Wrist Arthroplasty	91
4.7	Results of Studies on Meuli Wrist Arthroplasty	95
4.8	Results of Studies on Trispherical Wrist Arthroplasty	98
4.9	Results of Studies on Geupar Wrist Arthroplasty	101
4.10	Results of Studies on Biaxial Wrist Arthroplasty	103
4.11	Results of Studies on Destot Wrist Arthroplasty	106
4.12	Results of Studies on Anatomic Physiologic Wrist	108
4.13	Results of Studies on Universal Wrist Arthroplasty System	111
4.14	Results of Studies on Universal 2 Wrist Arthroplasty System	113
4.15	Results of Studies on Total Modular Wrist System	116
4.16	Results of Studies on Maestro Wrist Reconstructive System	118
4.17	Results of Studies on Remotion Wrist Arthroplasty	120
4.18	Design Parameters Table	121
8.1	Further Description of Project Stages	195
8.2	Ligaments of the Wrist	204
8.3	Causes of Failure – Table 1	213
8.4	Causes of Failure – Table 2	214
8.5	Causes of Failure – Table 3	215
8.6	Causes of Failure – Table 4	215

LIST OF TABLES

Number	Title	Page
8.7	Failure Mechanism Table	216
8.8	Further description of Project Stages	223
8.9	Different Research Methodologies	225
8.10	Risk Assessment Table	231
8.11	Possible Consequences Table	231
8.12	Risk Assessment of Information used in Design of Implant	232
8.13	Risk Assessment on Completion of Project	232
8.14	Resource Planning	233

ABBREVIATIONS

SLAC - Scapholunate Advanced Collapse

SNAC - Scaphoid Non-union Advanced Collapse

PRC – Proximal Row Carpectomy

4CF – Four Corner Fusion

TWF – Total Wrist Fusion

TWA – Total Wrist Arthroplasty

DTM – Dart Throwers Motion

ROM – Range of Motion

VAS - Visual Analog Scale

STT – Scapho-Trapezio-Trapeziodal

DASH – Disability of the Arm, Shoulder and Hand

NSAID - Non-Steroidal Anti-Inflammatory Drug

DISI - Dorsal Intercalated Segment Instability

VISI – Volar Intercalated Segment Instability

QALY - Quality Adjusted Years

ADL - Activities of Daily Living

PRWE - Patient Related Wrist Evaluation

TMW - Total Modular Wrist System

FDA – Food and Drug Administration

CHAPTER 1 – INTRODUCTION

"All prostheses will fail sometime. It is a race between the life of the patient and the life of the prosthesis"

(Wang, cited in Gonzalez-Mora et al. 2011, p. 375)

1.1 Outline of the study

Wrist arthroplasty has a history of high failure rate due to complications such as loosening of components, fracturing and dislocation this has significant implications for the patient. This dissertation aims to address the aforementioned limitations through a conceptualise design for a total wrist arthroplasty, using an evidence based design methodology. The design methodology utilised the steps of; identification of a need, definition of the problem/specifications, search for existing solutions and developing designs. First, the need of the wrist arthroplasty surgery was examined. This specifically examined the various forms of arthritis that cause the wrist to fail while simultaneously exploring the surgical options available to the patient. Following this, the findings were used to identify gaps in surgical outcomes of current wrist arthroplasty, the patient candidature and key indicators of post-operative success. Definition of the problem/specifications and search for existing solutions were addressed through review of optimal design parameters. This was achieved through failure analysis of past wrist arthroplasty design and research into wrist anatomy / biomechanics. Finally, these design parameters were then applied to determine an initial concept wrist arthroplasty design.

1.2 Introduction

Total wrist arthroplasty is a surgical option for a patient suffering late stage arthritis who wish to maintain range of motion within the wrist. This surgical procedure has been viewed as a novel approach due to its high rate of complications. These complications include fracture of implant, pain in wrist, tendon imbalance, component loosening, ulnar drift, soft tissue imbalance, recurrent synovitis, infection, malposition, subluxed component and dislocation (Reigstad 2014), (Lawler & Paksima 2006), (Lin & Paksima 2017). Although the total wrist arthroplasty has been plagued with complications in its design the advantages of the procedure necessitate the need for an improved design. Conceptual designs for the total wrist arthroplasty will be devised in this dissertation to address the previously mentioned complications.

1.3 The Problem

Current total wrist arthroplasty have a high rate of complication often requiring revision surgery. This has significant impact on the patient including; financial, increased infection risk, increased risk of complications, significantly increased failure rate on future revision surgery, psychological burden and overall decreased functionality of the wrist (Lin & Paksima 2017) (Moussa et al. 2015). This has become more of a challenge with the increased life expectancy of patients (Moussa et al. 2015). Wrist arthroplasty designs must overcome this problem by improving the longevity of these designs.

1.4 Research Questions

To determine the conceptual designs for our wrist arthroplasty the following research questions will need to be addressed

1. What are the various forms of arthritis that cause it to fail and how do they differ?

2. What are the various surgical options available to the patient and what are the strengths and weakness?

3. Why is the wrist arthroplasty surgical option necessary and what is the typical patient requiring this option?

4. What is the anatomy and biomechanics of the wrist? What design parameters are important in the recreating the wrist?

5. What are the limitations and strengths of all previously available wrist arthroplasty designs? How can these limitations and strengths be used to determine relevant design perimeters?

6. How can the determined design parameters be applied to conceptualise a wrist arthroplasty design?

1.5 Research Objectives

There will be a set of learning objectives that will need to be completed to achieve the aim of the dissertation. These objectives include the following;

1. Understand the anatomy and biomechanics of the wrist.

2. Understand why the wrist fails

3. Identify the surgical need for the total wrist arthroplasty

4. Complete a detailed failure analysis on the previous designs.

5. Determine key design parameters from previous research

6. Apply the design parameters to conceptualise initial design for a total wrist arthroplasty

1.6 Chapter List

In achieving the aforementioned research objectives, the following chapters were devised;

Chapter Number	Chapter Title	Description of Chapter
2	Research Design and Methodology	Details the design methodology used in completing the dissertation. This methodology includes the steps of identification of a need, definition of the problem/specifications, search for existing solutions and developing designs. There are also the later steps of analyses of designs, decision on design, test and verify and communication of design which will be discussed in conclusion of dissertation
3	Identify Need for Total Wrist Arthroplasty	Identification of the need for the wrist arthroplasty procedure and the requirement for an improved design. These needs will be identified by exploring the various forms of arthritis that cause the wrist to

		fail and the various forms of surgery available to the patient will be explored. This research will identify the patients requiring the wrist arthroplasty surgery thus identifying the surgical need. The research will also identify the limitations of the wrist arthroplasty that are hindering is suitability as a surgical procedure.
4	Design Parameters	Design parameters were determined through exploration of the wrist anatomy /biomechanics while also conducting a failure analysis of previous commercially available wrist arthroplasty models. These design parameters included suitable material selection, alterations in design, suitable cementless fixation etc.
5	Conceptual Designs	Conceptualisation of a total wrist arthroplasty design utilising key design parameters. Sketches and FEA models were generated of the design along with discussion on the advantages and possible limitations.
6	Conclusion	Conclusion on key findings from the dissertation including the need for the arthroplasty surgery and better designed arthroplasty, key design parameters of arthroplasty along with the concept determined in dissertation. The progression following concepts were then considered in context of the later design steps of analyses of designs, decision on design, test and verify and communication of design.

Table 1.1 Chapters of Dissertation

1.7 Conclusions

This dissertation has determined a concept design of a total wrist arthroplasty aimed at addressing the high complication rates of previous design. This concept design was developed through failure analysis of previous designs in conjunction with research on the anatomy / biomechanics of the wrist. It is intended that the results of this dissertation will be utilised in the development of a marketable total wrist arthroplasty design.

CHAPTER 2 – RESEARCH DESIGN AND METHODOLOGY

2.1 Introduction

The dissertation methodology consisted of the initial steps of the engineering design process which are; identification of a need, definition of the problem/specifications, search for existing solutions and developing designs. Concurrently, a systematic literature review was conducted to collect relevant information while simultaneously critically evaluating the source of the information. The results of both of these methodologies were used in generating a concept design of a total wrist arthroplasty.

2.2 Dissertation Methodology

Utilisation of an evidence design methodology is the integral to the success in the design of a new product. This process consists of several key steps which were developed from Dartmouth Engineering Design Model (Draper 2009).

1. Identification of a need
2. Definition of the problem/specification
3. Search for existing solutions
4. Develop Designs
5. Analyze of Designs
6. Decision on Design
7. Test and Verify Prototype
8. Communication of Results

Figure 2.1 Design Process Steps (Draper 2009)

Dissertation was limited to first four steps of the design process due to the limited scope.

Identify the Need (Step 1)

The first step is to identify the need for the total wrist arthroplasty surgery. This involves understanding the various forms of arthritis causing the wrist to fail and the surgical options available to the patient. This will identify why the arthroplasty is an important surgical option for certain patients wishing to maintain a functional wrist. This research will also identify the limitations in the arthroplasty design that need to be address through the design process.

Determining Design Parameters (Steps 2 and 3)

This section involved determine design parameters that will guide the conceptual design. The design parameters were determined by exploring the complexity of the wrist and limitations of previous total wrist arthroplasty designs. The wrist was explored by researching the anatomy and biomechanics which are imperative considerations in the successful design of a total wrist arthroplasty. Following this, a failure analysis of previous designs was conducted. This failure analysis process consisted of critical evaluation of previous total wrist arthroplasty failures to determine root causes of failure and possible corrective actions (Berk, N.D). Failure analysis will identify strengths and weakness in current designs while also ensuring an innovation of in the developed concept design. The information collected in the failure analysis and research into the wrist will be formulated into a table to identify design parameters to mitigate the identified limitations / requirements.

Design feature	Limitations / requirements	Cause	Design parameters

Table 2.1 Design parameters table

Conceptual Designs (Step 4)

This section identified a conceptual design using the previously determined design parameters. It is vital that the determine design concept meet all the design parameters, constraints and specifications that have been previously determined (Draper 2009). This will ensure that the design will overcome the limitations of current wrist arthroplasty. This concept will be examined along other concept determined through the company ‘Field Orthopaedics’ to determine a working design that will be further developed to a marketable total wrist arthroplasty.

2.3 Research Methodology

In researching to optimise the design of the total wrist arthroplasty there are several types of review strategies that can be employed that can be categorised into three broad categories. These categories include Traditional/ narrative, Systematic / quantitative and Meta- Analysis (Pickering N.D). Each category has it strengths and weakness which are detailed in table 2.1 below.

	Traditional/ narrative	Systematic/ quantitative	Meta-Analysis
Description	Narrative review utilises a less rigorous approach. The literature is qualitative analysed with no formal attempt to rate the papers credability. The author contrasts the papers in narrative fashion comparing the papers when required	Systematic review answer a set of research objectives utilising a systematic process to review the available literature. The literature is selected by a predefined selection criteria with a wide selection of research investigated to ensure all relevant research is considered which minimises bias in research.	Meta-Analysis summarises the results of systematic literature review using statistical methods to formulate a conclusion
Who utilises review methodology	Experts and University students	University Student	Team of Experts
How are papers selected and compiled	Rarely systematic	Systematic	Systematic
Comparing papers	Expert evaluation	Quantitative or expert evaluation	Expert Evaluation
Statistical Analysis	No	If you want to	Yes
Structure of paper	Narrative	Standard	Standard
Ease of updating	Limited	Easy	Statistical Analysis must be redone

Table 2.2 Different Methodologies for Literature Review (Pickering N.D), (Elsevier N.D), (University of Southern Australia N.D)

This dissertation will utilise a systematic literature review approach as is best suited for the following reasons;

- The systematic literature is often utilised by university student's due to the fact it suits their style of dissertation.
- The systematic literature review allows the use of quantitative analysis to compare papers and doesn't necessary require the expert evaluation.
- Systematic literature review helps the student to improve the knowledge on the research topic
- The systematic literature review is easier to update then the other methodology techniques
- The systematic literature review is not as in-depth and convoluted as the meta-analysis which can take large number of researchers to complete. Thus, the meta- analysis process will make the dissertation workload too large to complete by the due date.
- The systematic literature review is more structured and analytical then the narrative approach.

The systematic literature review uses a systematic approach to collect and evaluate literature papers. The methodology is the same regardless of the topic and is outlined below in figure 2.1.

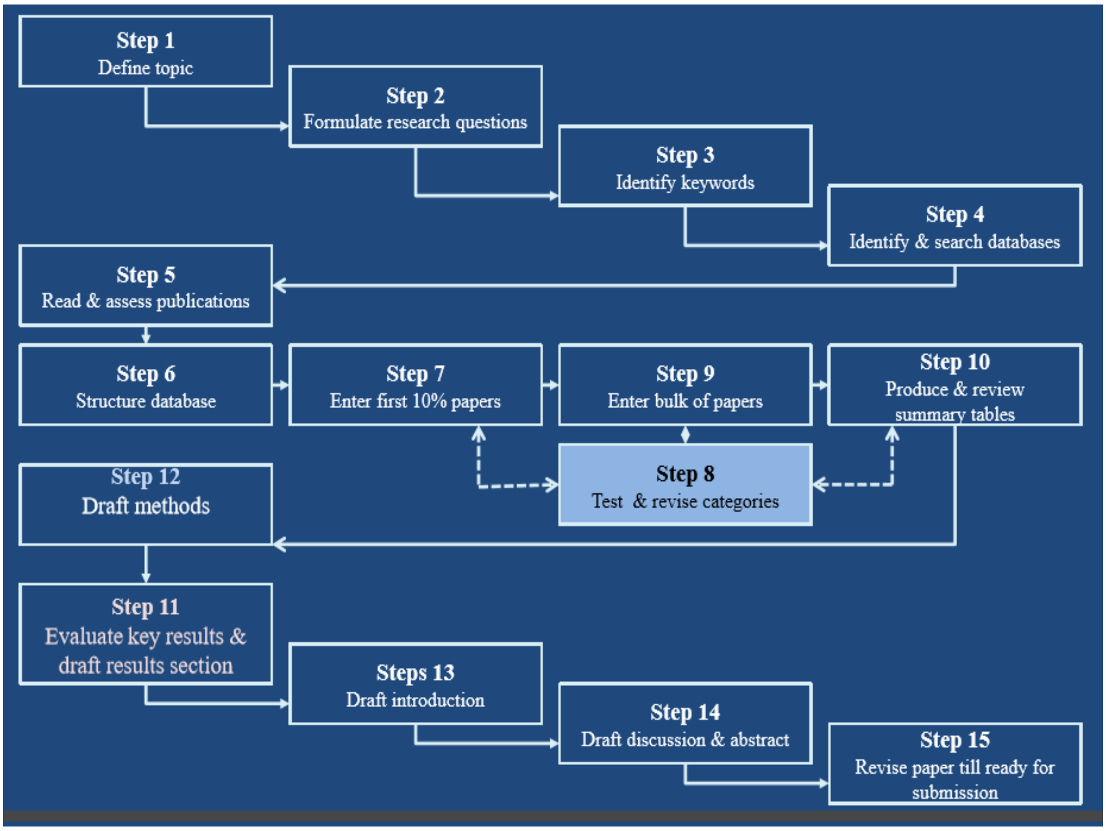


Figure 2.2 Systematic Literature Review Process (Pickering N.D)

The first steps in the systematic review process is to define a topic where specific research questions/keywords will be defined. The research topic for this dissertation is designing the total wrist arthroplasty to reduce the complication rates. Research into this topic generated six research questions.

These research questions include;

1. What is the anatomic structure of the wrist and how does it function in the biomechanical actions?

2. What are the various forms of arthritis that cause it to fail and how do they differ?

3. What are the various surgical options available to the patient and what are the strengths and weakness of each surgical option?

4. Why is the wrist arthroplasty surgical option necessary and what is the typical patient requiring this surgical option?

5. What are the limitations and strengths of all previously available wrist arthroplasty that have been commercially available?

6. How can the previous research on the wrist and failure analysis of previous wrist arthroplasty be applied to conceptualise a wrist arthroplasty design?

The next step in the process was to determine key search terms in reference to the research questions which are outlined below

Anatomy

- Bones
- Ligaments
- Extrinsic
- Intrinsic
- Distal row
- Proximal row

Biomechanics

- Dart throwers motion
- Theories
- Biomechanics

Wrist failure

- Arthritis
- Osteoarthritis
- Rheumatoid arthritis
- SLAC
- SNAC

Surgical Treatments

- Ablative
- Arthrodesis
- Arthroplasty

Wrist Arthroplasty

- Arthroplasty
- 1st, 2nd, 3rd and 4th Generation
- Complication
- Failure
- History

The search terms will be utilised on the *Science Direct database*, *National Centre for Biotechnology Information Database* and the *University of Southern Queensland library journal article access*. These databases were selected due to the articles generated from the databases from credible sources and are peer reviewed.

The fifth step in the process was to review and critically evaluate the journal articles. This will involve defining a clear set of exclusion and inclusion criteria to determine what articles are relevant to the research questions which are outlined below;

Inclusion criteria

Journal articles on the topics of;

- wrist anatomy
- wrist biomechanics
- arthritic causes of wrist failure,
- surgical treatments of arthritic wrist

The use of case studies in determining of clinical outcomes of current wrist arthroplasty designs.

Articles from credible sources

Exclusion criteria

Theoretical case studies

Studies in other language where translation cannot be sourced

Findings from non-credible sources (e.g wikipedia)

20 articles meet the inclusion / exclusion criteria. The relevant information was extrapolated from these articles to form an information database. The articles were evaluated through use of the following categories;

- **Categories about paper:** Name of paper, authors of paper, databased that article was sourced from, date, search term, reference.

- **Evaluation of paper:** credability of authors, credability of study, evaluation of relevance and useful information.

The result from this literature review process were used to determine optimal design parameters for a total wrist arthroplasty. These design parameters were used in the conceptual design of a total wrist arthroplasty.

CHAPTER 3 – IDENTIFY NEED OF TOTAL WRIST ARTHROPLASTY

3.1 Introduction

This section will identify both the surgical need for the wrist arthroplasty surgery and the need for an improved wrist arthroplasty design. These will be determined by exploring the cause of wrist failure which include osteoarthritis, rheumatoid arthritis, Kienbocks disease, post-traumatic trauma and scapholunate advanced collapse (SLAC)/ scaphoid non-union advanced collapse (SNAC)). The surgical treatment options were also investigated, these included;

1) **Ablative surgery***:* Arthritic component of the wrist is surgically removed (Proximal Row Carpectomy (PRC)).

2) **Arthrodesis surgery:** Components of the wrist are fused together (Four Corner Fusion (4CF) and Total Wrist Fusion (TWF)).

3) **Total wrist arthroplasty (TWA):** Arthritic component wrist is surgically replaced with an artificial wrist.

This research will determine the surgical importance of the total wrist arthroplasty along with its limitations. This is important as it justifies the need for the total wrist arthroplasty surgery while simultaneously identifying the need to improve the wrist arthroplasty design.

3.2 Cause of Wrist Failure

3.21 Introduction

Arthritis is a chronic disease that severely affects the patient's quality of life. Arthritis results in inflammation of the joint that causes pain / stiffness making the completion of daily activities difficult (Brubacher & Jennings 2016). Brubacher & Jennings (2016) describes the process of arthritis as the deterioration of the articular cartilage that surrounds the bones of the wrist preventing the smooth articulation of the wrist joint. This deterioration of the cartilage eventually results in the bones of the wrist rubbing against each other which results in irreparable wrist joint damage. There are several types of arthritis that can be developed in the wrist which will be discussed below.

3.22 Osteoarthritis

Osteoarthritis is an irreparable disease caused by wear of cartilage within in the wrist resulting in pain to the patient. Brubacher & Jennings (2016) describes the cyclic process of osteoarthritis that develops due to wear of the smooth articular cartilage covering the bone coupled with an inability to repair itself due to limited blood supply. The bones surface is roughened from this wear decreasing availability of space between the bones. This decreased space eventuates in the bones rubbing against each other accelerating deterioration of the remaining cartilage until the wrist fails. Patients suffering from osteoarthritis have a wrist joint that is stiff and swollen (University of Washington 2017). This pain can severely restrict that functioning of the patient in performing everyday activities often restricting their quality of life. Osteoarthritis is a cyclic degenerative painful disease that results in the eventual failure of the wrist.

There several risk factors that predispose the individual as a higher risk to develop osteoarthritis. The age of the individual is a risk factor with the older generation are at higher risk due to the combination of impact on the cartilage extracellular matrix structure / components as well as declining chondrocyte function / response rate to stimuli that occur due to the aging process (Dewing, Setter & Slusher 2012). Another risk factor is gender of the patient with studies have shown nearly 40% of women over the age of 60 have developed osteoarthritis in hand or wrist (University of Washington 2017). Obesity and previous trauma to the wrist place a patient at a higher risk to develop osteoarthritis due to the damage these conditions have placed on the cartilage (Dewing, Setter & Slashed 2012). Osteoarthritis has several other causes for the disease to develop including endocrine and metabolic disorders, nutritional deficits, genetic lack of protection for cartilage, Kienbock's disease, scapholunate advanced collapse and post-traumatic conditions (University of Washington 2017). The older, obese and women patients are at a high risk to develop osteoarthritis with various causes such as Kienbock's disease, scapholunate advanced collapse and post-traumatic conditions often developing into osteoarthritis.

3.23 Post-Traumatic Arthritis

There are several conditions that are classed as post-traumatic conditions in the wrist. These include sequelae after distal radius fracture, scaphoid fracture, and scapho-lunate and intercarpal ligament injuries (Reigstad 2014). These conditions can be quite common in the general population especially the distal radius and scaphoid fractures. Reigstad (2014) notes that the occurrence of distal radius fracture and scaphoid fracture together in Norway have an annual incidence of about 42/10,000 resulting in about 20,000 factures in Norway annually. Distal radius fracture rarely results in osteoarthritis in the radiocarpal joint of the wrist but complex intraarticular fractures where surrounding cartilage has been damaged result in untreated joint incongruence which often leads to degenerative arthritis in the wrist (Reigstad 2014). The incidence of arthritis due to post traumatic conditions has been reduced as the as the majority of fractures are operative with treatments constantly improving (Reigstad 2014).

Figure 3.1 Wrist after Distal Radius Fracture (Reigstad 2014)

3.24 Kienböck's Disease

Kienböck's disease (also known as Lunate malacia) is a multifactorial disease that promotes the eventual collapse of the lunate bone resulting from avascularity of the wrist (Reigstad 2014). This avascularity of the wrist is caused by blood supply to the lunate being disrupted, causing the bone to die and slowly collapse (Brubacher & Jennings). The progression of this disease occurs in stages. Reigstad (2014) cites an article by Lichtman that describes that there are 4 stages to the disease with the final stage includes carpal collapse resulting in secondary wrist degenerative changes. The late stage of this disease results in irreversible damage to the wrist with the only option being either replacement of wrist (total wrist arthroplasty) or fusion of wrist (arthrodesis) (Reigstad 2014). There are several factors that have been postulated as increasing the likelihood of the occurrence of Kienböck's disease including the shape of the lunate bone, the length of the ulna, the shape of the radius, vascular vulnerability due to high intraosseus pressure and sex of patient (young men most often affected) (Reigstad 2014).

Figure 3.2 Wrist Suffering Kienböck's Disease (Reigstad, 2014)

3.25 Scapholunate Advanced Collapse (SLAC) and Scaphoid Non-union Advanced Collapse (SNAC)

Scapholunate advanced collapse (SLAC) in the wrist is usually predated by the presence of an incompetent scapholunate ligament resulting in an unbalanced scaphoid-lunate joint (Miller & Streubel 2016). SLAC is a common form of arthritis being responsible for 55% of cases of degenerative wrist arthritis with 95% of degenerative wrist arthritis occurring around the scaphoid (Rainbow et al. 2015), (Lyons & Weiss 2003). SLAC is an important form of arthritis affecting the scaphoid bone of the wrist which is closely related to Scaphoid Non-Union Advanced Collapse (SNAC). SNAC results from untreated scaphoid non-union in the wrist with 75- 100% of patients with longstanding non-union (greater than 5 years) demonstrated some arthritic degenerative change (Lyons & Weiss 2003), (Reigstad 2014). SLAC and SNAC are two prolific forms of arthritis that affect the scaphoid bone of the wrist resulting in the failure of the wrist.

Although SLAC and SNAC have different initial causes the progression of these arthritis are similar. Reigstad (2014) describes that both SLAC and SNAC create a dorsal intercalated segment that is unstable due to the scaphoid falling into flexion while the remaining proximal row bones falls into extension. This unstable segment in the wrist alters the wrist kinematics that results in degenerative arthritis developing in the wrist. SNAC and SLAC begin between the radial styloid tip and the distal scaphoid the progresses distally between the radius and scaphoid to the fracture/non-union (SNAC patients) or the whole radio-scaphoid joint (SLAC patients. This is followed by progression of the disease to the midcarpal joint of the wrist (Lyon & Weiss 2003), (Reigstad 2014). In the later stages of this disease the area between the scaphoid and lunate are affected resulting in the eventual collapse of the capitate leading to a widened scapholunate joint that is shortly followed by arthritis developing in the capitolunate joint (Reigstad 2014) (Miller & Streubel 2016). This development of SLAC and SNC arthritis in the wrist can be split into three stages which stage I involves the radial styloid-scaphoid joint, stage II encompasses the whole radioscaphoid joint and stage III encompasses capitolunate degeneration (Lyons & Weiss 2003). In conclusion both SLAC and SNAC arthritis originate in distal scaphoid progressing to the arthritis developing in the capitolunate joint.

The presence of SLAC results in a reduced quality of life for the patient. This is primarily due to several contradictions including exhibiting dorsoradial wrist pain when under high load demand especially in the full dorsoflexion position (push up position), decreased grip strength and limited range of movement (ROM) due to the arthritic changes at the radioscaphoid surface (Miller & Streubel 2016). This reduced quality of life means the patient must seek treatment. Regarding treatment it is vital that the patient is treated as early as possible for the greatest chance for complete recovery. When the patient is given surgical treatment for SLAC and SNAC before any degenerative changes are present it tends to halt the degenerative process. Alternatively, if the degenerative process has already begun within the wrist the surgical process will aid in slowing the arthritis but further arthritic degeneration of the wrist should be expected (Reigstad 2014). Patients exhibiting SNAC and SLAC in the wrist that have earlier surgical intervention have a greater likelihood of maintaining normal function of the wrist but it is often difficult to assess the need for the patient to undergo surgery (Reigstad 2014). In the later stages of progression of SLAC / SNAC more serious treatments such as total wrist fusion or total wrist arthroplasty may be the only viable options for a patient.

Figue 3.3 Wrist Suffering SNAC (level 3) (Reigstad, 2014)

3.26 Rheumatoid Arthritis

Rheumatoid arthritis is an autoimmune disease where the body's defences that typically protect it from infection attack the cartilage surrounding the radius and ulna bones while simultaneously softening the bone (Brubacher & Jennings 2016), (Dewing, Setter & Slusher 2012). Rheumatoid arthritis has a specific progression beginning with the triggering of an immune response causing the cells to produce autoantibodies and inflammatory cytokines. These antibodies then create a cascade of inflammation resulting in the formation of pannus that initially destroys the synovial lining then progresses to cartilage. (Brubacher & Jennings 2016), (Dewing, Setter & Slusher 2012), (Lawler & Paksima 2006). Rheumatoid arthritis is thus a contradictory disease in that body's defences are damaging the wrist until its eventual failure.

Patient suffering rheumatoid arthritis eventually develop severe arthritis throughout the wrist. Reigstad (2014) details that 50% of patients suffering from rheumatoid arthritis will develop arthritis throughout the wrist in the first two years while 90% will develop arthritis within 10 years. This disease is bilateral in nature and dramatically alters the biomechanics of the wrist. The development of rheumatoid arthritis causes the expansion and erosion of the synovial lining resulting laxity of the surrounding ligaments (Lin & Paksima 2017). This laxity causes the proximal carpal row of the wrist to sublux in the palmar and ulnar direction that results in a change in the center of rotation of the wrist (Lin & Paksima 2017). This results in instability in the wrist with the flexion/extension and radioulnar deviations being different. The altered kinematics of the wrist results in a hinge like motion with the axes of rotation being closer to the capitate (Lawler & Paksima 2006). This change in biomechanics accelerates the cartilage erosion which causes the eventual failure of the wrist (Lin & Paksima 2017). Rheumatoid arthritis is a devastating disease that alters the wrist biomechanically and structurally with little information known on what is the underlying cause.

The cause of rheumatoid arthritis is still a mystery. Brubacher & Jennings (2016) details that the cause of rheumatoid arthritis is unknown with some researchers suggesting its development is associated with bacteria and/or virus which is contracted from the surrounding environment. While University of Washington (2017) notes that some researchers believe that some individuals can be genetically predisposed to have this form of arthritis with the disease often seen running in families. There is much debate on the cause of osteoarthritis which is either genetic or bacterial in nature but what can be certain is that particular factors put an individual at a higher risk to contract the disease. The articles by University of Washington (2017) and Dewing et al (2017) outline these risk factors include family history (risk doubles with first degree relative having rheumatoid arthritis), old age, women (3.6% compared to 1.7% for men), high rates disease onset associated during pregnancy, cigarette smoking can increase risk more than 2-fold and is the strongest risk factor and presence of the human leukocyte antigen. When a patient does have these risk factors in their life they are much more likely to contract the rheumatoid arthritis disease and start to exhibit symptoms.

The symptoms of the patient with rheumatoid arthritis can range from mild to debilitating with relative impact to the patient's quality of life. University of Washington (2017) describes that individuals exhibiting rheumatoid arthritis have stiffness and swelling in the wrist, fatigue that ranges from mild to debilitating and ulnar drift of the fingers which is where the fingers drift at the knuckles towards the small fingers. Brubacher et al (2016) also reports that the inflammation caused by rheumatoid arthritis can result in the tendons eroding which then results in the fingers drooping which is known as extensor lag. The tendons at the back of the hands and fingers which are known as the extensors tendons are most vulnerable to extensor lag. University of Washington (2107) also recognised that if left untreated rheumatoid arthritis it can leave the patient with permanent damage to bone/cartilage as well as surrounding soft tissue and could also result in the rupture of tendons in the hand and wrist causing loss of normal function of the hand.

The first line of treatment for the diseases is to usually try to mitigate disease progression through drug therapy and splinting (Brubacher & Jennings 2016). Reigstad (2014) states that some of the drug therapy options include new biological therapeutic options (TNF α inhibitors) which are very efficient, but due to their side effects the first choice for all patients is still the more traditional drugs (disease modifying anti-rheumatic drugs (DMARD's), NSAIDS and cortisone). Although using drug therapy will slow down disease progression throughout the wrist but eventually the patient will exhibit painful symptoms resulting in a poorer quality of life whereby surgical treatment may be the only option. The type of surgery performed depends on the progression of the disease and what the patient requires from the surgery. Reigstad (2014) details that Synovectomies is a surgical option performed on patient exhibiting painful inflammation with the main goal of the treatment to prevent extensor tendon rupture in the wrist. Although this surgical option protects the extensor tendon this option is severely limited in its viability due to the arthritis degeneration in the wrist still progress after surgery. Treatment for early stage rheumatoid arthritis where only the radiocarpal arthritis has developed consists of a combination of denervation and partial wrist fusion with the midcarpal joint being spared in the treatment (Lin & Paksima 2017). While for later stage rheumatoid arthritis the surgical options typically available to the patient include total fusion of the wrist or total wrist arthroplasty for patients who wish to preserve motion (Lin & Paksima 2017).

3.27 Conclusion

There are several forms of arthritis in the wrist that cause pain to the patient who then seek surgical treatment. These forms of arthritis include osteoarthritis, post-traumatic arthritis, Kienbocks disease, scapholunate advanced collapse, scaphoid non – union advanced collapse and rheumatoid arthritis. The arthritis can be disease based in nature such as rheumatoid arthritis which occurs due to the antibodies attacking the cartilage of the bones or Kienbocks disease where the lunate bone collapses due to disruption of blood supply to this bone. The arthritis can also be traumatic in nature such as post traumatic arthritis where complex intraarticular fractures results in surrounding cartilage has been damaged leading to degenerative arthritis or SNAC / SLAC where either untreated non-union surrounding the scaphoid or incompetent scapholunate ligament lead to progression of arthritis throughout the wrist. Although the initial causes differ, the different forms of arthritis typically result in a disruption of the kinematics of the wrist. This cause the bones to rub against each other leading to the arthritic decay of the bones, leading to the failure of the wrist and the need for surgical treatment.

3.3 Surgical Treatments

3.31 Introduction

Patient suffering an arthritic wrist will often seek treatment options to relieve pain, regain mobility and limit disease progression. The first treatment option for early stage arthritis is generally non-surgical treatment. Reigstad (2014) list several of these options which include analgesics like NSAIDs or paracetamol, change and adaption of the activity level and the use of different kinds of splinting devices, from slight to significant restriction of wrist motion. These non-surgical treatments will often slow but will not stop the disease progression (Reigstad, 2014). If the arthritis has progressed to the stage of cartilage degeneration the only viable option is to undergo surgery. There are several surgical options available to a patient's whose wrist is at risk of failure due to cartilage degeneration. These treatment options are grouped into three different categories which include ablative surgery, arthrodesis surgery and arthroplasty surgery. The surgical procedures are also grouped as either early or late stage arthritis treatment dependent on the degree of the disease progression. This following section will first discuss how the surgeon evaluates the best surgical procedure for the patient. Following this, each surgical procedure will be discussed in more detail describing the procedure, outcomes experienced by patient, outcomes of the surgery. This section will illustrate the surgical need for the total wrist arthroplasty and its limitations.

3.32 Selection of Surgical Procedure

The selection of the surgery is a complex task that requires the consideration of various factors which increases the likelihood of post-operative success. These factors include the age of patient, demands on wrist, condition of the wrist, residual mobility of wrist and the arthritic conditions present. Surgeon may choose to use a flow chart to aid in their decision on the surgery for the patient as shown in figure 3.4 below.

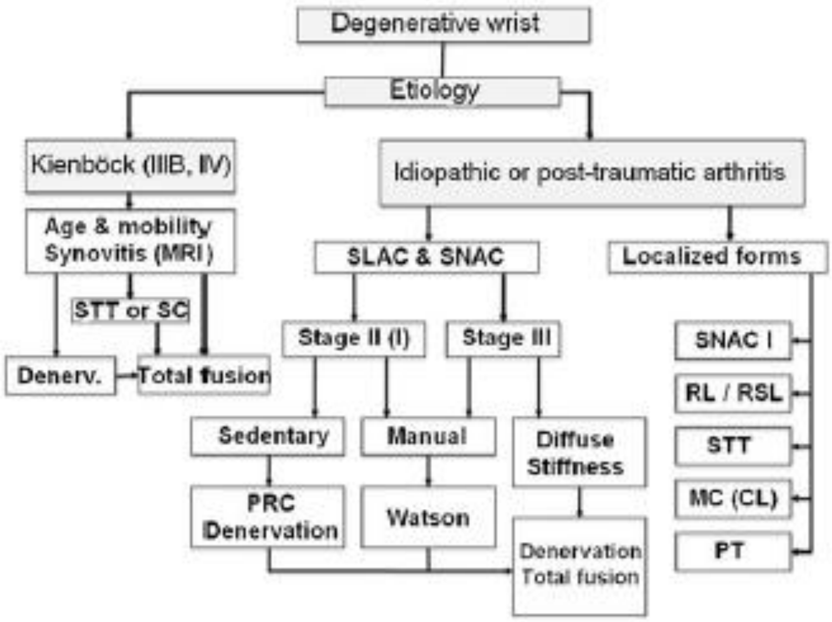


Figure 3.4 Decisional Flow Chart for Type of Surgery (Laulan et al. 2011)

The use of the above flow chart in determining the optimal surgical procedure for the different arthritic conditions will be discussed. As shown in figure 3.4 the treatment of Kienbock's disease consists of two surgical options of denervation or total wrist fusion. When Kienbock's disease has progressed to it later stages where synovitis is present (IIIB or IV) only viable option is total wrist fusion (Laulan et al. 2011). Proximal row carpectomy (PRC) and scapho-trapezio-trapeziodal (STT) fusion are not viable treatments for Kienbock's disease due to their inferior results. Laulan et al. (2011) notes that STT fusion results in more failures than total wrist fusion with a 40% complication rate and 14% non-union rate. Figure 3.4 shows that for SLAC and SNAC wrist arthritis the viable surgical treatment are PRC, denervation, Watson and total wrist fusion. For stage I and II of the disease PRC, denervation and Watson are the main surgical options while for stage III of the disease Watson, denervation and total wrist fusion are the surgical options. Figure 3.4 shows that a patient must decide between two or three surgical options that vary on the type arthritis present within the wrist. When deciding on the type of surgery there are factors that must be considered which include age of patient, residual mobility in wrist, activity of the patient, radiolunate joint space and presence of synovitis around the wrist (Laulan et al. 2011). The article by Laulan et al. (2011) examined the relationship between the surgical options and aforementioned decision factors with the results shown in figure 3.5 below.

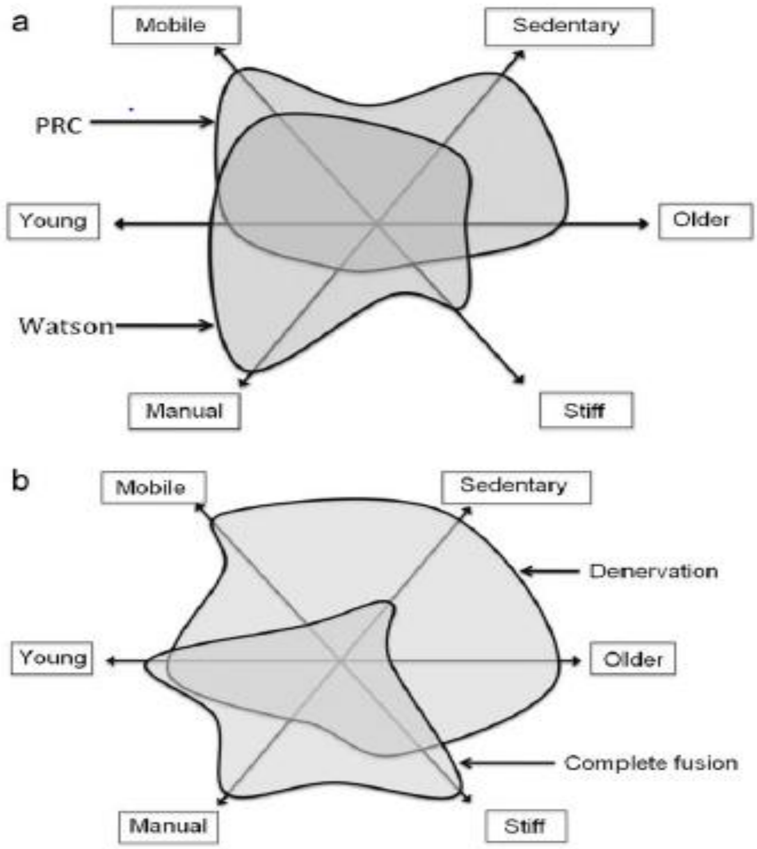


Figure 3.5 Surgical technique in relation to functional requirements (Laulan et al. 2011)

Determining the correct surgical treatment based on the functional requirements of the patient will now be discussed. PRC results in greater mobility in the wrist for this reason it is often recommended to sedentary patients suffering early stage arthritis. Laulan et al. (2011) reiterates that the PRC results in greater mobility in the wrist than the Watson procedure (50% vs 66%). Although PRC does provide superior mobility there are contraindications for the surgery. These contrindications include patients with severe cartilage degeneration around the radiocapitate joint, patients with no cartilage left in the lunate fossa of the radius, patients with the head of the capitate collapsed, patients with inflammatory arthritis present in the wrist due to it accelerating effect, patients with large cartilage lesions present in wrists and heavy manual labours due to the pain experienced in extreme wrist positions and repeated motions post operation (Richou et al. 2010), (Sobczak et al. 2011), (Laulan et al. 2011). Denervation is another surgical option for patients suffering early stage arthritis wishing to maintain mobility (Laulen et al. 2011). Advantages of denervation include post-operative salvageability of the wrist, minimal immobilization time and low complications rates (Laulan et al. 2011). Patient candidature for the denervation include patients with early stage arthritis with the radiolunate space in good condition. For patients wishing to maintain strength within the wrist the denervation surgical procedure is typically not recommended. Laulan et al. (2011) states that comparative studies have shown the Watson procedure was better at maintaining strength in the wrist (75% vs 66%) with lower risk of joint space degeneration and good long-term results. The Watson procedure is chosen if the radiolunate joint space is maintained with good functional ability in the wrist (Laulan et al. 2011). When severely arthritic wrist which has resulted in radiolunate joint being irrepairably damaged then the denervation, PRC and Watson might not be viable options. This leaves the patient with two surgical options of total wrist fusion or total wrist arthroplasty.

Typical candidature for total wrist fusion are younger patients wishing to maintain strength within the wrist. Due to comparison of wrist mobility between pre-and post-surgery, patients with low wrist mobility are also ideal candidature for this surgery (Laulan et al. 2011). Contradictions for a patient to avoid total wrist fusion include older sedentary patients with good wrist mobility with total wrist arthroplasty being recommended for these patients. Total wrist arthroplasty is a surgical procedure where the late stage arthritic wrist is replaced with an artificial wrist joint. Primitive design in the early 1960's made it an unviable option due to the high failure rates. But with improved design which has resulted in higher survivability the use of total wrist arthroplasty has become a competitive option. Regarding patient selection there are certain characteristics that make a patient ideal candidature for the procedure;

- Lin & Paksima (2017) describes ideal candidates as those suffering pancarpal rheumatoid arthritis causing unremitting pain. They must lead a low-demand lifestyle, be unable to perform activities of daily living and have been unsuccessful with non-operative options. The low demand lifestyle is important because the total wrist arthroplasty places activity restrictions on the wrist with the patient unable to bear heavy weight or participate in sports (Lin & Paksima 2017). Because of this activity restrictions the surgery is generally recommended for older sedentary patients over younger active patients involved in manual labour (Lawler & Paksima 2006).

- The total wrist arthroplasty operation surgical aims are to maintain wrist motion. This wrist motion is vital for conducting the activities of daily living such as writing, opening doors etc (Lin & Paksima 2017). Patients in greatest need to maintain the wrist motion are those suffering arthritis in multiple upper extremity joints. Patients suffering bilaterial rheumatoid arthritis who have undergone total wrist fusion and wish to maintain mobility in the remaining wrist (Adams 2006), (Lin & Paksima 2017).

- Recently patients with osteoarthritis due to post traumatic injury or degenerative osteoarthritis have also been identified as suitable candidates for total wrist arthroplasty. These patients typically exhibit qualities that give high probability of success including improved bone stock, soft tissue quality, muscle strength within the wrist and correct wrist alignment (Adams 2006), (Lin & Paksima 2017). There have been several studies on the suitable of non-rheumatoid patients compared to rheumatoid patients. These studies have shown no significant differences in revision rates, grip strength or disability of the arm, shoulder and hand (DASH) scores between rheumatoid and non-rheumatoid patients (Lin & Paksima 2017). Although the results of these studies are promising the samples sizes where small so it remains to be seen if larger studies will confirm these findings. (Lin & Paksima 2017)

There are several contradictions restricting the viability of a patient for total wrist arthroplasty;

- Patient who exhibit poor bone stock and severe deformity are advised to not undergo total wrist arthroplasty. This is because soft tissue balance is difficult to achieve when there is bone loss in the ulnar/volar subluxation and fixed supination of the carpus which result in higher risk of complication e.g. dislocations (Chakrabarti 2009). Women often have poorer bone stocks then male and as a result are not recommended to undergo total wrist arthroplasty due to the higher associated risk of dislocation failure (Lin & Paksima 2017).

- Patients with restricted mobility in the hand due to lack of wrist extension power are not recommended to undergo total wrist arthroplasty surgery. This lack in power could be due to rupture of the long flexors and finger extensors or radial nerve palsy (Chakrabarti 2009), Total wrist arthroplasty could be a viable option if suitable soft tissue balance is exhibited by the wrist provided the previously mentioned conditions have been surgically treated (Chakrabarti 2009), (Adams 2006).

- Patients exhibiting pre-existing underlying infection (Chakrabarti 2009).

- Patients who exhibit highly active synovitis resulting in severe bone erosion or joint hyperlaxity due to higher risk of implant loosening and dislocation (Adams 2006)

- Patients suffering severe osteopenia, bone erosion or joint deformity resulting in higher risk of dislocation/loosening. (Adams 2006)

The correct selection of the patient is important as it can improve the chances of post-surgical success. When the wrist is required to maintain mobility, and is in early stages of arthritis disease then PRC or denervation is typically recommended procedures. When the wrist is suffering early stage arthritis and the maintenance of the strength is the main functional requirement then Watson procedure will be the optimal surgical option. The aforementioned surgical options require the radiolunate joint to be maintained. If the patient exhibit late stage arthritis where inflammatory arthritis is present, large cartilage lesions have developed and severe cartilage degeneration then only viable surgical options are either total wrist arthroplasty or total wrist fusion. Total wrist fusion is typically performed on patients suffering advanced arthritis requiring functional strength in the wrist. For older patients with advanced arthritis wishing to maintain mobility the total wrist arthroplasty is the optimal surgical option. These patients are typically suffering pan carpal rheumatoid arthritis with suitable bone stock, no bone erosion or deformities, no pre-existing infections and no previous surgeries. This research has shown that each surgical operation has specific patient candidature. The following sections of this dissertation are going to explore each of the surgical treatments in more detail to gather a deeper understanding of the strengths and limitations of the procedures.

3.33 Early Stage Arthritis Treatments

3.331 Ablative Surgery

Ablative surgical procedure is where the pain generating segment of the arthritic wrist is removed to provide relief from pain while simultaneously slowing the progression of the arthritis (Rainbow et al. 2015). There are several ablative procedures available to the patient with proximal row carpectomy (PRC) and denervation being discussed due to their high prevalence as a surgical option.

Proximal Row Carpectomy

Proximal row carpectomy (PRC) is a surgical procedure that is utilised for stage II scaphoid non-union collapse where a joint is created between the head of the capitate and the lunate fossa of the radius through the removal of the scaphoid, lunate and triquetrum bones (Sobczak et al. 2011). There are several indications where proximal row carpectomy is utilised on patients including SLAC or SNAC (stage II) wrists, Kienbocks disease and sequelae after distal radius fracture (Reigstad 2014). PRC does have advantage including lower risk of infection, no implant related complications, simplicity of procedure and shorter rehabilitation (Richou et al. 2010). Proximal row carpectomy provides effective pain relief to the patient with one study reporting 83% of patients reported no pain in wrist and satisfaction with results post-surgery (Sobczak et al. 2011), (Richou et al. 2010). PRC also shows promising results in the maintaining of functionality with research showing 2/3 of patients who received the procedure maintained mobility (Laulan et al. 2011). Patients who received the procedure reported an average DASH score of 25 with a range from 9 to 36 possible (Laulan et al. 2011). PRC changes structure of the wrist while maintaining suitable range of motion (ROM). Sobczak (2011) and Richou et al (2010) describes the range of motion relatively well preserved to 76° in dorso-palmar flexion and 45° during radioulnar deviation. As it can be seen the reported high level of patient satisfaction, pain relief and preservation in ROM make PRC a viable surgical option but there are restrictive characteristics post-operation.

PRC can have negative aspect limiting the capabilities of the wrist post operation. Richou et al. (2010) reported patients exhibiting pain in extreme wrist rotations and weakness with repeated movements post-surgery. Primarily due to the removal of the radiocarpal ligament resulting in rotational instability in the wrist. Although the patient can have pain in extreme rotations the available range of motion should allow them to complete everyday functional activities (Richou et al. 2010). PRC surgery also decreases the mean moment arm of the muscles in the wrist due to the surgical reduction in height of carpus and lengthening of tendons (Richou et al. 2010), (Sobczak et al. 2011). This reduction in mean moment arm reduces the grip strength of the patient to between 60 – 90% (Sobczak et al. 2011). The reduction of the moment arms results in limited capacity of the abductor pollicis longus and palmaris longus muscles resulting in partial preservation of dynamical stability in dorso-palmar flexion motion (Sobczak et al. 2011). Finally, patients who receive a PRC often still exhibit degenerative changes in the wrist. Reigstad (2014) notes that on the 10 years follow up the majority of patients exhibit degeneration within the wrist with almost 20% of patients requiring conversion to total wrist fusion. Proximal row carpectomy has promising results in preserving wrist kinematics but reduced grip strength, reduced dynamic stability in dorso-flexion motion, pain in extreme rotations and weakness in repeated movement could remove PRC as a viable surgical option for certain patients.

Figure 3.6 Wrist after Proximal Row Carpectomy (Reigstad 2014)

Denervation

Denervation surgical procedure is the surgical division of nerve fibres responsible for transmitting pain in the wrist (Greching, Mahring & Clement 1998). Prior to the denervation surgery being conducted the patient is screened for the suitability through administering a preoperative nerve blockade to the relevant nerves (Greching, Mahring & Clement 1998). Following this, if the blockade provides symptomatic relief the surgery is then administered (Greching, Mahring & Clement 1998). The operative technique used in denervation is described by Greching, Mahring & Clement (1998). The patient is administered a general anaesthesia or auxiliary block, using a tourniquet. The patient's nerves are then selectively divided with redon drains utilised in the major incisions and compression bandage applied with temporary splintage. The relevant nerves are then divided with the required skin incision shown in figure 3.7 below. Post operatively, the wrist is protected through immobilisation with a splint, elevation and administered non-steroidal anti-inflammatory drugs (NSAIDs).

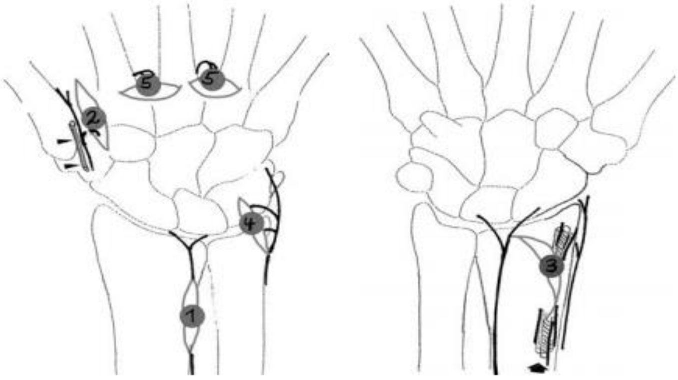


Figure 3.7 Incisions for Wrist Denervation (Greching, Mahring & Clement 1998)

The main advantage of the denervation surgical procedure is it is possible even when the radiolunate joint space in the wrist has been altered through previous surgery and allows the patient to have surgical revision if required (Laulan et al. 2011). The denervation surgical procedure has positive results in comparison to the other surgical procedures with research showing 75 to 80% of patients reporting pain relief with minimal impact on the wrist mobility and few post-operative limitations or complications (Laulan et al. 2011). Regarding post-operative functionality of wrist, the denervation procedure results in a visual analogue scale (VAS) score of 2 to 3, strength of the wrist being reduced to 80% and a DASH score between 25 to 30 (Laulan et al. 2011). The main problem with the procedure is patients report pain the wrist when it is exerted during heavy manual labour tasks (Laulan et al. 2011). Denervation is surgical technique for early stage arthritis to provide symptomatic relief for the associated pain while maintaining functionality in the wrist.

3.332 Arthrodesis Surgery

Arthrodesis is the surgical procedure were certain sections of the wrist are fused together to provide pain relief and stability to the wrist. There are several available procedures available to the patient which include radioscapholunate arthrodesis, midcarpal arthrodesis, Watson procedure and total wrist fusion. The two main arthrodesis procedures that will be discussed are the Watson procedure and total wrist fusion. The Watson procedure is one of the main surgical procedures conducted on early stage arthritis due to the favourable results for non-union rate (4.3%) and a union time of around 7 weeks (Lyons & Weiss 2003). The other procedure discussed is total wrist fusion which is the only arthrodesis surgical procedure available for late stage arthritis (Lyons & Weiss 2003).

Watson Procedure

The Watson procedure (also known as four corner fusion) is a hybrid procedure involving the excision and fusion of bones in the wrist. The procedure begins with the dorsal transverse incision in the distal direction to the radial styloid allowing the excision of the scaphoid being careful to protect the volar ligaments, branches of the superficial radial nerve and the various surrounding muscles (Lyons & Weiss 2003). The surgeon then begins the process to fuse the capitate, lunate, hamate and triquetrum bones. This process begins with the removal of the cartilage of the adjacent surfaces of the fused bones through a transverse incision in the wrist at the level of the capitolunate joint (Lyons & Weiss 2003). The surgeon then places pins between the fused bones while simultaneously packing cancellous bone between the fused joints (Lyons & Weiss 2003). The bones are then fused together using a three-dimensional recessed plate such as the Spider plate (Lyons & Weiss 2003). This surgical procedure requires that there is intact cartilage on the lunate and the lunate facet of the radius but is an effective surgical procedure for patients suffering SNAC, SLAC (stage 2 and 3) and in some instances intraarticular distal radius fractures (Reigstad 2014).

There have been mixed results reported for the Watson procedure. The rate of conversion of failed Watson procedures to full wrist fusion has been variable ranging from 2 to 36% depending on the study (Laulan et al. 2011). The procedure is comparable to PRC with a satisfaction rate of 80%, DASH scores ranging between 15 – 30, patients reported a decrease in pain and an overall increase in satisfaction of the wrist post-surgery (Reigstad 2014), (Laulan et al. 2011). Watson procedure is advantageous in that the patient maintains the height in the carpus and preserves the radiolunate relationship in the wrist (Lyons & Weiss 2003). The aforementioned results for Watson procedure has shown is surgical advantages but there also negative outcomes that need to be considered.

Watson procedure has several post-operative issues that should be considered. Lyons & Weiss (2003) details how procedure can result in the degeneration of the radiolunate ligaments causing ulnar translation of the wrist that can lead to the destruction of the wrist. Another negative outcome is the potential dorsal impingement and loss of extension of the wrist due to an uncorrected pre-operative residual dorsal intercalated segment instability (DISI) deformity (Lyons & Weiss 2003). Watson procedure restricts the functionality of the wrist post-surgery with patients maintaining 50 – 60 % of mobility and 60-80% of strength compared to contralateral side (Reigstad 2014). This reduced strength is a result of the fusing of the capitolunate joint leaving the radiolunate joint responsible for taking the remaining wrist load in articulation (Lyons & Weiss 2003).

Figure 3.8 Wrist (SNAC 3) after Four-Corner Fusion (4CF) (Reigstad 2014)

When the wrist is suffering late stage Kienbock disease (IIIB or IV) especially if synovitis is present or there has been severe degeneration to the radiolunate joint space severely affecting residual mobility, the only viable option may be the total wrist fusion or total wrist arthroplasty. The total wrist fusion surgical option will be explored in the following section.

3.34 Late Stage Arthritis Treatments

3.341 Arthrodesis

Total Wrist Fusion

Total wrist fusion (TWF) involves the utilisation of a fixation component such as metal plate, K wires, rush rods (Tomilinson 2012). These are utilised to fuse all the wrist joints together to prevent any movement in the wrist (Tomilinson 2012). During the surgical procedure, all the cartilage surfaces of the bones are stripped off and bone graft material is placed into gaps to facilitate bone to bone fusion (Tomilinson 2012). Various fixation devices have been used in this surgery with mixed results Reigstad (2014). K-wires and large Steinmann pins have been utilised since the 1960s but have been problematic due to rotational instability and high rates of non-union while rush rods, plate fixation and staples have been regular fixation devices due to the high union rate achieved (Reigstad 2014). Examples of other fixation devices that can be utilised include screw fixation, tension band wiring and bio-absorbable devices (Reigstad 2014). Fixation methods include the Mannerfeldt method which is reserved for patients with inflammatory wrist degeneration while plate fixation method is used in both inflammatory and non-inflammatory arthritis (Reigstad 2014).

Post-operative restriction of the wrist following the TWF must be consider. Reigstad (2014) describes that TWF substantially restricts the functional ability of the wrist often resulting in the patient having to compensate with the use of shoulder, elbow and forearm motion. Due to the restrictions on mobility, the procedure is often utilised on severe arthritic conditions (Tomilinson 2012), (Reigstad 2014). TWF is commonly used as a rescue procedure after previously failed surgery with verification of results complicated due to the damage from previous surgery (Laulan et al. 2011). The TWF in certain circumstances can also be utilised as an initial treatment option (Laulan et al. 2011).

Outcomes of TWF have been mixed. The main advantage of this surgical option lies in its ability to maintain strength in the wrist with 80-90% of strength maintained compared to uninjured side (Laulan et al. 2011), (Reigstad 2014). TWF has been shown as an effective procedure to provide pain relief with patients reporting a VAS score of 2 simular to this a study by Solem et al. found 28/40 rheumatoid arthritis patients found pain relief post-operation. (Laulan et al. 2011) (Reigstad 2014). The study by De Smet also examined non-rheumatoid patient's post-surgery results showing pain being resolved in 20/36 patients at rest but only 6/36 patients while active (Reigstad 2014). This research demonstrates that while TWF is effective for pain management but may only be effective in circumstances where activity is restricted. The aforementioned study by Solem also found several of the patient experienced complications post-surgery which included 5 patients having to remove the plate or rod and 2 patients not achieving union in the radiocarpal joint. The above results on the TWF show that it maintained strength and resolved pain but at the cost of the functional capacity. This restriction of the functional capabilities of the wrist following TWF necessities the need for an alternative surgical option.

3.342 Total Wrist Arthroplasty

Total Wrist Arthroplasty (TWA) surgery replaces the arthritic wrist with an artificial joint. TWA is for low physical demand patients suffering pan-carpal rheumatoid arthritis who desire pain relief while preserving functional range of motion in the wrist. (Adams 2006) (Lin & Paksima 2017). Despite the improved ROM, TWA remains a relatively uncommon procedure due to the high complication rates (Lin & Paksima 2017) (Lawler & Paksima 2006).

Several articles have reported on the positive surgical outcomes of the TWA. The study by Murphy examined functionality of wrist post-surgery found comparable DASH score to TWF and only 21% of patients reporting limitations (Lin & Paksima 2017). TWA can also provide post-operative pain relief with the study by Cavaliere and Chung finding that 91% of patients found pain relief and were satisfied with the procedure (Lin & Paksima 2017). Although the procedure can provide post-operative relief and functionality to the wrist, high complication rates have plagued the surgery especially in the earlier models. Lin & Paksima (2017) describes that the complications rate in TWA being significant reportedly reaching as high as 43% in 1st generation models. While a study by Cavaliere and Chung found complication rate of 21% for the TWA (Lin & Paksima 2017). Complications typically experienced post-surgery can include fracture of implant, pain in wrist, tendon imbalance, component loosening, ulnar drift, soft tissue imbalance, recurrent synovitis, infection, malposition, subluxed component and dislocation (Reigstad 2014), (Lawler & Paksima 2006), (Lin & Paksima 2017). The latest 4th generation TWA have tried to address the aforementioned complications through improving functional range of motion, better wrist balance, reduced risk of loosening, and better implant stability (Adams 2006). The Remotion wrist arthroplasty is one of these 4th generation TWA which has demonstrated survivorship between 90% - 96% at 8 to 9 years (Lin & Paksima 2017). The continued development of the TWA will result in a steady decline in the complication rates. This reduced complication rate along with the maintenance of functionality of the wrist post-operation will result in the TWA becoming the gold standard treatment for late stage arthritis.

	Flexion (°)	Extension (°)	Radial Deviation (°)	Ulnar Deviation (°)
Wrist Normal ROM	70	73	22	30
Wrist Functional ROM				
(Palmer, 1984)	5	30	10	15
(Brumfeld, 1985)	10	35	—	—
(Ryu, 1991)	40	40	12	28
Swanson implant	39	6	-2	21
Volz	37	17	2	23
Meuli	30	40	10	10
Trispherical	50 (total) flex + ext	—	10	10
GUEPAR	39 (total) flex + ext	—	—	—
Universal	41	36	7	13
Biaxial	29	36	10	20

Table 3.1 Range of Motion for TWA (Lawler & Paksima 2006)

TWA is a competitive surgical option due to the post-operative wrist maintaining a functional range of motion (ROM). For the wrist to retain functional ability the ROM required is; 5° of flexion, 30° of extension, 10° of radial deviation and 15° of ulnar deviation (Reigstad 2014). Table 4.1 shows the ROM that can be achieved for several models of the TWA achieving between 30 – 50° flexion, 30-40° extension, 7-12° in the radial deviation and 10-23° in ulnar deviation dependent on model. Comparison of the ROM's shows that the TWA can achieve the ROM required to maintain a functional wrist. TWA ability to maintain a functioning wrist was a topic explored in the study by Wolff with results shown in figure 3.9 (Rainbow et al. 2015).

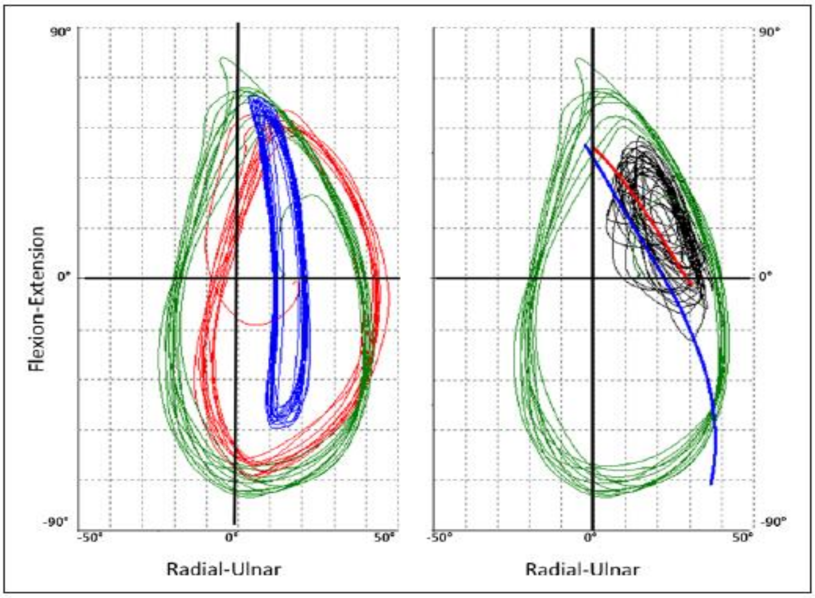


Figure 3.9 Comparison of Wrist Motion for different surgeries (Rainbow et al. 2015)

The left diagram in Figure 3.9 shows the ROM of the normal wrist (green envelope), wrist post TWF (blue envelope) and wrist post TWA (red envelope). The diagram on the right of figure 3.9 shows the motion required to perform certain activities with the blue line being the motion required to throw a dart, red line is the motion to swing a hammer and the black scribbles is the motion required for the winding action of the wrist. Comparison of the two diagrams shows that the TWF results in a wrist unable to achieve the motion to perform the everyday activities such as winding, hammering and throwing. TWA results in a less restricted wrist that can achieve all the motion required to complete the everyday activities of hammering, throwing and winding. This preservation of motion in the wrist is important as research has shown that patients are inclined to choose a surgical procedure that preserves motion, and will often be reluctant to undergo surgery when TWF is the only option (Reigstad 2014)

TWA does have a higher initial surgical cost then TWF, however TWA is economically competitive when adjusted for patient's quality of life. A study by Cavaliere and Chung undertook a cost analysis on the TWA and the TWF (Lin & Paksima 2017). The study determined the cost of the different surgical options based on cost of implants, surgeon fees, anaesthesia, as well as costs associated with the ambulatory surgery center. The results from this study indicated that the TWA was significantly more expensive surgery at an average cost $18,478 compared to $6,607 for the TWF. When costs of surgery were adjusted for the quality adjusted years (QALY) gained from the surgery the two options become more comparable. Cavaliere and Chung did this adjustment to their cost figures with the two surgeries producing similar figures, with $2,281/ QALY for TWA versus $2,328/QALY for TWF. As it can be seen, the two surgical options are economically competitive when the post-operative quality of life is considered in the calculations.

This section examined the TWA as an alternative surgical option to TWF for late stage arthritis. TWA maintained suitable range of motion resulting a post-operative functional wrist. TWA is also a cost competitive option to TWF when the quality adjusted years is considered in the calculations. The main limitation of TWA has been the high complication rates which are reported as high as 43% in earlier models. Although the complication rates have reportedly improved to as low as 10%, there is still room for improvement in the design.

3.35 Conclusion

Patients suffering arthritis in the wrist has several surgical options available. These options include denervation, Watson procedure, total wrist fusion (TWF), proximal row carpectomy (PRC) and total wrist arthroplasty (TWA). When selecting the correct surgical procedure, the identification of the arthritis type and the functional requirements are imperative. Patients suffering early stage arthritis requiring to maintain mobility have the surgical options of denervation or PRC. While patients requiring maintenance of strength will typically undergo Watson surgical procedure. Late stage arthritis is indicated by inflammatory arthritis, large cartilage lesions or severe cartilage degeneration. For these patients, there are only two viable surgical options of either TWF or TWA. TWF is typically conducted on younger patients requiring functional strength in the wrist who are suffering either advanced stage Kienbock disease (stages IIIB or IV) or stage III SLAC/SNAC. TWF typically restricts the functional abilities of the wrist post operation. In comparison, TWA is conducted on patients suffering pan carpal rheumatoid arthritis with suitable bone stock, no bone erosion or deformities, no pre-existing infections or previous surgeries. The patients are typical older mobile patients needing to maintain the motion in the wrist to complete activities of daily living (ADL's). TWA has a history of high complication rates reaching 43% for early models but later generation models have demonstrated reduced complication rates. These complications have limited the TWA necessitating the need for a better design.

CHAPTER 4 Determining Design Parameters

4.1 Introduction

This section will investigate the essential design parameters through research into the wrist and previously discussed Total Wrist Arthroplasty (TWA) designs. The research was conducted to determine the relevant anatomical properties required in the design. Research was conducted through an extensive failure analysis to determine the strength and limitations of past TWA's. The results from both research topics were then tabulated to extrapolate the key design parameters.

4.2 Research into Wrist

The wrist is a set of complex joints comprised of bones, muscles and ligaments (Berger 1996). Each component of the wrist (bones, ligaments) plays a vital role in its kinematic motion. This section of the dissertation will examine these various components of the wrist and how they work in unison to provide motion to the complex joint.

4.21 Anatomy of Wrist

4.211 Bones of the Wrist

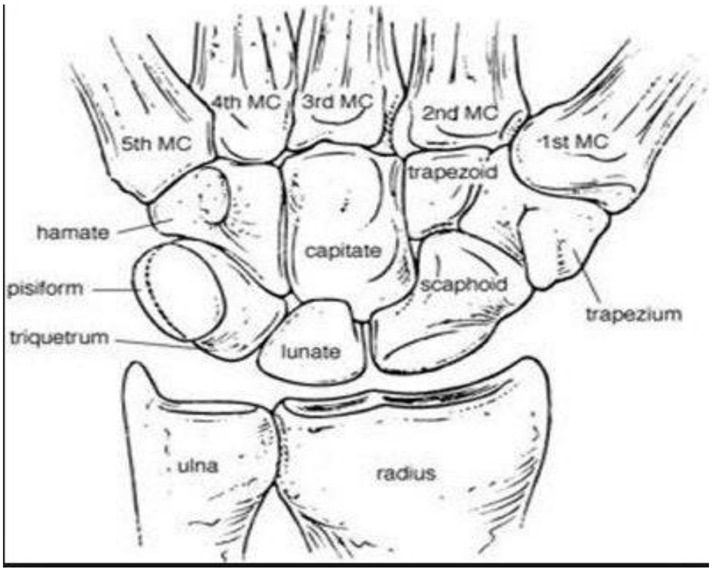


Figure 4.1 Bone Anatomy of the Wrist (Wordpress 2013)

The bones of the wrist include the distal radius, ulna and the carpal bones which are divided into the distal and proximal row and the bases of the metacarpals (Berger 1996), (Kijima & Viegas 2009). The carpal bones are classified as either proximal or distal row based on their position in the wrist (Berger 1996). The proximal carpal row is composed of (radial to ulnar); scaphoid, lunate, triquetrum and pisiform. The distal carpal row is comprised of (radial to ulnar); trapezium, trapezoid, capitate, and hamate (Berger 1996), (Kijima & Viegas 2009). The metacarpals are numerically labelled from the thumb metacarpal which is named the first metacarpal finishing with the fifth metacarpal that is on the other side of the wrist (Berger 1996), (Kijima & Viegas 2009).

4.212 Joints of the Wrist

The wrist can be split into two joint segments which are the radiocarpal joint and midcarpal joint. These joints work together to provide kinematic motion in the wrist. The midcarpal joint and radiocarpal joint are shown in the figure 4.2.

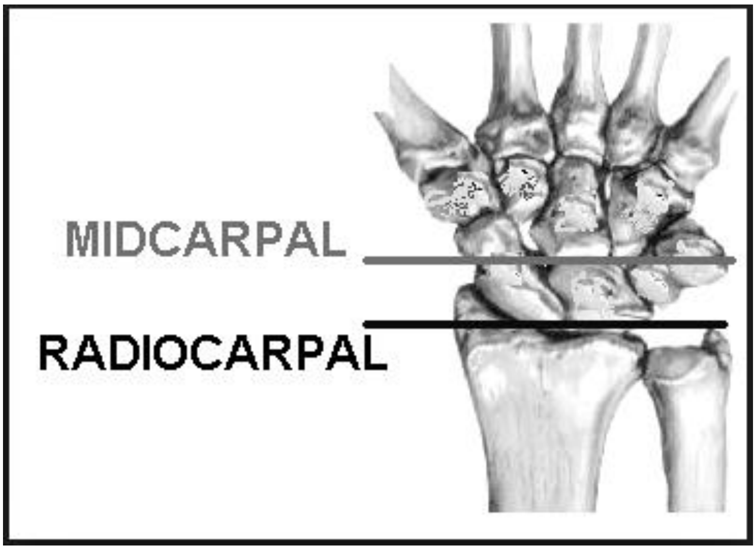


Figure 4.2 Joints of the wrist (Apergis 2013)

Radiocarpal joint

The radiocarpal joint is the articulation joint between the antebrachial glenoid (distal articular surface of the radius and the TFFC) and the carpalcondyle (convex proximal articular surface of the proximal carpal row bones) (Apergis 2013). Dimensions vary dependent on the individual, the two articular surfaces of the joint having radioulnar diameters between 4 to 5 cm, dorsopalmar diameters between 1.5 to 2 cm and the articular cartilage that covers the distal articular surface of the radius varies in size between 0.7 to 1.2mm (Apergis 2013). The similarities in dimensions between the distal articular surface of the distal radius is commonly tilted at 10° in the sagittal plane, while the ulnar bone has an average inclination of 24° in the frontal plane (Apergis 2013). The above description demonstrates that differences exist between the size and curvature of the opposing articular surfaces of the joint that increases the stability of the joint. Scaphoid stability is present in the joint even after soft tissue injury due to the larger curvatures of the scaphoid fossa / proximal scaphoid as well as a deeper scaphoid fossa and a greater volar tilt of the radius (Apergis 2013).

Midcarpal joint

The midcarpal joint has three separate articulation components which are the scapho-trapezium-trapezoid joint, scapholunocapitate joint and the triquetrohamate joint (Apergis 2013).

Scapho-Trapezium-Trapezoid Joint

Scaphi-trapezium-trapezoid joint consist of the convex articular surface of the scaphoid articulating against the concave surfaces of trapezium-trapezoid (Apergis 2013). 81% of the surface area of the scaphoid in this articulation joint is the interfacet ridge that runs obliquely from radiodorsal to ulnopalmar direction (Apergis 2013). There are two theories on the role of the interfacet ridge (Apergis 2013). The first theory is that the ridge guides the joints motion which coincides with the plane of the dart-throwing motion while the opposing theory is the ridge doesn't have a role in guiding the motion due to the ridges cartilaginous composition (Apergis 2013).

Scapholunocapitate Joint

Scapholunocapitate joint consists of the convex surfaces of the capitate in conjunction with the proximal pole of the hamate articulating against the concave surfaces of the lunate and scaphoid (Apergis 2013). Scapholunocapitate joint is variable between individuals with the possibility of two different combination for the lunate and capitate bones (Apergis 2013). These combinations are either large lunate with small distal capitate facets or small lunate with large capitate facets (Apergis 2013). The lunate is also variable in this joint with two types possible which include **type 1** that has no medial facet and a capitate–triquetrum distance equal to or less than 2mm or **type 2** that has a medial facet that articulates with the hamate which ranges in size between 1 to 6mm and has a capitate–triquetrum distance equal to or greater than 4mm (Apergis 2013). The type 2 lunate is more common with an incidence range between 46 % to 73 % and has associated impacts to the joint (Apergis 2013). These associated impacts include causing arthritic changes in proximal pole of the hamate, development of Kienbock's disease and development of STT arthritis (Apergis 2013).

Triquetrohamate Joint

Triquetrohamate joint is the articulation between the distal surface of the triquetrum and the proximal surface of the hamate that can take either a helicoid or screw shape appearance (Apergis 2013). Apergis (2013) describes two versions of this joint which are;

Triquetrohamate joint 1 – Double faceted joint that has a helicoidal appearance. The articular surface is concave while the triquetrum possesses a complimentary concave surface.

Triquetrohamate joint 2 – This variation has an oval convex shape with the concave surface of the triquetrum acting as a dish for the flatter surface of the hamate.

4.213 Ligaments of the wrist

Ligaments are composed of parallel collagen fascicles that are bound together by loose perifascicular connective tissue (Berger 1996). The surface of the ligaments features a synovial lamina layer that is composed of cuboidal synoviocytes while the superficial surface is covered by a fibrous lamina. The synovial and fibrous laminae completely encircle the collagen fascicles to form the epiligamentous sheath. In the wrist, the ligaments serve several roles which include and are not limited to constraining displacement, guiding motion, and providing afferent neural input regarding the mechanical status of the joint (Berger 1996). The different ligaments throughout the wrist have varying mechanical properties to suit their role (Berger 1996). Ligaments in the wrist are grouped as either extrinsic or intrinsic. Extrinsic ligaments are defined as crossing the radiocarpal joint, the midcarpal joint or both (Fisiokinesiterapia n.d). While intrinsic ligaments are defined as being located between the bones of either the proximal or distal carpal rows (Fisiokinesiterapia n.d). Ligaments can also be further sub classified into several groups which include distal radioulnar, palmar radiocarpal, dorsal radiocarpal, ulnocarpal, palmar midcarpal, dorsal midcarpal (Kijima et al. 2009). Within the aforementioned sub classifications, the ligaments can be split into volar and dorsal ligaments (Kijima et al. 2009). Volar ligaments are typically stronger having a role of the stabilizer of the bone while dorsal ligaments are typically weaker having the role of the support ligament (Kijima et al. 2009). Table 2.1 is a list the various ligaments of the wrist.

Extrinsic Ligaments	Intrinsic Ligaments
Radiocarpal Ligaments **Palmer** - Radioscaphocapitate - Long Radiolunate - Short Radiolunate - Radioscapholunate **Dorsal** - Dorsal Radiocarpal	Proximal carpal row - scapholunate (dorsal, volar and proximal) - lunotriquetral (dorsal, volar and proximal)
Ulnocarpal ligaments - ulnotriquetral - ulnolunate - ulnocapitate	Distal carpal row - trapeziotrapezoid ligament - trapeziocapitate ligament - capitohamate ligament

Midcarpal **Palmar** - scaphotrapeziotrapezoid - scaphocapitate - triquetralcapitate - triquetralhamate - Capitate Trapezium - Palmer scaphotriquetral **Dorsal** - Dorsal Intercarpal - Dorsal scaphotriquetral	
Distal Radioulnar Joint - Triangular fibrocartilage complex (TFFC) - Dorsal radioulnar - Palmar radioulnar - Meniscus homologue	

Table 4.1 Ligaments of the Wrist (Apergis 2013)

The ligaments in the wrist all serve their own purpose in the functioning of the wrist. Table 4.2 lists the function of the various ligaments in the wrist.

Ligament	Function of ligament
Radioscaphocapitate	(1) Some of the fibres form a radial collateral ligament (2) Provide resistance to passive pronation of the radiocarpal joint (3) Along with the other palmar radiocarpal ligaments, this ligament provides restraint to dorsal translation of the carpus, (4) Constrains ulnar translation of the carpus, (5) Stabilizes the distal pole of the scaphoid, and (6) Acts as a fulcrum around which the scaphoid rotates (7) This ligament acts as a primary stabilizer of the wrist after PRC and prevents ulnar drift.
Long Radiolunate	Primary restraint to ulnar translocation of the lunate and participates in the formation of the antipronation sling, which is responsible for the control of intracarpal pronation.
Short Radiolunate	The main function is to stabilizes the lunate (and hence the proximal carpal row) and prevents its volar, dorsal, and ulnar translation. The deficiency of the short radiolunate ligament is mainly responsible for the dorsal subluxation of the radiocarpal joint during the dorsal stress test of the wrist and has been considered the primary soft tissue restraint against volar translation of the carpus. Consequently, fracture of the volar radial rim where the short radiolunate ligament is attached, could destabilize the carpus leading to volar subluxation of the wrist.
Radioscapholunate	This ligament plays a role as a mechanoreceptor and is also a likely source for synovial filtration, producing synovial fluid and possibly resorbing metabolic waste.
Dorsal Radiocarpal	(1) This ligament covers the dorsal aspect of the proximal scaphoid alongside deltoid fibres which combine to provide dorsal support to the scaphoid. (2) Helps to constrain the ulnar translocation of the carpus. (3) Acts as a stabiliser and pronator of the wrist. (4) Provides resistance to passive supination of the radiocarpal joint thus participating as a key component of the antisupination sling. (5) Key ligament for the scaphoid and lunate kinematics during dynamic wrist motion. (6) Attenuation or disruption of this ligament has been implicated in playing a key role in development of instability in the wrist. (7)

	Superficial component of ligament plays important role in stabilization of distal radioulnar joint especially in extreme pronation
Ulnolunate	The function of this ligament is to aid the short radiolunate ligament in proximally stabilising the lunate during all phases of wrist motion which it achieves by mirroring the short radiolunate ligaments shape changes during dorsiflexion and palmar flexion of the wrist.
Ulnocapitate	The role of this ligament is to reinforce the ulnocarpal joint capsule and the luno-triquetral joint while also playing a role in the stability of the distal radioulnar joint
Scaphotrapeziotrapezoid	The main function of this ligament is as a stabilizing component of the Scaphotrapezium-trapezoid joint. This ligament is a secondary stabiliser with the distal ligamentous complex of the scaphoid to stabilise the scaphoid. The Scaphotrapezium-trapezoid ligament assists in maintaining the scaphoid in a palmar-flexed attitude preventing it from lying horizontally while simultaneously minimising excessive scaphoid flexion.
Scaphocapitate	The scaphocapitate ligament is the thickest ligament with the largest attachment to the scaphoid which acts as a stabilizer of the distal pole of the scaphoid. The scaphocapitate ligament also forms part of the antipronation sling which constrains the midcarpal pronation. The scaphotrapezium and the scaphocapitate ligaments also function as collateral ligaments of monoaxial articulation, thus consequently are the only ligaments guiding dart-throwing motion.
Triquetralcapitate	Key functions of this ligament include aiding in the ulnar and anteromedial midcarpal stability as well as being a key ligament in the formation of the antisupination sling which provides the constraint of midcarpal supination.
Capitate Trapezium	The capitate-trapezium functions as a labrum for the distal pole of the scaphoid helping to reinforce the palmar aspect of the scaphotrapeziotrapezoid joint.
Palmer scaphotriquetral	Key function of this ligaments is to support the head of the capitate during dorsiflexion of the wrist, acting as volar labrum for the lunocapitate joint.
Dorsal Intercarpal	Important functions of providing indirect dorsal stability to the scapholunate complex during wrist motion, maintaining carpal stability and alignment and play an important role in preventing the development

	of dorsal intercalated segment instability (DISI) and volar intercalated segment instability (VISI) deformities.
Dorsal scaphotriquetral	The role of the dorsal scaphotriquetral ligament is to provide transverse stability of the proximal carpal row. The dorsal scaphotriquetral ligament also has secondary functions of creating a labrum for the head of the capitate and the proximal pole of the hamate dorsally thereby deepening the midcarpal joint.
Triangular fibrocartilage complex (TFFC)	(1) The articular disk component acts as a supporting cushion for the ulnar carpus which can carry up to 20% of the load the forearm is subjected to. (2) The peripheral component of the TFC is the major stabilizer of the dorsal radioulnar joint. (3) The ulnocarpal ligaments and the sheath of the extensor carpi ulnaris contribute to the stability between the ulnar head and the ulnar carpus
Radioulnar ligament	The deep components (also known as Ligamentum subcruentum) on the other hand form an obtuse angle of attachment which provides much higher mechanical strength which provides the stabilisation required during the rotation of the radius around the fixed ulna. Also, the superficial and deep components of the radioulnar ligaments have different roles in forearm pronation. The dorsal superficial fibres of the radioulnar ligament must tighten for stability, as do the deep palmar fibres of the Ligamentum subcruentum. Conversely, in supination, the palmar superficial radioulnar fibres (to the ulna styloid) tighten, as do the deep dorsal fibres of the Ligamentum subcruentum.
Scapholunate (dorsal, volar and proximal)	Overall, the main function of the scapholunate ligament is to provide the primary stabilisation of the scapholunate joint during the joints articulation. Disruption to this ligament results in the destabilisation of the scapholunate joint which results the scaphoid and lunate kinematics being altered which ultimately leads to DISI and/ or SLAC.
Lunotriquetral (dorsal, volar and proximal)	**Volar region -** function of the volar region in constraining mutual translation of the lunate and triquetrum. **Dorsal region -** The key function of the dorsal region is to provide rotational constraint for the lunate-triquetrum joint.
Capitohamate ligament	**Dorsal region -** principal stabilizing structure for volar rotation/translation and proximal and distal translation of the capitate relative to the hamate. **Volar region -** acts as a pivot point for rotation of the capitohamate joint.

	Deep region - plays an important role in constraining dorsal rotation and dorsal translation of the capitate relative to the hamate. As described above the volar and deep region exhibit greatest strength which contributes substantially to the transverse stability of the distal row

Table 4.2 Function of Ligaments (Apergis 2013), (Kijima & Viegas 2009), (Woon N.D)

Note : Table 4.2 was devised from the detailed information on the ligaments of the wrist that can be found in the appendix of this dissertation.

The different ligaments in the wrist all play a role in the stabilisation and functioning of the wrist in its kinematic motion. This correct biomechanical functioning of the wrist through guidance of the ligaments is important to ensure that the surgery doesn’t fail. This can be seen in the scapholunate ligament where disruption of this ligament results in the failure of the wrist through the development of SLAC in the wrist (Miller & Streubel 2016).

4.22 Biomechanics of the Wrist

4.221 Introduction

The wrist has three possible motions which include flexion – extension, (90 – 70 degrees), radial – ulnar deviation (20 – 50 degrees), pronation supination movement (90 – 90 degrees), as shown in figure 4.3 (fisiokinesiterapia N.D).

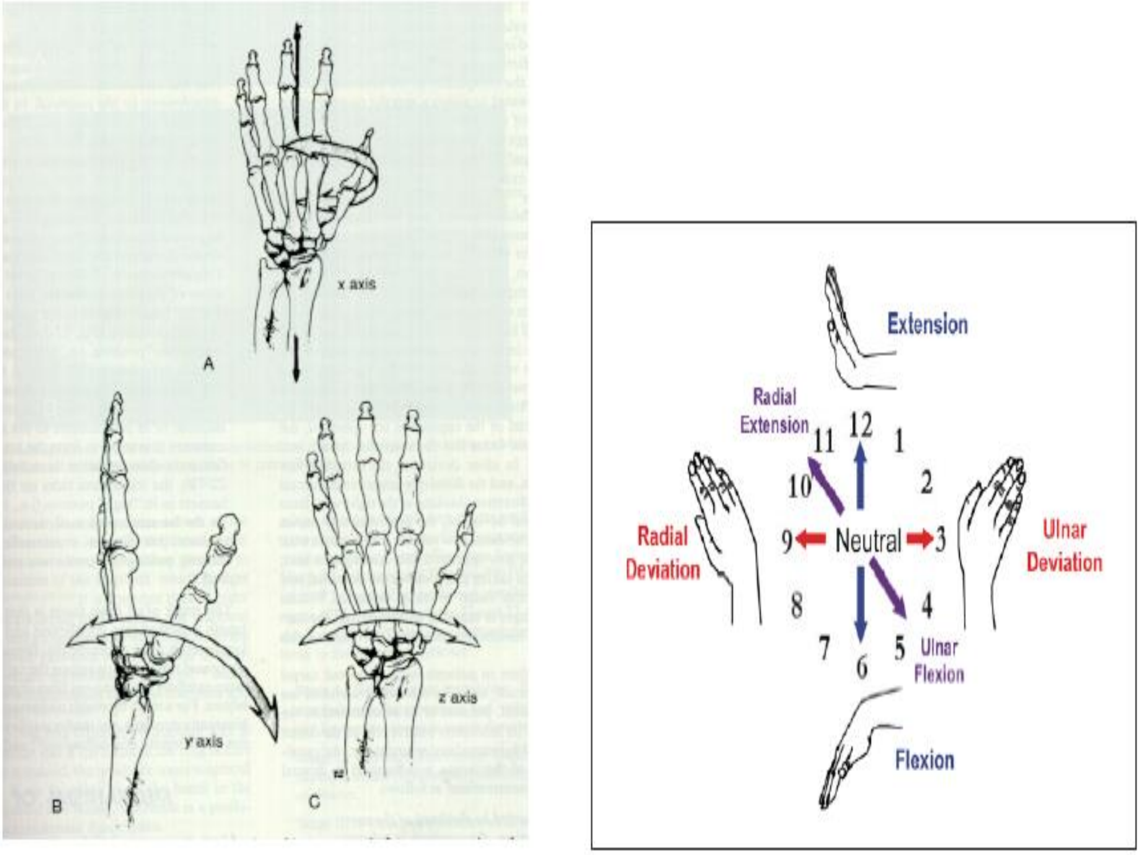


Figure 4.3 Motions of the Human Wrist (fisiokinesiterapia N.D), (Rainbow MJ et al 2015)

The motions of the wrist require the bones and ligaments to work in unison. There have been several theories developed over the last century to explain how exactly the bones and ligaments achieve motion in the wrist. These theories have evolved as more information has been discovered but a unifying theory remains elusive.

4.222 Evolution of Wrist Theory

The theory of the biomechanics of the wrist has been evolving over the last century from the foundational row theory to the central column theory. These theories are constantly changing with researcher developing a greater understanding of the wrist. Table 4.3 list the various theories that have been developed.

Theory	Author	Classification (Row, Column, Both)	Year Proposed
Navarro 3 Column Theory	Navarro	Column	1921
Foundation Row Theory	Bryce, Destot	Row	1926
Screw-Vice Theory	MacConaill	Both	1941
Link Theory	Gilford	Column	1943
Modified Column Theory	Taleisnik	Column	1978
Longitudinal Chain Theory	Kauer	Column	1980
Oval Ring Theory	Lichtman	Row	1981
Triquetrum-Hamate Articulation Theory	Weber	Column	1984
Carpal Stability through Balanced Moments applied to Lunate	Garcia-Elias	Both	1997
Central Column Theory	Sandow	Column	2013

Table 4.3 Evolution of Wrist Kinematic Theories (Rainbow et al. 2015)

The above theories are different in how they describe the behaviour of the wrist. Table 4.4 gives a description and key details of each of the above theories.

Theory	Description of theory	Key characteristics of theory
Navarro 3 Column Theory	The wrist is composed of three independent columns which include the lateral/radial column (scaphoid, trapezium and trapezoid), central column (lunate, capitate and hamate) and the medial/ulnar column (triquetrum, pisform and distal carpal row)	- The role of the lateral column is to support the thumb and transfer load between carpal rows. - The scaphoid in the lateral column is mobile in this theory and plays a role along with the triquetrum of the medial/ulnar column in controlling the radial and ulnar deviations of the wrist that occurs around the central column. - The flexion/extension of the wrist also occurs through luno-capitate articulations in the central column in this theory. - The medial/ulnar column plays a role in controlling the rotation of the wrist in this theory.
Foundation Row Theory	The wrist consist of two rows. The distal row consisting trapezium, trapezoid, capitate and hamate which acts a single unit due to the constraining of bones by the metacarpal ligaments. The proximal row (also known as intercalated segment) consists of the scaphoid, lunate and triquetrum	- Midcarpal joint was responsible for transmitting force between the rows in flexion / extension - Articulation of the ulnar and radial deviation of the wrist is controlled by scaphoid in conjunction with the radius of radiocarpal joint. - Not suitable theory to describe wrist biomechanics because it oversimplified the kinematics of the wrist.
Screw-Vice Theory	This theory states that the mechanism of wrist occurs through the scaphoid which acts as the jaws of the vice becoming fixed to the	- The force responsible for deviation of the wrist occurs from transmission of muscular forces from forearm bones to proximal carpal row.

	distal carpal row that acts as the base of the vice while the hamate acts as a screw that pins the lunate and triquetrum against the scaphoid.	- Triquetrum is the most mobile bone followed by the lunate and the scaphoid is the least mobile bone - Fails to address wrist flexion/extension in adequate detail which limits its overall applicability of the theory..
Link Theory	This theory describes the radius, lunate and capitate acting as three links in a chain that work together to provide the motion in the wrist	- Extension of the wrist occurrs at the radiolunate joint . - Flexion occurring the lunocapitate joint. - Head of the capitate acts as the center of rotation while both the distal and proximal row act as single units with the proximal row is also an intercalated segment with no direct tendon attachments. - Theory fails to explain radial and ulnar deviation. - Theory also states that the scaphoid was the key to normal carpal alignment which is not a valid theory.
Modified Column Theory	Modification of the column theory where the distal carpal row as a single unit that acts as part of the central column while the pisform bone is ignored as doesn't form an integral part of the carpal motion.	- The central column is controlled by the scaphoid on the lateral side and the triquetrum on the medial side. - When the wrist is subjected under axial load the obliquely orientated scaphoid rotates in flexion while in contrast the triquetrum is pulled into extension by the palmar hamotriquetral ligament. - When the ligaments connecting the bones are intact the proximal row is dynamically stable - Equilibrium of the wrist depends on the ligaments to stabilise the opposing moments produced by the scaphoid and the triquetrum. The dorsal scapholunate ligament prevents scaphoid flexion and

		palmar lunotriquetral ligament that prevents extension of the triquetrum.
Longitudinal Chain Theory	Theory describes the wrist as being composed of three parallel and interdependent chains.	- The motion in the wrist occurs because the scaphoid rotates faster on the radius than the lunate. - In the flexion motion the wrist moves as the scaphoid rotates palmarly and shifts proximally with respect to the lunate and the capitates while in extension the scaphoid rotates dorsally and shifts distally. - Theory accounts why the wrist can move simultaneously at the midcarpal and radiocarpal joints simultaneously, describes the role of the interosseous ligaments in intercarpal stability and relates the morphology of the carpal bones to their kinematic profile. - The weakness of this model is that the scaphoid and lunate are the primary focus of the model with the rest of the carpus not being address by the model.
Oval Ring Theory	Describes the wrist as a ring instead of rows and columns that previous theories utilised. The bones of the wrist form an oval ring that are comprised of four segments (distal carpal row, scaphoid, lunate and triquetrum) with ligaments attaching each segment attached to adjacent segment.	- The ligaments are continuous throughout the oval of the wrist which assures synchronous synergetic wrist motion during wrist kinematics - Disruptions to the ligaments result in instability of the wrist. There are two forms of instability described in this theory which include radial disruption leading to instability in the scaphoid – lunate – capitate articulation while ulnar disruption leads to midcarpal instability. - Theory provides an explanation on how carpal instability doesn't always occur longitudinally as well as describing how the intercarpal ligaments allow the

		proximal row to rotate as one functional unit. - Cadaver study conducted by Lichtman found that when the dorsal triquetrohamate ligament was divided it didn't induce midcarpal instability which would be expected to occur per the theory.
Triquetrum-Hamate Articulation Theory	Theory describes the carpus of the wrist being comprised of three longitudinal columns (central force bearing column, ulnar control column and a radial thumb-axis column).	- Extension / ulnar deviation of the wrist is achieved by the palmar displacement of the lunate which then compresses the capitate that results in the elevation of the distal pole of the scaphoid that causes in the scaphoid extending. The above occurs in reverse for flexion and radial deviation of the wrist. During the flexion/extension or radial/ulnar motion of the wrist the triquetrum translates on the slope of the hamate. - Theory provides explanation to all four wrist motions (flexion, extension, radial and ulnar deviation) also the theory provides foundation for understanding of the pathological conditions of DISI that can progress to SLAC and tears of lunotriquetral ligament - Theory state the triquetrohamate joint is the major point of control for wrist kinematics which is contradictory to other theories that state the scaphoid as a bone that spans both rows of the wrist and is the main stabilising structure of the wrist
Carpal Stability through Balanced Moments	This theory describes the carpus of wrist being stabilised and provided motion by four mechanism areas. These	- The position of the lunate is maintained through the tendency of the scaphoid to flex while the triquetrum tends to extend. - In this theory the disruption of the scapholunate ligament results in DISI

applied to Lunate	mechanisms include the proximal row stabilization, distal row stabilisation, midcarpal stabilisation and the radiocarpal stabilisation	occurring when the scaphoid subluxes dorsally that produces an extension/supination moment on the lunate. The second important ligament is the lunitriquetrum ligament which any disruption can eventuate in VISI occurring when the lunate follows the scaphoid into a flexion/pronation moment. - Main strength of this theory is that it doesn't describe the wrist with one model. Instead the theory divides the wrist into four separate segments and assessing the kinematics of each sections of the wrist separately in a systematic manner. - Another strength of this theory is its simplicity in that describes the balance of the wrist as a simply balance of forces. - The main weakness of this theory is that it doesn't allow the wrist to be conceptualised due the treatment of the wrist as four independent systems.
Central Column Theory	Theory describes the carpus functions as a stable central column (formed by unite and distal carpal row) which is controlled by the surrounding bones that act like a four-bar linkage system.	- The scaphoid comprises a lateral column that supports the central column, the triquetrum functions as a restraint against ulnar translation while the trapezoid functions to rotate the central column in the dart throwers motion axis. - The theory was derived from analysis of 3D generated models of the wrist which is different to previous theories which are first proposed subjectively then later supported with subjective data. - The theory has not been tested and validated for all wrist motion and functional tasks for a large cohort of patients and controls. This testing to justify

		the theory is important as the theory did find differences to previously established theories. - The theory found no isometric constraints between the hamate and the triquetrum that doesn’t agree with previous theories. - The theory is also unique in that it attempts to reconstruct the courses of the ligaments using an isometric lengthening assumption which could lead to insight into the subtle nuances of carpal mechanics.

Table 4.4 Description of wrist kinematic theories (Woon N.D), (Freeland & Geissler 2005), (Rainbow et al. 2015) (Garcia-Elias 2013)

Note : More detailed information on the different wrist kinematic theories in table 4.4 can be found in the appendix.

The aforementioned theories described how the understanding of wrist kinematics has evolved over the last century. At present, there is no unifying theory for explaining wrist mechanics due to the wide variability in ligament laxity, anatomic variability and bone morphology (Rainbow et al. 2015). Although the unifying theory remains elusive, there is a general understanding on the kinematic behaviour of the wrist.

4.223 Wrist Kinematics

The wrist is a complex joint that a simplistic kinematic model to describe its biomechanical behaviour will not suffice. The wrist functions neither as two horizontal rows or three vertical columns but instead the bones behaviour depends on the motion of the wrist and the laxity of the surrounding ligaments (Rainbow et al. 2015). The wrist components act differently as the wrist moves from neutral position to 60 degrees of flexion with the scaphoid flexing approximately 70% of the capitate and the lunate flexing approximately 45% of the capitate while the midcarpal and radiocarpal joint share the flexion (Rainbow et al. 2015). The components also act differently as the wrist moves from neutral position to 60 degrees of extension with the scaphoid synching with the capitate and the lunate flexing approximately 65% of the radio-capitate while the radiocarpal joint is the prominent joint (Rainbow et al. 2015). When the wrist extension goes to the extreme position, the distribution shifts with the capitate extension increasing by 25% over the scaphoid and lunate bones while the midcarpal joint takes a more pronounced role due to increased restraint by the volar ligaments (Rainbow et al. 2015). Radial-ulnar deviation of the wrist is accomplished by a minor radiocarpal translation and angulation (with flexion of the scaphoid/extension of the capitate in radial deviation and the opposite in ulnar deviation) and a larger midcarpal angulation mainly by the capitate (Reigstad 2014). Laxity of the surrounding ligaments has a direct effect on the behaviour of the wrist during the ulnar deviation motion with stiffer ligaments resulting in the scaphoid having a tendency for ulnar deviation (row type wrist) while lax ligaments exhibit more of a tendency for the scaphoid to extend (column type wrist) (Rainbow et al. 2015). This current understanding of the wrist kinematics also highlights the existence of the dart throwers motion.

4.224 Dart Throwers Motion

Dart throwers motion (DTM) is the maximum unrestricted movement from dorsoradial position to the ulnavolar position (Reigstad 2014). Scaphoid and lunate have minimal rotation during this motion as the bones tendency to extend is balanced by their tendency to flex result in all the motion occurring in the midcarpal joint (Rainbow et al. 2015), (Reigstad 2014). The orientation of the mechanical axis of the ligaments in the DTM plane, lack of constraining ligaments between the lunate and the capitate and the flexor carpi ulnaris and the extensor carpi radialis longus and brevis muscles all insert at oblique axis that is orientated in the transverse view to the dart-throwing motion (DTM) plane all provide anatomical evidence that the wrist is predisposed to the dart throwers plane of motion (Rainbow et al. 2015), (Reigstad 2014). The dart thrower motion of the wrist has been demonstrated to be fundamental action to all ballistic activities (throwing, hammering etc) as well as vital to several everyday essential activities such as opening a door (Rainbow et al. 2015). Due to the importance of the DTM it can be an accurate measurement of performance of the wrist (Rainbow et al. 2015).

4.25 Relevant Information on Wrist for Design Parameters

The most relevant points from the literature review are listed below in the context of design parameters;

- Wrist joint is comprised of several bones that are involved in the kinematic behaviour of the wrist to varying degrees dependent on the action being performed and the laxity of the surrounding ligaments. Mimicking these scenarios through artificially recreating the wrist with components that act different depending on motion would be too complex of a task. To address this problem the previously utilised ball and socket design will be utilised for simplicity.

- There are 25 ligaments within the wrist working together to provide stability and guide the bones during their motion. These various ligaments are important, as such they shouldn't be damaged during the surgical procedure or impeded by the design. Scapholunate ligament is of particular importance because when damaged it will result in the development of SLAC that will cause the wrist to fail.

- Dart throwers motion (DTM) is an important motion to maintain functionality in the wrist. There are various anatomical components in the wrist that are aligned with the dart throwers motions such as mechanical axis of the ligaments, orientation of the muscles and the interfacet ridge in the Scapho-Trapezium-Trapezoid Joint. These anatomical features help to guide the wrist in the dart throwers motion. Key point to take from this is that the wrist arthroplasty must be designed to facilitate the dart throwers motion while working with the other components in the wrist during this motion.

- The anatomy of the wrist varies dependent on the individual which must be factored into the design of the wrist arthroplasty. One possible solution could be creating several sizes of the arthroplasty being designed to account for the individual variability of the wrist.

4.3 Failure Analysis

"*Failure is success if we learn from it – Malcolm Forbes*" (Zoe, 2013)

Failure analysis was conducted on the previous total wrist arthroplasty (TWA) designs to understand their strengths / limitations. This process will also ensure past design flaws that have caused failure in the TWA aren't repeated. The information collected in this failure analysis will be collaborated with key findings on the anatomy research to determine the key design parameters for the TWA design.

The progress of the total wrist arthroplasty over the last century has been much slower than the artificial hip with long term results less encouraging and often being reserved for low demand patients (Reigstad 2014). Romanian – German surgeon Thomas Gluck (1853 – 1942) performed the first total wrist arthroplasty on a 21 year old male patient who was suffering tuberculosis on June 1890 (Reigstad 2014), (Lin & Paksima 2017). The implant was made of ivory for the biocompatibility of and was cemented in position (Lin & Paksima 2017), (Chakrabarti 2009). The device was described as a ball and socket articulation with forks on either side that inserted in the ulna and radius proximally and the metacarpals in the distal direction to fixate the device (Reigstad 2014). One year after the surgery the patient was examined by Gluck who noted that the patient had developed chronic fistula in the wrist causing its eventual failure (Reigstad 2014). After Thomas Gluck failed attempt at recreating an artificial wrist replacement there was a long break of 77 years before the next advancement of wrist arthroplasty. This advancement was the first-generation wrist arthroplasty called the Swanson Silicone implant created in the late 1960's.

First Generation

The first-generation wrist arthroplasty consisted of a single piece component called the Swanson Silicone Implant. Early results for the Swanson were promising, providing the patients with pain relief and a suitable ROM. Although early results were promising, longer term studies showed that the Swanson implant was prone to synovitis and fracture (Lin & Paksima 2017).

Swanson Arthroplasty

Figure 4.4 Swanson Arthroplasty (Reigstad, 2014)

Alfred Swanson created the Swanson arthroplasty in 1967 which was the first total wrist arthroplasty (TWA) to receive U.S wide commercial distribution (Adams 2006), (Lin & Paksima 2017). The Swanson was a silicone spacer that functioned to space the radiocarpal joint after resection surgery rather than replace the wrist joint (Lin & Paksima 2017), (Lawler & Paksima 2006). The resection surgery consisted of the distal radius and ulnar head being surgically removed followed by reaming of the medullary canal to create 2 square smoothed surfaces for insertion of the Swanson (Reigstad 2014). The Swanson was then inserted with the proximal stem that tilted into the medullary canal of the radius while the distal stem was inserted into the third metacarpal (Lin & Paksima 2017), (Lawler & Paksima 2006).

Swanson arthroplasty aimed to provide pain relief for the patient while maintaining spacing, alignment and stability within the wrist (Lin & Paksima 2017), (Lawler & Paksima 2006). Silicone was chosen as it was thought to be totally inert, durable, elastic and could sustain a substantial load without deforming (Reigstad 2014). Swanson arthoplasty was a double stemmed, flexible hinged arthroplasty with a barrel-shaped midsection and a Dacron reinforced core that provided axial stability and resistance to torque (Reigstad 2014), (Lawler & Paksima 2006). Midsection was a barrel shaped design to create a wider joint space in the hope to prevent subsidence of the implant into the surrounding bone (Reigstad 2014). Swanson arthroplasty achieved its movement from a combination of the flexibility of the hinge and the correct positioning of the arthroplasty (Adams 2006).

Modifications on design

The Swanson implant has undergone several design and material modifications;

- From 1974 the original silicone rubber was replaced with high performance silicone elastomer to improve the fatigue and fracture performance of the implant (Reigstad 2014), (Lawler & Paksima 2006).

- Two stems of the implant were shortened to improve survivability (Lawler & Paksima 2006).

- Metal liners where introduced to the mid-section of the implant from 1982 to protect the material from sharp edges of the surrounding bone which minimised wear debris and the likelihood of fracturing (Reigstad 2014).

Throughout is design life the Swanson implant has displayed mixed results.

Studies on Performance

There have been several studies on the Swanson wrist arthroplasty with the results shown in table 4.5 below

Researchers and date	**Outline of Study**	**Clinical Outcomes**	**Source of Information**
Goodman and colleagues, 1980	Results of 37 Swanson arthroplasty in patients suffering rheumatoid arthritis were examined after a minimum six month follow up	31 patients had pain relief, 3 patients sustained a periprosthetic fracture and the average postoperative range of motion increased from 50° to 64°	(Lawler & Paksima 2006)

Brase and Millender, no date provided	Reviewed 71 patients who were implanted with the Swanson arthroplasty.	20% fracture rate among patients and an additional 5% of patients that had to undergo revision surgery due to pain or deformity within the wrist	(Lawler & Paksima 2006)
Swanson, 1984	Examined 181 wrist that have undergone Swanson total wrist arthroplasty at 4 years and 5 years post operation	Early on the implant achieved good pain relief, acceptable ROM (average 88° flexion, extension, radial and ulnar deviation), good grip strength and relatively low complication rate. Results after 4 years showed that 90% of patients received complete pain relief, 7% experienced mild pain while 3% had moderate pain after prolonged activity. The 4 year follow up showed the Swanson implant had a 14% revision rate (25 patients) which included 9 patients revised for fracture, four for tendon imbalance and five for recurrent synovitis with three wrist being converted to total wrist fusion. After 5 years the results of the implant deteriorated to 50% pain relief and a 36% revision rate	(Reigstad 2014), (Lin & Paksima 2017) (Lawler & Paksima 2006)
Fatti and associates, 1991	Examined 58 implantations that were conducted on 47 patients that were followed up after an average of 5.8 years	2.5 year follow up showed 75% of patients had pain relief, 4.8 years showed 67% pain relief while at 5.8 years only 51% patients received pain relief. Also at the 5.8 year follow up there were radiographic changes exhibited in 100% of the patients	(Lawler & Paksima 2006)

Table 4.5 Results of Studies on Swanson Arthroplasty

Second Generation

Second-generation arthroplasties featured a cemented ball and socket design which included the Meuli and Volz arthroplasty (Lin & Paksima 2017). These arthroplasties consisted of a radial component with a polyethylene insert that articulated against a metal ball that was fixated to metacarpals through protruding distal prongs (Reigstad 2014) (Chakrabarti 2009). These designs had a single center of rotation, 3 degrees of freedom which provided little resistance to axial load, torque between the articular surfaces and minimal ability to transmit forces from hand to forearm (Lawler & Paksima 2006). The large prongs where constrained across the mobile carpometacarpal joint resulting in abnormal stress causing eventual failure of the arthroplasty by loosening of the component or metacarpal fracture of the wrist (Chakrabarti 2009). Soft tissue imbalance was another issue especially in the Volz implant (Lin & Paksima 2017), (Chakrabarti 2009). The second-generation arthroplasties had high long-term complication rates due to soft tissue imbalance, fracturing of metacarpals and loosening of components resulting in the eventual discontinued use of arthroplasties (Chakrabarti 2009)

Volz Wrist Arthroplasty

Figure 4.5 Original Volz Arthroplasty (Reigstad 2014)

Volz Wrist arthroplasty is a two-part ball and socket arthroplasty that was developed for clinical use by Robert Volz in 1973 (Lin & Paksima 2017). Volz consisted of a long stemmed proximal component that was cement fixated into the medullary canal of the radius and a concave articulating surface (Reigstad 2014). Distal component features a cobalt chrome convex surface that extended to two prongs which were cement fixated into the 2nd and 3rd metacarpals (Reigstad 2014). The articulation section featured a semi constrained hemispherical configuration with a toroidal section that aimed to recreate the biaxial motion of the wrist (Lawler & Paksima 2006). Articulation surfaces were between the concave polyethylene insert for radial component and the distal chrome-cobalt convex surface (Reigstad 2014). The toroidal configuration featured two different radii of curvature which allowed for either a maximum of 90° flexion-extension and 50° radial-ulnar deviation before impingement occurred (Reigstad 2014), (Lawler & Paksima 2006), (Lin & Paksima 2017). This configuration didn’t allow the wrist to either rotate or translate post-operation. (Lawler & Paksima 2006), (Lin & Paksima 2017).

Modifications on design

Figure 4.6 Modified Volz Wrist Arthroplasty (Reigstad, 2014)

The following modifications have been conducted on the Volz wrist arthroplasty during its design life;

- In 1976, the distal component was modified to a single-prong design to mitigate the ulnar drift complication (Lawler & Paksima 2006).

- In 1988 the arthroplasty was redesigned to address the complications associated with cement usage and problems with radioulnar imbalance. The new design which aimed to facilitate wrist balance was called the Clayton-Ferlic-Volz (CFV) device and consisted of a modular titanium prosthesis with an articular surface offset (Lawler & Paksima 2006). The change in design did not have its desired effect with report revision rate of 40% due to complications such as tenosynovitis, carpal tunnel syndrome and soft tissue balancing (Reigstad 2014).

Studies on Performance

There have been several studies on the Meuli wrist arthroplasty with the results shown in table 4.6 below.

Researchers and date	**Outline of Study**	**Clinical Outcomes**	**Source of Information**
Volz, 1976	Volz published a study he conducted on his distal double pronged version of the Volz wrist arthroplasty for 17 implants in 14 different patients	The results from the study showed that good pain relief was achieved from the implant. 12 patients developed increase in range of motion which resulted in an increase in functional ability of the wrist. The patients with rheumatoid arthritis in the study demonstrated the largest increase in ROM with the implant achieving 50° of flexion-extension and 35° radial-ulnar deviation. The study also had the finding that the patient's post-operation demonstrated a tendency for ulnar drift within the wrist.	(Reigstad 2014), (Lawler & Paksima 2006)
Multicenter review, 1997	Review that was conducted on 50 patients	Volz wrist arthroplasty results in superior clinical results when compared to the Swanson implant. This study did also confirm that ulnar deviation is a major hindrance for the Volz arthroplasty being exhibited by 33% of patient's post-operation.	(Lawler & Paksima 2006).
Volz, 1984	New study on the modified prosthesis which examined 25 wrists at a follow up of 3.2 years	The patients exhibited superior patient functionality in the wrist (total ROM of 100%) as well no radioulnar imbalance that was causing the ulnar drift in the original design. The study also noted that no revision surgeries were required due to infection, dis.location, implant fracture or loosening	(Lawler & Paksima 2006) (Reigstad 2014)
Dennis and coworkers, 1986	25 patients followed up after	Results of the study showed 86% of patients reporting improvement post-operation. Extended follow up found 79% of patients	(Lawler & Paksima 2006) (Lin

	average of 5.75 years	exhibiting radiographic signs of bone resorption beneath the collar of the radial component that eventuates in the loosening of the component.	& Paksima 2017)
Bosco and colleagues, 1994	Long-term study of the Volz arthroplasty examining 18 patients with a follow up average of 8.4 years	The initial results of the study found promising results in the 15 patients demonstrated mild to no pain with good functional motion. Study found 22% patients had a loose distal component, 6% patient had a loose proximal component,22% of patients had the metacarpal components perforating the bone with an increasing collapse of the carpus being observed. Even longer term follow up of 10 years or longer found that the carpal height of the wrist reduced in height by as much as 30% (Lawler, 2006) (Lin, 2017). In the study 75% of post-traumatic patients experienced loosening so a recommendation of the study was the Volz arthroplasty be limited to patients who are suffering rheumatoid arthritis and live a low demand lifestyle	(Lawler & Paksima 2006), (Reigstad 2014), (Lin & Paksima 2017)
Gellmann, 1997	examined 14 wrists on 13 patients at a mean follow up of 6.5 years	Patients received good pain relief from the implant and suitable ROM with the prosthesis (mean total of 57°). Volz arthroplasty was flawed due to the high complication rate which included 2 articular dislocations (one of which was chronic in nature), radiolucency being observed in seven wrists, migration observed in 2 radial and 5 metacarpal components, 1 patient had the components dislocated while in 2 wrists both components had subluxed	(Reigstad 2014)

Table 4.6 Results of Studies on Volz Wrist Arthroplasty

Meuli Wrist Arthroplasty System

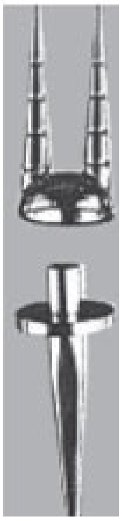


Figure 4.7 Meuli I (Polyester Head)   (Reigstad 2014)

Meuli wrist arthroplasty system was a second-generation implant that was developed in 1972 by Hans Christoph Meuli from Berne, Switzerland (Reigstad 2014), (Lin & Paksima 2017), (Lawler & Paksima 2006). Three versions of the Meuli were created which included Meuli I, Meuli II and Meuli III (Reigstad 2014). These modifications aimed to address the complications that were present in the previous model arthroplasty (Reigstad 2014). Meuli I was the first version consisting of a cemented, unconstrained and non-hinged ball and socket design with three components and no axial offset (Lin & Paksima 2017), (Lawler & Paksima 2006). The components included a polyester ball, a single stem proximal component and a two-prong distal component (Reigstad 2014), (Lin & Paksima 2017). The proximal and distal components where manufactured using Protasul 10 (Ti6AlNb) and the shape of these components could be manipulated prior to fixation to suit the patient's requirements (Reigstad 2014). Prior to insertion the distal ulna, radius distal, scaphoid, lunate and capitate where all resected then the stem of the proximal was inserted into the radius while the two prongs of the distal component was inserted into the 2nd and 3rd metacarpal (Reigstad 2014), (Lin & Paksima 2017).

Modifications on design

During the design life of the Meuli had two major design modifications which produced the Meuli II and Meuli III wrist arthroplasty systems.

Meuli II

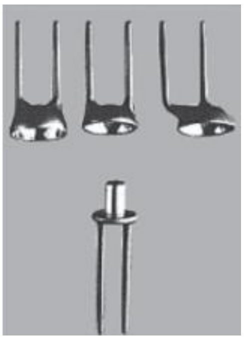


Figure 4.8 Meuli II (Polyethylene Head) (Reigstad 2014)

Following the 1974 study by the Mayo clinic were soft tissue balancing and ulnar deviation were outlined as major design issue with the Meuli I there were major design changes (Lin & Paksima 2017) (Lawler & Paksima 2006). Meuli II was produced with the polyester material used for the ball component being changed to UHMWPE for better biocompatibility while the socket was positioned with a slight volar and ulnar offset (Reigstad 2014), (Lin & Paksima 2017), (Lawler & Paksima 2006).

Meuli III

Figure 4.9 Meuli III (Metal-on-UHMWPE Articulation) (Reigstad 2014)

Meuli III was designed in 1986 to address the poor outcomes of the previous models. Meuli III was a complete change from previous designs to mitigate stability and imbalance problems (Reigstad 2014), (Lawler & Paksima 2006). Components of the arthroplasty were composed of titanium alloy (Ti6AI7Nb) which had a corundum rough-blasted surface for cementless fixation or cemented fixation when patients bone stock was inadequate (Reigstad 2014), (Lawler & Paksima 2006). Proximal component had a nitride coated ball that articulated against the UHMWPE insert of the distal component (Lawler & Paksima 2006). Another modification in the design was that the anchoring prongs of the carpal component being angled 15° dorsal to the median axis (Lawler & Paksima 2006)

Studies on Performance

There have been several studies on the Meuli wrist arthroplasty with the results shown in table 4.7 below.

Researchers and date	**Outline of Study**	**Clinical Outcomes**	**Source of Information**
No researcher given in references	Initial study of 41 patients.	6 patients suffered complications due to the initial use of polyester and center of rotation being too far radial. The complications present included polyester synovitis, dislocations, infection, stem breakage, excessive ulnar deviation.	(Reigstad 2014), (Lawler & Paksima 2006)
Cooney and colleagues (Mayo Clinic), 1974	Clinical trials on the Meuli I wrist arthroplasty where 101 arthroplasties were implanted into patients over a 3 year interval	The results at a 2 year follow up found that 96% of patients received pain relief while 85% of patients reported significant improvement post-operation. Post-surgery there were two main complications present in the patients which were ulnar deviation of the wrist and soft tissue imbalance.	(Lin & Paksima 2017), (Lawler & Paksima 2006)

Cooney and colleagues (Mayo Clinic), 1984	Published a follow up study of 140 Meuli I and II arthroplasties	This study found a reoperation rate of 33% which included 8.6% due to dislocation, 2.9% due to prosthetic loosening, 3% due to deep infection and 12.1% due to soft-tissue deformity or contracture.	(Reigstad 2014), (Lin & Paksima 2017), (Lawler & Paksima 2006)
Hanz Meuli, 1997	Conducted a study on 40 Meuli III arthroplasties for a follow up period of on average 5.5 years	The results from the study showed 32 patients were satisfied while 86% of patients noticed a functional improvement in their wrist. Post-operative range of motion (30° flexion, 40° extension, 10° radial deviation, and 10° ulnar deviation) was achieved and the grip strength was moderately improved post-operatively (rheumatic arthritis patients 3kg improvement while posttraumatic arthritis patients achieve grip strength of 10kg). The study also found that eight of the components of the implant loosened (6 distal and 2 proximal) requiring revision surgery. Main reason attributed to this loosening was incorrect positioning of the components.	(Lawler & Paksima 2006), (Reigstad 2014).
Strunk and Bracker, 2009	Study compared the Meuli, Biax and Universal II arthroplasties	Results of the 15 Meuli III arthroplasty after a follow up of a mean of 9 years; 2 patients died before following up, 3 patients experienced dislocations (2 being stable after closed reduction surgery and 1 converted to arthrodesis), 2 patients experiencing deep infection (both converted to arthrodesis) while radiographic imaging showed only 1 implant still had firm attachment to bone with others showing signs of loosening (mainly around distal carpal component). Results also showed that the arthroplasty gave the patient a total range of motion of 70°.	(Reigstad 2014)

Table 4.7 Results of Studies on Meuli Wrist Arthroplasty.

Third Generation

Third-generation wrist arthroplasty kept the ball and socket design but the designers started to experiment with mixed results. There were several positive design changes that were discovered in the third generation including the use of cementless fixation (Biaxial, Destot and Universal), use of ellipsoid head (Biaxial) and screw fixation of distal plate (Universal). There were also several factors of the design that had disastrous results including microscrew fixation of convex head to distal plate (Guepar), metal on metal articulation (Anatomic) and polyethylene radial stem (Guepar). These arthroplasties were an important learning stage for the designers, that lead to the discovery of several important designs parameters that were later applied to improve the 4th generation wrist arthroplasty.

Trispherical Wrist Arthroplasty

Figure 4.10 Trispherical Wrist Arthroplasty (Reigstad 2014)

Trispherical wrist arthroplasty was a semi-constrained ball-and-socket design with a fixed axle (Reigstad 2014). Trispherical was developed at the Hospital for Special Surgery (Reigstad 2014), (Lawler & Paksima 2006), (Lin & Paksima 2017). Both the distal and proximal stems were manufactured with titanium (Reigstad 2014). Distal component consisted of a long stem that was cemented into the 3rd metacarpal and a shorter offset prong cemented into the 2nd metacarpal to provide resistance to torque (Reigstad 2014), (Lin & Paksima 2017) (Lawler & Paksima 2006). Proximal component consisted of single stem cemented into the radius following the resection of the distal ulna (Reigstad 2014). Articulating components were a ball composed of vitallium (chrome-cobalt alloy) that attached to the proximal component and UHMWPE socket that was attached to the distal component (Reigstad 2014), (Lin & Paksima 2017). Articulating surface design provided a moving center of rotation which allowed maximum flexion – extension of 170°, maximum radial-ulnar deviation of 30° and 10° of axial deviation (Reigstad 2014), (Lawler & Paksima 2006).

Studies on Performance

Several studies on the Trispherical wrist arthroplasty which have shown good results but have highlighted that loosening of the components has still a design issue. The important information from the various studies are shown in table 4.8.

Researchers and date	**Outline of Study**	**Clinical Outcomes**	**Source of Information**
Figgie and coworkers, 1990	The study followed 34 patients suffering from rheumatoid arthritis who collectively received 44 arthroplasties between the years of 1977 and 1983 at an average of a 9 year follow-up.	Results of the follow up found excellent pain relief among patients (30 out of 35 patients reporting excellent pain relief) with a 6% revision rate (1 due to implant loosening and 1 implant due to persistent pain), radiolucent lines being present in 7 of the wrists, 3 wrist presented with migration of the distal component and 6 cases of postoperative extensor tendon attrition Results also showed postoperative ROM was 70° with the available range of motion in flexion-extension increasing from 30° to 50°.	(Lin & Paksima 2017) (Reigstad 2014) (Lawler & Paksima 2006)
Kraay and Figgie, 1995	Review of 67 patients suffering inflammatory arthritis at 5 years, 10 years and 12 years.	Results of the study found a 97% survivorship at 5 years and a 93% survivorship at 10 and 12 years follow up	(Lawler & Paksima 2006), (Lin & Paksima 2017)

Lorei and colleagues, 1997	Review of 87 patients at an average follow-up of 8.7 years.	Results of the study found 8 revisions (9% revision rate) were required which included 2 patients developing attritional rupture of the extensor tendons which resulted loss in ability of extension of the wrist, 3 patients suffering loosening of the metacarpal component which resulted in the eventual perforation of the metacarpal shaft, 1 patient suffering radial component loosening, 1 patient suffering a combination radial and metacarpal components fracturing and 1 patient developing late sepsis infection in the wrist. Treatment of these 8 revisions included 5 patients receiving an arthrodesis revision, 2 receiving a revision arthroplasty and 1 receiving a resection arthroplasty.	(Lin & Paksima 2017), (Reigstad 2014), (Lawler & Paksima 2006)

Table 4.8 Results of Studies on Trispherical Wrist Arthroplasty

Guepar Wrist Arthroplasty

Figure 4.11 Guepar Wrist Arthroplasty (Reigstad 2014)

Guepar arthroplasty was a new design concept compared to previous wrist arthroplasty design that was developed by Alnot in Paris (Reigstad 2014). Radial component was made completely of polyethylene which was fixated using cement (Reigstad 2014). The distal component was composed of cobalt-chrome which was anchored into the medulla of the 2nd and 3rd metacarpal using two long screws (Reigstad 2014), (Chakrabarti 2009). Screw fixation was used in the distal component as an attempt to mitigate the problem distal component loosening present in previous arthroplasty designs (Lawler & Paksima 2006). Distal component consisted of two parts which included an egg-shaped ball connected to a plate via a microscrew (Reigstad 2014). The minimally constrained elliptical geometry of the ball allowed the arthroplasty to mimic the radiocarpal articulation which could translate in the ulnar direction to centralise the rotation (Lawler & Paksima 2006), (Reigstad 2014). The available ROM post-operation was reduced to 39° flexion–extension compared to 47° in preoperative condition (Reigstad 2014).

Studies on Performance

Guepar wrist arthroplasty system has shown poor clinical outcomes for the arthroplasty with the results from the various studies shown in table 4.9.

Researchers and date	**Outline of Study**	**Clinical Outcomes**	**Source of Information**
No researcher given, 1988	Review of 32 implants in 28 patients having a follow-up after 2.5 years	Results of the study found 5 patients developing postoperative stiffness, 4 implants became either loose or dislocated with 2 patients requiring revision surgery due to subsidence of the carpal component and 18 (56%) implants showed radiographic evidence of loosening.	(Lawler & Paksima 2006)
Fourastier and colleagues, 1996	Retrospective study examined 72 implants in 64 patients at an average follow-up of 4 years.	Results from the study found that 86% of patients had no pain while 96% had improved function. 11 implants required revision (15%) which was made up of 5 revision due to loosening of distal articulation component as a result of micro screw motion, 4 revisions due to proximal component loosening which was attributed to wear induced osteolysis and 2 revisions due to distal component loosening as a whole component. Another observation by the researcher was osteolysis and bone resorption under the carpal plate was observed in 56% of the remaining implants that didn't require revision believed to be attributed to the micromotion between plate and screws.	(Lawler & Paksima 2006), (Reigstad 2014)

Table 4.9 Results of Studies on Geupar Wrist Arthroplasty

Biaxial Wrist Arthroplasty

Figure 4.12 Biaxial Wrist Arthroplasty (Reigstad 2014)

Biaxial wrist arthroplasty was developed at the Mayo Clinic between 1978 and 1982 by researchers Cooney, Beckenbaugh and Linscheid (Reigstad 2014), (Lawler & Paksima 2006). Biaxial consisted of an ellipsoidal-shaped articulation that operated in two axes (flex/ext and rad/ulnar deviation) (Lawler & Paksima 2006). This configuration aimed to achieve better wrist balance while solving the problem of loosening of components (Adams 2006), (Reigstad 2014), (Lawler & Paksima 2006). Distal component featured an ellipsoid shaped head that attached to a long porous coated stem which fixated into the 3rd metacarpal along with an additional short porous coated stem for rotational stability which fixated into the capitate (Lawler & Paksima 2006), (Lin & Paksima 2017), (Chakrabarti 2009). Radial component consisted of a single porous coated stem that was fixated into the radius with a concave head (Lawler & Paksima 2006), (Chakrabarti 2009). Both the components were manufactured with chrome-cobalt and were intended for cement fixation with the possibility for uncemented fixation (Reigstad 2017), (Chakrabarti 2009). Although uncemented fixation was possible, it became apparent that the distal fixation required the use of cement (Chakrabarti 2009). Articulation of the Biaxial was between the concave polyethylene liner of the radial component and the convex ellipsoid head of the distal component (Lawler & Paksima 2006). This articulation was non-constrained ellipsoid motion which was offset in the ulnar and palmar direction with the aim of replicating the natural motion of the wrist (flexion/extension and radial/ulnar deviation) (Lawler & Paksima 2006), (Lin & Paksima 2017).

Modification of design

Biaxial was modified in the 1990s due to the prevalence of distal component loosening in patients with poor bone stock (Lawler & Paksima 2006), (Reigstad 2014). The modification included increasing the length of the main stem of the distal carpal component which fixated into the 3rd metacarpal (Lawler & Paksima 2006). This increase in length aimed to bypass weakened bone in the distal row (Lawler & Paksima 2006). Another modification was the addition of a stem onto the distal component which fixated into the second metacarpal (Lawler & Paksima 2006). Modified Biaxial was intended as either a primary or revision arthroplasty option (Reigstad 2014).

Studies on Performance

There have been several studies conducted on the clinical performance of the Biaxial with the results shown in table 4.10

Researchers and date	**Outline of Study**	**Clinical Outcomes**	**Source of Information**
Lirette and Kinnard, no date given	Results of 13 different patients who were all suffering rheumatoid arthritis at an average follow-up of 54 months.	All patients reported either good or excellent outcomes for their prosthesis. 4 patients demonstrating mild radiolucent lines and 1 patient experiencing dislocation of arthroplasty.	(Lawler & Paksima 2006)
Cooney, Beckenbaugh and Linscheid (Mayo Clinic), 1996	Review of 57 implants at a minimum follow-up of 5 years. In the study 52 patients were suffering wrist degeneration due to rheumatoid arthritis.	91% rating their symptoms as better or much better and 97% stating that there was little or no pain. Clinical results found 11 cases required revision due to failure of the arthroplasty system which included 8 due to distal carpal component loosening, 1 due to infection, 1 due to dislocation and 1 due to soft tissue imbalance. Postoperatively ROM increased from 78° to 90°.	(Lawler & Paksima 2006), (Reigstad 2014), (Adams 2006)
Takwale, 2002	Reviewed 66 out of a beginning total of 76 rheumatoid arthritis	The subjective results were excellent or good in 41 of the patients. 25 patients reported fair or poor results, 9 patients	(Reigstad 2014),

	patients (5 were dead and 5 lost at follow up) at a mean follow-up of 52 months.	reported mild pain while 41 patients reported no pain in the implant. Post-operative range of motion (ROM) of 66° was achieved. Clinical results found 11 patients with soft tissue imbalance while 14 distal components and 5 arthroplasty required revision.	(Chakrabarti 2009)
Kretschmer and Wannske, 2003	Study followed 42 patients suffering post-traumatic or degenerative arthritis at a follow up of 2.4 years. Patients profiles had low manual labour demands and had received cementless fixation for the arthroplasty.	Results of the study found loosening in 7 of the components due to polyethylene wear on the dorsal rim and 2 patients with permanent dislocation. The remaining 31 patients there were 9 who exhibited radiographic evidence of osteolysis. There was early radiocarpal dislocation exhibited in 4 patients but was treated by closed reduction and temporary k-wire fixation.	(Reigstad 2014)
Harlingen, 2011	Study examined 40 wrist arthroplasties at an average follow up of 6 years.	Clinical results found that 7 arthroplasty required revision which included; 3 as a result of loosening of components, 2 due to infection, 1 due to malposition, 1 due to distal component breakout. 22 of the remaining patients showing radiographic signs of loosening.	(Reigstad 2014)
Rizzo and Beckenbaugh, 2003	Study examined the modified Biaxial in 17 patients at an average follow up of 74 months.	There were 14 patients that were retrospectively examined. Results from the study found no revision surgery was required, high patient satisfaction with minimal to no pain reported, good range of motion / strength demonstrated and 24% of implants showed evidence of radiographic lucency.	(Reigstad 2014), (Lawler & Paksima 2006), (Lin & Paksima 2017)

Table 4.10 Results of Studies on Biaxial Wrist Arthroplasty

Destot Wrist Arthroplasty

Figure 4.13 Destot Wrist Arthroplasty (Reigstad 2014)

Destot wrist arthroplasty was developed in the 1990's by a group of French and Belgian surgeons that called themselves 'The Destot group' (Reigstad 2014). Destot was unique in that it was the only arthroplasty that was intended for use in patients who were suffering posttraumatic wrist arthritis (Reigstad 2014). Proximal component consisted of sandblasted and porous coated steel peg with a UHMWPE radial cup. Distal component consisted of a proximal steel carpal ball which attached to a condylar UHMWPE cylinder that were then attached to a distal steel component with a steel screw that went off at an angle to provide additional fixation (Reigstad 2014). Articulation design of the implant allowed double articulation which included rotation in the distal direction, flexion/extension articulation and radial/ulnar articulation (Reigstad 2014). This double articulation aimed to provide a greater post-operative ROM in comparison to previous wrist arthroplasty designs (Reigstad 2014).

Studies on Performance

There have been several studies conducted on the clinical performance of Destot with results shown in table 4.11 below.

Researchers and date	**Outline of Study**	**Clinical Outcomes**	**Source of Information**
Levadoux and Legre,	Study examined 35 patients at a mean follow up of 47 months. Patient sample included 80% male with a mean age of 62.5 years.	Postoperative ROM increased from 78° to 123°, forearm rotation from 105° to 167° and grip strength from 20 to 32 kg. Subjective results found that 7 patients experienced moderate to severe pain while 23 patients were either satisfied or very satisfied with the arthroplasty. Clinical results found 6 cases of distal loosening observed with twisting out of the second metacarpal screw and 2 metacarpal stem fractures (patients with fractures were asymptomatic according to researchers), 3 revisions due to pain (fused or revised with new arthroplasty), 1 early infection (treated with surgical cleaning, healing uneventfully but later experienced metacarpal stem fracture) and 1 late infection (revised to arthrodesis).	(Reigstad 2014)
----	Short term study on 28 Destot prosthesis	Found 4 of the Destot wrist arthroplasty had poor results. Conclusion from study was the implant should only be used in low-demand patients over the age of 50	(Chakrabarti 2009)

Table 4.11 Results of Studies on Destot Wrist Arthroplasty

Anatomic Physiologic Wrist

Figure 4.14 Anatomic Physiologic Wrist (Reigstad 2014)

Anatomic Physiologic wrist (APH) was non-cemented arthroplasty designed in Berlin, Germany by the researchers Radmer, Reimer Andresen and Martin Sparmann (Reigstad 2014) (Lawler & Paksima 2006). Proximal component consisted of a cobalt-chrome peg that was coated in hydroxyapatite (HA) for cementless fixation into the radius and a concave articular surface coated in titanium-niobium which was sloped at 10° towards the ulnar direction (Reigstad 2014), (Lawler & Paksima 2006). Distal component consisted of a HA coated cobalt- chrome coronal plate with a large central peg that was cementless fixated into the 3rd metacarpal and 2 smaller side pegs that was cementless fixated into the surrounding distal carpal bones (Reigstad 2014) (Lawler & Paksima 2006). Attached to the distal plates was a mobile ellipsoid bearing surface that was composed of chrome-cobalt covered with titanium-niobium to improve wear properties (Reigstad 2014). The logic behind the design was that the shape and inclination of the components will aid the proximal carpal bones to adjust to a normal ROM (Lawler & Paksima 2006)

Studies on Performance

Researcher Radmer conducted the only study on the anatomic physiologic wrist which highlighted the catastrophically high failure rates due to metal induced osteolysis. The results of this study can be seen in the table 4.12

Researchers and date	**Outline of Study**	**Clinical Outcomes**	**Source of Information**
Radmer, 2003	Study examined 40 patients who had received the APH implant at a mean follow up times of 18 months and 52 months.	Initial results at the 18 month follow up included 87% of patients reported there being no pain in the implant, no signs of loosening, total ROM increasing from average 58° to 101° and grip strength increased from average 18 kPa to 29 kPa. 3 early complications identified which included 1 progressive soft tissue imbalance with subsequent dislocation that was revised with an arthrodesis procedure, 1 dislocation of the carpal component revised with a new carpal component and 1 deep infection that was revised with arthrodesis surgery. The 52 month follow up showed a higher rate of revision of 36/37 (97%). Radiolucent lines greater than 2 mm were present in 30 out of 36 remaining patients, migration of the carpal component was present in 33 patients where 9 also perforated the third metacarpal. Subsidence was also noted in 14 of the radial components. The above information showed loosening of the components was a major problem in this design causing 33 patients to undergo revision surgery (12 patients had loosening in both components). The material failure of the component was another issue causing 3 patients to undergo revision surgery.	(Reigstad 2014), (Adams 2006), (Lawler & Paksima 2006)

Table 4.12 Results of Studies on Anatomic Physiologic Wrist

Universal Wrist Arthroplasty System

Figure 4.15 Universal Wrist Arthroplasty (Reigstad 2014)

Universal wrist arthroplasty was a uncemented (cementing optional) and unconstrained arthroplasty designed by Jay Menon in 1998 (Lin & Paksima 2017), (Chakrabarti 2009), (Reigstad 2014), (Lawler & Paksima 2006). Universal arthroplasty aimed to have minimal constraint, not require cement for fixation, contain the fixation of the implant within the carpus and have a distal carpal component that was fixed with screws (didn't transgress the ulnar and resulted in a more mobile carpometacarpal joint) (Chakrabarti 2009), (Adams 2006). Universal consisted of 3 components which include a cobalt-chrome radial component, distal carpal titanium plate that was fixated with screws and a UHMWPE egg shaped component.

Radial component was manufactured using cobalt-chrome with a Y shaped tie mesh around the stem to allow cementless fixation into the radius bone (Lawler & Paksima 2006), (Reigstad 2014), (Lin & Paksima 2017), (Chakrabarti 2009). The head of the radial component consisted of a concave articular surface which had a 20° radial inclination (Lawler & Paksima 2006). Distal carpal plate was ovoid in shape, composed of titanium and had a 20° inclination similar to the articulating surface on the radius (Reigstad 2014). Fixation of the plate was achieved with three titanium screws (one 6.5mm screw into the capitate, one 4.5mm screw into the hamate and one 4.5mm into the scaphoid/trapezoid) and titanium tie mesh covering the back side of the plate to promote bone ingrowth (Lin & Paksima 2017), (Reigstad 2014). UHMWPE toroidal shaped insert was attached to the distal carpal plate for articulation with the concave head of the radial component (Reigstad 2014), (Chakrabarti 2009).

Modification of design

Figure 4.16 Universal Wrist Arthroplasty (second edition) (Reigstad 2014)

Universal wrist arthroplasty was modified to improve on the clinical results of the original design. These modifications included changing the central fixation screw of the distal carpal plate to a cement fixated peg with indentation and increasing the length of the radial-sided screw to penetrate the 2nd metacarpal (Reigstad 2014).

Studies on Performance

Results from the studies on the Universal wrist arthroplasty are shown in table 4.13.

Researchers and date	**Outline of Study**	**Clinical Outcomes**	**Source of Information**
Menon, 1998	Study examined 37 wrist patients after a mean follow-up of 6.7 years.	Results found the prosthesis good pain relief with 88% of patients reporting no pain and the total ROM increased from 73° to 96°. Clinical results found a complication rate of 33% which included 5 patients experiencing dislocations, 2 patients had radial component loosening, 2 patients suffering deep infections and 1 patient suffered muscular imbalance that was converted to arthrodesis. The study found the survival rate at 10 years was reported at 50%.	(Reigstad 2014), (Chakrabarti 2009), (Lin & Paksima 2017)

Divelbiss, 2002	Study examined 22 patients at an average 2 year follow up.	Results of study found increase in the ROM in all planes and a significant improvement in DASH scores from 14 to 24 points. The clinical results found 3 patients experiencing dislocations and 6 screws were seen to develop osteolytic lines but no implants were determined to be loose. The remaining 19 patients were later followed up after 7.3 years where 9 patients requiring revision due to distal loosening, 1 patient requiring revision due to chronic instability while 2 patients showed signs of component loosening but didn't require revision surgery.	(Reigstad 2014), (Adams 2006), (Lawler & Paksima 2006)
Murphy, 2003	Study compared the results of the modified Universal arthroplasty with TWF after a mean follow-up of 26 months.	Study found that out of 27 arthroplasty that were conducted there were 4 patients who suffered dislocation.	(Reigstad 2014)
No author or date given	Multicenter study that follow 53 patients with a follow up between 1 to 5 years.	Results found that dislocation occurred in 9% of the patient and 4 patients where distal component loosened.	(Adams 2006), (Lawler & Paksima 2006)

Table 4.13 Results of Studies on Universal Wrist Arthroplasty System

Fourth Generation

Fourth generation arthroplasty set to overcome the complications of past TWA by utilising uncemented fixation (Lin & Paksima 2017). Uncemented fixation was achieved through porous coating and/or plasma sprayed coating which improved the osteointegration on the modified surface (Lin & Paksima 2017). Although the intended fixation was for uncemented fixation many of the models offered an option to use cement for fixation (Lin & Paksima 2017). The typical fourth generation design consisted of a radial stem (titanium or cobalt-chrome), carpal plate (titanium or cobalt-chrome), and carpal ball (UHMWPE). There are four 4th generation arthroplasties commercially available which include Remotion, Universal 2, Total modular wrist arthroplasty and Maestro Wrist Reconstructive System (MWRS).

Universal 2 Wrist Arthroplasty System

Figure 4.17 Universal 2 Wrist Arthroplasty System (Reigstad 2014)

Universal 2 wrist arthroplasty system is a modified version of the Universal wrist arthroplasty system that is available for cemented or cementless fixation (Lin & Paksima 2017), (Lawler & Paksima 2006). Modifications that were occurred included;

- Inclination angle on the radial stem was reduced to 14° and the width of the radial component was increased to provide greater capture of the carpal component thus conferring greater rotational stability (Lawler & Paksima 2006).

- Beaded porous coating has been applied to the radial and carpal components for fixation by possible osseous integration (Lawler & Paksima 2006).

- The shaped of the UHMWPE insert was changed from the toroidal shape to am ellipsoidal shape. This modification was due to finite element analysis and laboratory studies demonstrating that the ellipsoidal shape demonstrated more stable contact area and rotational resistance creating a more stable situation in the articulation (Reigstad 2014), (Lawler & Paksima 2006).

- Middle fixation stem of the distal carpal plate was changed to a press fit, titanium coated stem without indentations (Reigstad 2014).

- Carpal component was designed with a greater diameter, stronger central stem as well as full porous coating over its entire distal surface (stem and plate) for better durability and osteointegration (Adams 2006)

- Surgical procedure was modified to include decortication and fusion of the distal carpal row which has led to improved results (Lin & Paksima 2017)

Studies on Performance

There have been several studies conducted on the survivability of this implant. The important information from the various studies are shown in table 4.14 below.

Researchers and date	**Outline of Study**	**Clinical Outcomes**	**Source of Information**
No researchers or date given	Study examined the short-term results of 25 patients (20 women and 5 men).	Patients exhibited ROM of 37° flexion, 33° extension, 22° ulnar deviation and 9° radial deviation and rated their pain relief as good except for 5 patients experiencing mild ulnar sided wrist discomfort. Average DASH scores improved 20% and Patient Related Wrist Evaluation (PRWE) scores improved 35%. Short term clinical results showed no dislocation or radiographic	(Adams 2006), (Lawler & Paksima 2006)

		signs of loosening but one patient had a 3mm subsidence which plateaued shortly afterwards.	
van Winterswijk and Bakx, 2010	Study examined 15 patients (17 wrists, 8 Universal 1 and 9 Universal 2) after a mean follow-up of 46 months. All but one of the patients were suffering from rheumatoid arthritis.	Results found that pain and DASH scores were both improve postoperatively and the ROM increased from 68° to 91°. Clinical results found 2 complications which included 1 patient suffering an early dislocation which became stable after closed reduction and 1 patient suffering distal carpal component loosening. Interesting finding from the study was that patients suffering with osteoarthritis were less satisfied than the rheumatoid arthritis patients.	(Reigstad 2014)
Ferreres and colleagues, no date given	Study conducted a follow-up on patients at an average of 5.5 years	Clinical results found no dislocations or revisions were required at the 5.5-year follow-up. Although there was no dislocation they did find 10% of patients exhibited signs of radiographic osteolysis with 5% of patients showed signs of loosening of the carpal component.	(Lin & Paksima 2017)

Table 4.14 Results of Studies on Universal 2 Wrist Arthroplasty System

Total Modular Wrist System (TMW)

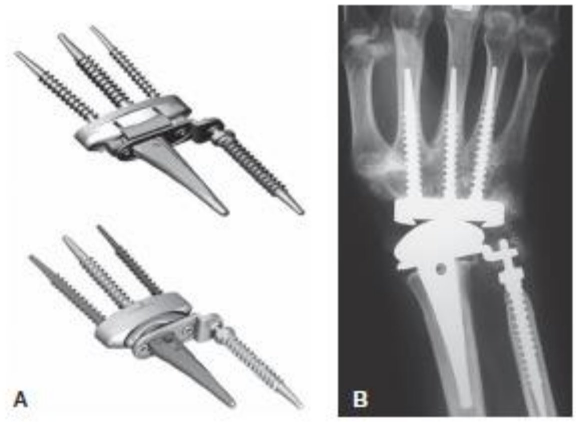


Figure 4.18 The Total Modular Wrist System (TMW).
(A) Constrained Version (B) Unconstrained Version (Reigstad 2014)

Total modular wrist (TMW) system was a cementless total wrist arthroplasty developed by researchers Rahimotoola and Hubach (Reigstad 2014), (Lawler & Paksima 2006). TMW was available as either a constrained or unconstrained device with an optional DRUJ prosthesis (Reigstad 2014), (Lawler & Paksima 2006). TMW consisted of 4 components which include radius component, distal carpal plate, polyethylene tray and an optional DRUJ component (Reigstad 2014), (Lawler & Paksima 2006). Radius plate component is manufactured with chrome-cobalt which is plasma sprayed with either hydroxyapatite or BonitR to promote cementless fixation but is also available in an uncoated version for cemented fixation (Reigstad 2014). Radius plate features a convex egg shaped offset head that articulates with the concave polyethylene tray (Reigstad 2014), (Lawler & Paksima 2006). Radius plate also features an optional modification with a DRUJ arthroplasty connection available to replace the distal radioulnar joint (DRUJ) (Lawler & Paksima 2006), (Reigstad 2014). Distal carpal plate is composed of titanium with HA/ BonitR coating (Reigstad 2014). The plate is fixated with three variable length HA/ BonitR-coated titanium alloy metacarpal screws into the 2nd, 3rd and 4th metacarpal (Reigstad 2014), (Lawler & Paksima 2006). Concave polyethylene tray is fixated onto the distal carpal plate and is available in various thickness dependent on patients' requirement (Lawler & Paksima 2006), (Reigstad 2014). Concave polyethylene tray articulates with the egg shaped head of the radius component allowing either constrained or unconstrained articulation dependent if the TMW is fitted with the DRUJ arthroplasty connection (Reigstad 2014).

Studies on Performance

There have been several studies conducted on the survivability of this implant. The important information from the various studies are shown in table 4.15 below.

Researchers and date	**Outline of Study**	**Clinical Outcomes**	**Source of Information**
Rahimtoola and Bucher, 2004	Study followed 32 patients for a mean time of 20 months postoperatively.	Results found that the overall patient satisfaction was good with an increase in total ROM of 25° (from 63° to 88°). Clinical results found 5 wrists that demonstrated osteolysis / signs of loosening, 1 patient with traumatic dislocation and 5 patients exhibiting progressive subluxation (3 treated with tendon release while 1 patient had their polyethylene insert changed).	(Reigstad 2014), (Lawler & Paksima 2006)
Hubach, 2008	Study examined 60 primary and 18 revisions after a mean follow-up of 4.2 years.	Clinical results found 14 revisions due to loosening (7 patients), instability in the arthroplasty (5 patients) and radius fracture in the arthroplasty (2 patients). ROM achieved averaged 99° and the majority of patients were satisfied with the achieved pain reduction.	(Reigstad 2014)

Table 4.15 Results of Studies on Total Modular Wrist System

Maestro Wrist Reconstructive System (MWRS)

Figure 4.19 Maestro Wrist Reconstructive System (Reigstad 2014)

Maestro wrist reconstructive system was developed by James Strickland, Andrew Palmer and Thomas Graham (Reigstad 2014). Maestro consists of 3 components which include a cobalt-chromium distal carpal component, titanium/cobalt-chromium radial stem and a UHMWPE insert (Lin & Paksima 2017), (Reigstad 2014). Radial component is intended for cementless fixation which consists of a titanium alloy stem that is fixed to a CO-Cr-Mo radial body which is coated with a thick titanium plasma spray (Macrobond) (Reigstad 2014). Radial component consists of a concave head in which the UHMWPE insert is fixated (Reigstad 2014). Distal carpal component is a monoblock structure with an ellipsoid head that is manufactured with cobalt-chromium (Reigstad 2014). Distal component is fixated with a central peg into the capitate, one titanium screw fixating into the 2nd metacarpal and the other titanium screw fixates into the hamate (Lin & Paksima 2017) (Reigstad 2014). Surface of the distal carpal component is plasma sprayed with Macrobond to aid with the cementless fixation (Reigstad 2014). Articulation for the Maestro is centred without inclination or volar angulation occuring between the ellipsoid head of the distal carpal component and the concave UHMWPE insert (Reigstad 2014).

Studies on Performance

Several studies have been conducted on the Maestro with the results shown in table 4.16.

Researchers and date	**Outline of Study**	**Clinical Outcomes**	**Source of Information**
No researcher or date given	25 procedures were performed by the developers between 2005 and 2008. The patients were then followed up with 14 patients having a follow up of more than 2 years.	Clinical results found no major complications (no loosening or dislocations), good pain reduction and good total ROM being achieved in implant (average 122°).	(Reigstad 2014)
Dellacqua	Researcher reported on the clinical results of 19 patients at an average follow-up of 27 months.	Researcher found an increase in total ROM (average 115°) and that 57% of patients reported good or excellent according to the Lamberta wrist score. The study didn't complete radiographic observations on the patient.	(Reigstad 2014)
Nydick and co-workers	Study evaluated 23 implants where 18 patients were post-traumatic arthritis with an average follow-up of 2.3 years	Results found the prosthesis provided the patient with reliable pain relief and wrist ROM which increased from 120 to 128°. Clinical results found a complication rate of 30% but most were minor (stiffness being the most common complication) There was 1 case of deep infection exhibited by a patient which was converted to an arthrodesis, 1 patient had a volar dislocation that was treated by closed reduction and 2 patients had wrist contracture.	(Lin & Paksima 2017), (Reigstad 2014)

Table 4.16 Results of Studies on Maestro Wrist Reconstructive System

Remotion Wrist Arthroplasty

Figure 4.20 Remotion Wrist Arthroplasty (Reigstad 2014)

Remotion wrist arthroplasty was developed by Cooney and Gupta with manufacturing conducted by the Small Bone Innovations Inc (Lin & Paksima 2017), (Chakrabarti 2009). Remotion is a uncemented, semi-constrained 3 component wrist arthroplasty that is available in 4 sizes with a standard or a plus version of the polyethylene insert (Reigstad 2014), (Lawler & Paksima 2006). The three components include UHMWPE insert, Vitallium (Co-Cr-Mo) distal carpal plate and Vitallium (Co-Cr-Mo) radial component (Lawler & Paksima 2006). Vitallium (Co-Cr-Mo) distal carpal plate is fixated with a titanium plasma sprayed central peg fixated into the 3^{rd} metacarpal. The carpal plate is also aided in fixation through two 4.5mm cancellous screws through the plate into the 2^{nd} and 5^{th} metacarpal (Chakrabarti 2009), (Lawler & Paksima 2006) (Reigstad 2014). The unique feature is the curvature of the carpal plate to prevent flattening of the distal row that leads to tendonitis and neuritis in the carpal tunnel (Chakrabarti 2009). Radial component is a plasma sprayed titanium stem that is cementless fixated into the radius (Reigstad 2014). During its design life, the dorsoradial part of the radial has had minor changes to provide a better fit into the radius (Reigstad 2014). Radial component has a highly-polished concave head with a volar (10°) and ulnar (10°) inclination (Reigstad, 2014) (Lawler & Paksima 2006). This configuration of the concave head aims to mimic the distal radius surface helping to preserve the radial styloid and the radioscaphocapitate ligament (Lawler & Paksima 2006), (Reigstad 2014). Remotion arthroplasty mechanics are similar to the Volz and Biaxial in that a narrow convex head of the radial component articulates against a crescentic concave UHMWPE distal carpal insert (Lawler & Paksima 2006). Remotions articulation allowed the patient a ROM of 40° of flexion and extension and 40° of radioulnar deviation while the higher contact surface achieved a greater stability (Lawler & Paksima 2006). Egg-shaped UHMWPE liner was snap fitted onto the distal carpal plate which can also rotate 10° with respect to the plate (Chakrabarti 2009), (Lin & Paksima 2017), (Reigstad 2014). This unique rotation feature reduces torque on the radial component while simultaneously allowing the patient to achieve dart throwers motion (Lin & Paksima 2017). The aforementioned benefits of the rotation reduce the risk of distal carpal component loosening (Chakrabarti 2009), (Lin & Paksima 2017).

Studies on Performance

Several studies have been conducted on the Remotion with the results shown in table 4.17.

Researchers and date	**Outline of Study**	**Clinical Outcomes**	**Source of Information**
Rahimtoola and Rozing	Study on 27 implants with an average follow up of 4 years.	At follow up all patients demonstrated a significant reduction in pain with 17 patients reporting that they were completely pain free at follow up. All patients noticed improvement in range of motion with 24 patients describing that their ability in daily life had been improved postoperatively. Clinical results found 3 patients who exhibited frank loosening at follow up with an additional 2 patients exhibiting signs of possible loosening.	(Lawler & Paksima 2006)
Herzberg, 2011	Study of 20 wrists arthroplasties in 19 patients (average age of 56 years) with an average follow up of 2.7 years.	Results found that no revision surgeries were required but 2 patients experienced loosening of the proximal or distal components. ROM achieved by the rheumatoid patient group was 71° and 49° in the degenerative arthritis patient group. Patients were satisfied with procedure with 14 patients reported good or excellent results.	(Reigstad 2014)
Herzberg and Boeckstyns	Multicenter trial with 129 rheumatoid and 86 non-rheumatoid patients.	Results found the implant provided reliable pain relief and good functional results with an average ROM of 58° in rheumatoid patients and 73° in non-rheumatoid patients. Clinical results found overall survival at 4-year follow-up was 92%.	(Lin & Paksima 2017)

Table 4.17 Results of Studies on Remotion Wrist Arthroplasty

4.4 Determining Design Parameters

Design parameters were determined utilising the information collected in both the failure analysis and the research information on the wrist. The process was carried out in table 4.18 below.

Design feature	Limitations	Cause	Design parameters
Parameters Relative to Distal Carpal Component			
Design of distal carpal plate	Fracture of distal carpal plate	Material utilised in the distal carpal plate can have a direct effect on whether the component will fracture. Fracturing can occur if the fracture toughness is not suitable enough to withstand stress.	Suitable material selection for the distal carpal component with adequate fracture strength that can withstand the stress that the wrist experiences during everyday activities.
Design of distal carpal plate	Loosening of distal carpal component	Material utilised in the distal carpal plate can have a direct effect on the loosening of the component. If the Young's modulus of the material is too high it will result in stress shielding occurring in the surrounding bone. This stress shielding will cause the surrounding bone to deteriorate resulting in the loosening of the component.	Selection of material for the distal carpal plate with properties similar to surrounding bone to prevent stress shielding.
Design of distal carpal plate	Carpal tunnel syndrome	When the carpal plate is flat it can cause the flattening of the distal row which can increase the likelihood of tendonitis and neuritis in the carpal tunnel.	The distal carpal plate of design will be curved to the shape of the distal row of bones

Design of fixation for the distal carpal component	Ulnar drift	The Meuli and Volz arthroplasty used two large prongs design into the 2nd and 3rd metacarpals for fixation of the distal carpal component. This design of fixation was believed to be the underlying cause of ulnar drift present in these models.	The fixation of the distal carpal component will avoid the use of the two large prongeed design used in the Meuli and Volz arthroplasty.
Design of fixation for the distal carpal component	Ulnar drift	The use of cement fixation created a weak point that can fracture resulting in the ulnar drift of the component.	Cementless fixation techniques will be utilised for the fixation of the distal carpal component.
Design of fixation for the distal carpal component	Fracture of fixation stems	If the fixation stems are not suitable size in dimensions or not made out of material with suitable fracture strength, there is a possibility that the stem could fracture.	Design will ensure the fracture strength and dimensions of the stem are able to endure the stress that could be encountered.
Fixation of convex articulating head to distal carpal plate	Loosening of distal carpal component	In the Geupar design the polyethylene convex head was attached to the distal carpal plate using micro screws. These micro screws vibrated which eventuated in their unscrewing resulting in the loosening of distal component.	Arthroplasty will not use the design of a two-part distal carpal component connected by micro screws. Instead the distal carpal component will seek alternative fixation method.
Fixation of convex articulating head to distal carpal plate	Reduced range of motion for arthroplasty, Loosening of radial component	When the convex articulating surface is attached to the distal carpal plate without ability to rotate between surfaces the patient is less likely to be able to complete the dart throwers motion in their wrist and there	Design the convex articulating head so that it can rotate with respect to the distal carpal plate. Remotion design allowed the convex head to rotate 10° with respect to the distal carpal plate which will

		is additional torque generated on the radial component increasing the likelihood of loosening.	be what out design will aim to achieve.
Shape for the convex articulating surface of the distal carpal component	Loosening of components, dislocation, ulnar drift, fracture of components	The toroidal shape compared to the ellipsoid shape for the convex head has been shown in laboratory testing and FEA modelling to generate higher stress in the components. This higher stress is on the volar and dorsal rims of the radial component. The result of this stress is a higher likelihood of loosening of radial component due to reabsorption of surrounding tissue, greater probability of component fracture and higher probability of ulnar drift.	The arthroplasty design will utilise an ellipsoid shape design for the convex head.
Convex articulating heads material	Synovitis, Osteolysis induced loosening, Ulnar drift	Silicone and polyester have been shown to be more bio-reactive to the joints (causing synovitis) and surrounding tissue (deterioration of supporting tissue resulting in loosening and ulnar drift) then UHMWPE.	Materials such as silicone and polyester will not be utilised instead using either a vitamin-e infused cross linked UHMWPE or PEEK material.
Articulating surfaces configuration	Limited ROM, Dislocation, loosening of components, Fracture of components	Design of articulating configuration for the Volz was a semi-constrained hemispherical configuration. This design didn't allow the wrist to rotate or translate post-operation. This is a major limitation as the patient need	The articulation configuration won't be a semi-constrained hemispherical configuration. Instead it will be an ellipsoid convex head against a crescentric concave design. The design will achieve a suitable range of motion and

		full ROM and dart thrower motion capability to conduct everyday tasks. The constrained design also creates areas of high stress which could increase the likelihood of fracture of the components, instability resulting in dislocation and loosening of component due to reabsorption of surrounding tissue.	designed to reduce the stress generated
Articulating surfaces materials	Failure of components, loosening of components, adverse biological reaction to wear particles	Metal on metal articulation caused 36/37 of anatomic physiologic wrist to fail at 52 month follow up due to high wear, adverse reaction to particles and failure of components.	Avoid the use of metal on metal articulation. Will use the metal on UHMWPE configuration instead.
Parameters Relative to Radial Component			
Design of fixation stem of radial component	Loosening of radial component	Cement fixation created a weak point that can fracture resulting in the loosening of the component.	Use cementless fixation techniques for the fixation of the radial component.
Design of fixation stem of radial component	Loosening of radial component	Incorrect design of the radial stem can increase the probability of the loosening as a result of an unstable component	Radial stem shape has changed between models from the screw peg used in the destot to the porous coated larger radial

		and higher stress generated in surrounding bone.	stem design used in the latest designs. The larger stem will be used in the conceptual design with an inclination angle.
Design of concave aspect of radial component	Dislocation of components	Dimensions of the radial concave component are not suitable there is a probability for convex head to become dislocated.	Dimensions of the radial concave component will be large enough to provide capture of the carpal component creating greater rotational stability
Design of concave aspect of radial component	Ulnar drift, soft tissue imbalance, loosening of components	No axial offset caused instability in the Meuli prosthesis resulting in the complications of ulnar drift, soft tissue imbalance and loosening of components.	Create the concave head of the radial component with a volar and ulnar inclination. The precise inclination will be determined later in the design. But Remotion has a volar (10°) and ulnar (10°) inclination for the concave head as a guide.
Radial component material	Loosening of radial component, pain in wrist	The use of polyethylene for the radial component resulted in wear induced osteolysis of the surrounding tissue in several of the patients. This osteolysis resulted in loosening of the radial components for these patients.	The radial component will be made of a metal to mitigate the complication of osteolysis induced loosening of the radial component.
Parameters Relative to Anatomy			
Whole Design	Complexity of Design	The biomechanical action of the wrist is too hard to recreate artificially. Artificially recreating the wrist requires components that act different depending on motion which is	Keep with the simpler ball and socket design that has current been utilised in arthroplasty design.

		beyond the scope of this dissertation.	
Whole Design	Surrounding Ligaments	The surrounding ligaments perform an important role in guiding and providing stability to the wrist. Damage to the ligaments could have a detrimental effect to the post-operative success of the TWA.	Care in the design to make sure that ligament damage is kept minimal during the surgical placement of the arthroplasty. Also, the design of the arthroplasty must no impede on the surrounding ligaments. Scapholunate ligament is a particular ligament that attempts should be made to preserve functionality.
Whole Design	Dart throwers motion	The impediment of the kinematics of the wrist so it is unable to perform the dart throwers motion restrict the patient's ability to perform activities of everyday living.	The arthroplasty will be designed to facilitate the dart throwers motion. Also, care will be taken in the design to ensure it works in conjunction with other components in the wrist (ligaments, muscles)
Whole Design	Sizing of components	The wrist has variability amongst individual with several different types of wrist being possible.	These vary wrist morphology will be considered in the design process. Several sizes for the design will be made available in the later stages of the design.

Table 4.18 Design Parameters Table

CHAPTER 5 CONCEPTUAL DESIGN OF TOTAL WRIST ARTHROPLASTY

5.1 Introduction

The previous chapters of this dissertation have determined key design parameters. This chapter will apply the design parameters to guide the design of our conceptual total wrist arthroplasty. There were several separate sections that were designed for the TWA which include distal carpal plate, convex head, radial stem, fixation screws. The important information for the aforementioned sections of the TWA will be detailed in the design information section while concept design section will apply the important information to determine a concept design for a TWA. This chapter will result in a concept design for the TWA that will address the limitations of current TWA design.

5.2 Design Information

Distal Carpal Plate

The distal carpal plate will feature the design requirements discussed in section 4.4 of this dissertation. The dimensions of the component will be similar to that used in the Maestro arthroplasty which are shown in figure 5.1 and figure 5.2;

180395	Tapered Carpal Plate	9 mm x 37 mm
180396	Tapered Carpal Plate	9 mm x 43 mm
180303	Tapered Carpal Plate	9 mm x 37 mm with 6 mm augment
180304	Tapered Carpal Plate	9 mm x 37 mm with 9 mm augment
180305	Tapered Carpal Plate	9 mm x 37 mm with 12 mm augment
180306	Tapered Carpal Plate	9 mm x 43 mm with 8 mm augment
180307	Tapered Carpal Plate	9 mm x 43 mm with 11 mm augment
180308	Tapered Carpal Plate	9 mm x 43 mm with 14 mm augment

Figure 5.1 Dimensions of Carpal Plate of Maestro Arthroplasty (Biomet Orthopedics 2008)

180320	Captitate Stem	12 mm
180321	Captitate Stem	15 mm
180322	Captitate Stem	18 mm

Figure 5.2 Dimensions of Capitate stem of Maestro Arthroplasty (Biomet Orthopedics 2008)

Convex Head

The distal carpal convex head will feature an ellipsoid shape design along with internal thread to screw onto the stem of the carpal plate. The dimensions of the component will be similar to that used in the Maestro arthroplasty which are shown below;

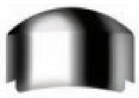
	**180363** **180364** **180365**	Carpal Head Carpal Head Carpal Head	STD 2 mm 4 mm

Figure 5.3 Dimensions of Convex Head of Maestro Arthroplasty (Biomet Orthopedics 2008)

Key feature of design is the ellipsoid shape. Ellipsoid is a symmetrical object with all planes of surface are ellipses with the typical equation explaining the ellipse being $x^2/a^2 + y^2/b^2 + z^2/ c^2 = 1$ (Taita 2013)

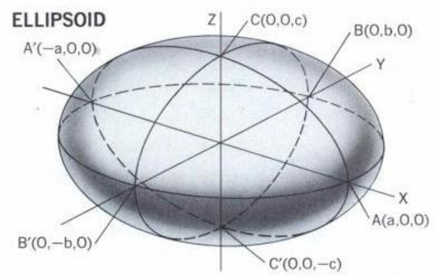


Figure 5.4 Ellipsoid (Taita 2013)

There are different types of ellipsoid shape dependent on the dimensions utilised for a, b and c above. The dimensions will be explored through FEA modelling which will help determine optimal dimensions.

Radial Stem

The radial stem will have the design requirements of a large radial stem body, suitable dimensions of concave head to provide capture of convex head as well as ulnar and volar inclination of concave head. The dimensions of the component will be similar to that used in the Maestro arthroplasty which are shown below;

	180150 180151 180152 180153	Radial Body—Left Radial Body—Right Radial Body—Left Radial Body—Right	7.5mm 7.5 mm 9.0 mm 9.0 mm
	180180 180181 180182 180183	Radial Stem Radial Stem Radial Stem Radial Stem	4.5 mm 6.0 mm 7.5 mm 9.0 mm

Figure 5.5 Dimensions of Radial Components of Maestro (Biomet Orthopedics 2008)

Key features are the ulnar and volar inclination of the concave head.

This ulnar and volar inclination ensures the arthroplasty is similar in design to the anatomy of the healthy human wrist. This is because the radius bone of the wrist has a tilt in the ulnar and volar inclination as shown in the figure below

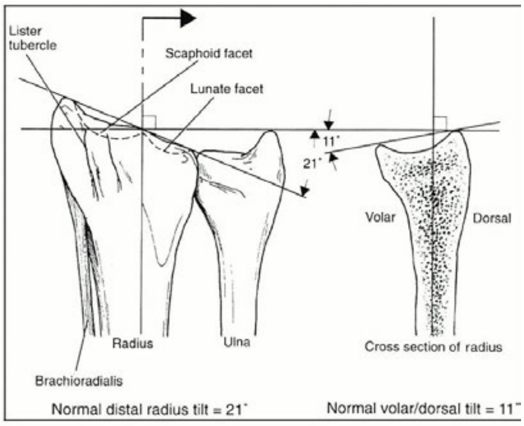


Figure 5.6 Inclination of the Wrist (monardo 2017)

Thus our concave head of the radial component will feature a 10 degree volar and ulnar inclinations.

Fixation Screws

The fixation screws will have the design requirements of suitable length to ensure proper fixation of the distal carpal plate. The dimensions of the component will be similar to that used in the Maestro arthroplasty which are shown below

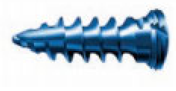
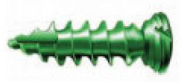
	180340	4.75 mm Fixed Locking Screw	15 mm
	180341	4.75 mm Fixed Locking Screw	20 mm
	180342	4.75 mm Fixed Locking Screw	25 mm
	180343	4.75 mm Fixed Locking Screw	30 mm
	180344	4.75 mm Fixed Locking Screw	35 mm
	180345	4.75 mm Fixed Locking Screw	40 mm
	180346	4.75 mm Fixed Locking Screw	45 mm
	180347	4.75 mm Fixed Locking Screw	50 mm
	180350	4.75 mm Variable Locking Screw	15 mm
	180351	4.75 mm Variable Locking Screw	20 mm
	180352	4.75 mm Variable Locking Screw	25 mm
	180353	4.75 mm Variable Locking Screw	30 mm
	180354	4.75 mm Variable Locking Screw	35 mm
	180355	4.75 mm Variable Locking Screw	40 mm
	180356	4.75 mm Variable Locking Screw	45 mm
	180357	4.75 mm Variable Locking Screw	50 mm

Figure 5.7 Dimensions of Fixation Screws for Maestro arthroplasty (Biomet Orthopedics 2008)

5.3 Concept Design

The design information detailed in section 6.2 are now going to be applied to determine conceptual designs for the total wrist arthroplasty.

Concept Design 1

<u>Distal Carpal Plate Design 1</u>

The design for the carpal plate can be seen in the sketches below.

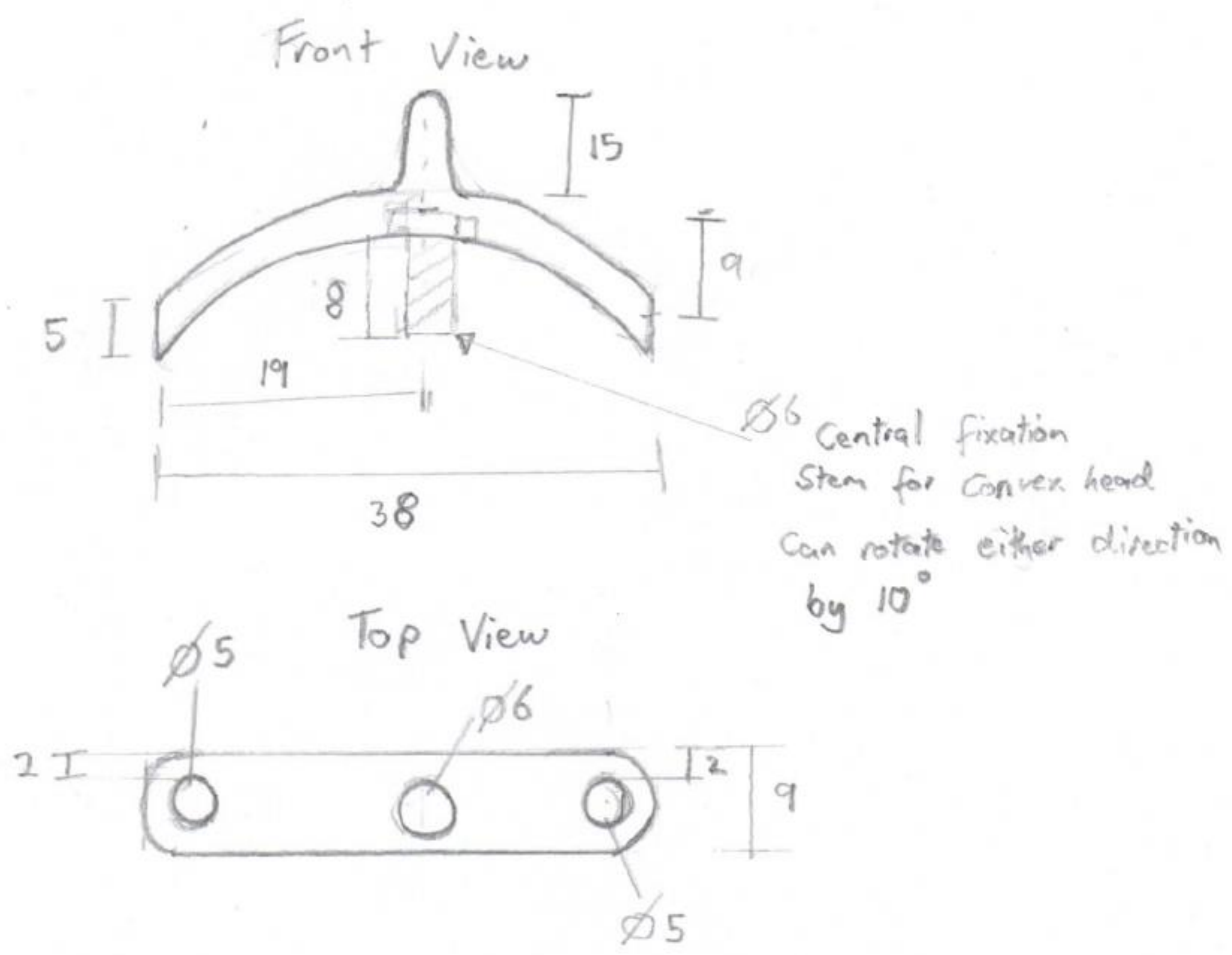


Figure 5.8 Sketches of Distal Carpal Plate

These sketches were used to design the carpal plate in CREO 3.0 with the resulting model shown below;

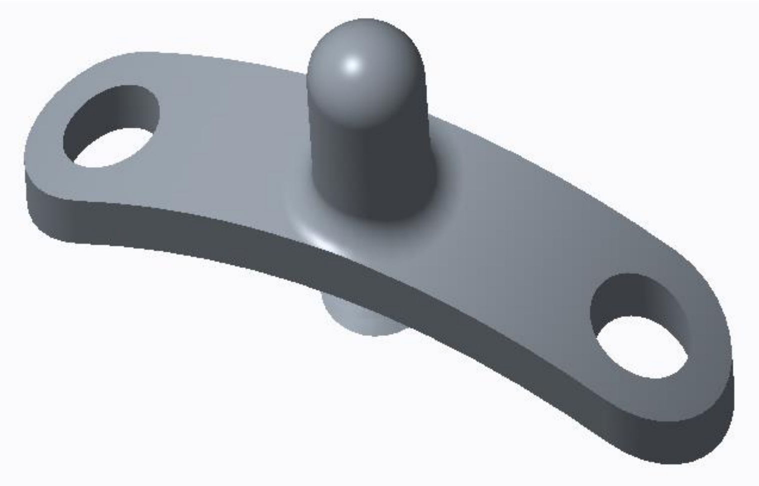


Figure 5.9 Creo Model of Distal Carpal Plate View 1

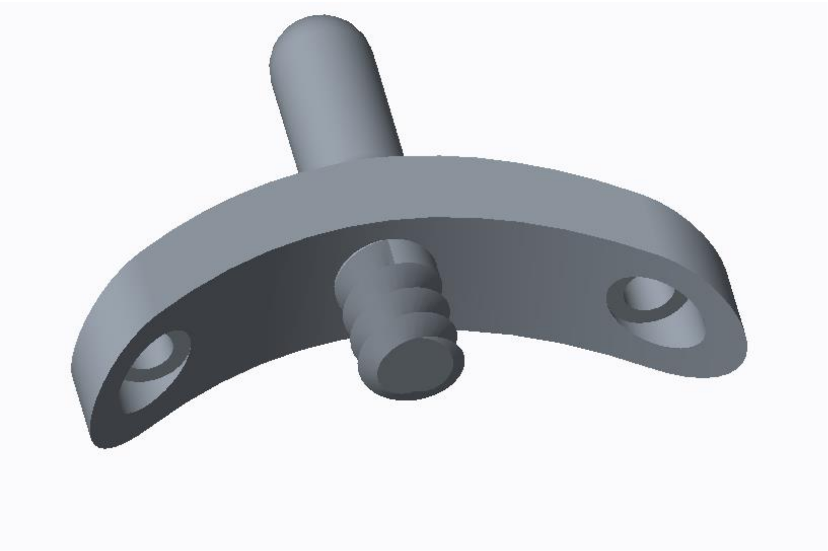


Figure 5.10 Creo Model of Distal Carpal Plate View 2

Convex Head Design 1

The sketch of the ellipsoid convex head

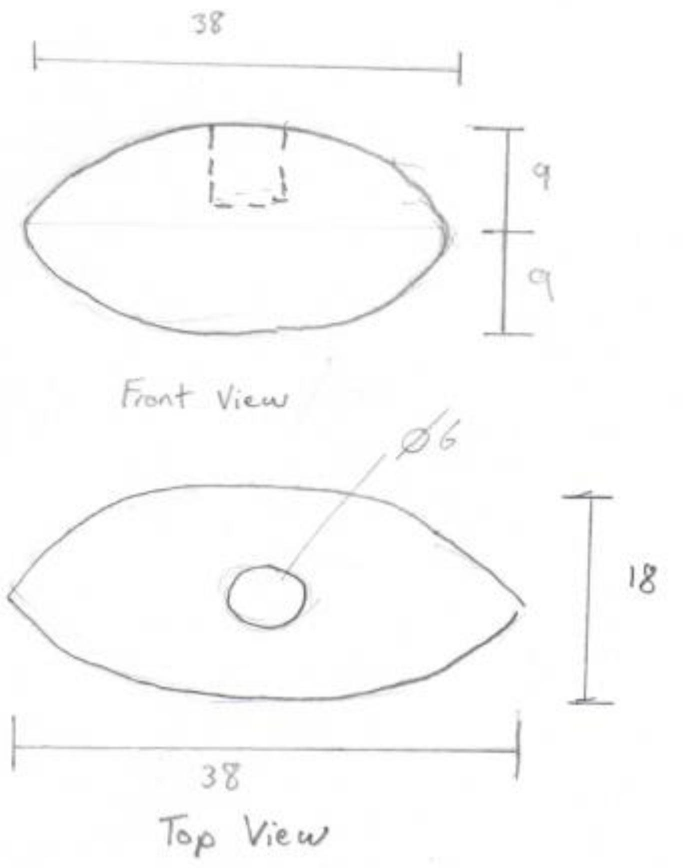


Figure 5.11 Sketches for Ellipsoid Convex Head

These sketches were used to design the convex head in CREO 3.0 with the resulting model shown below;

Figure 5.12 Creo Model of Convex Head View 1

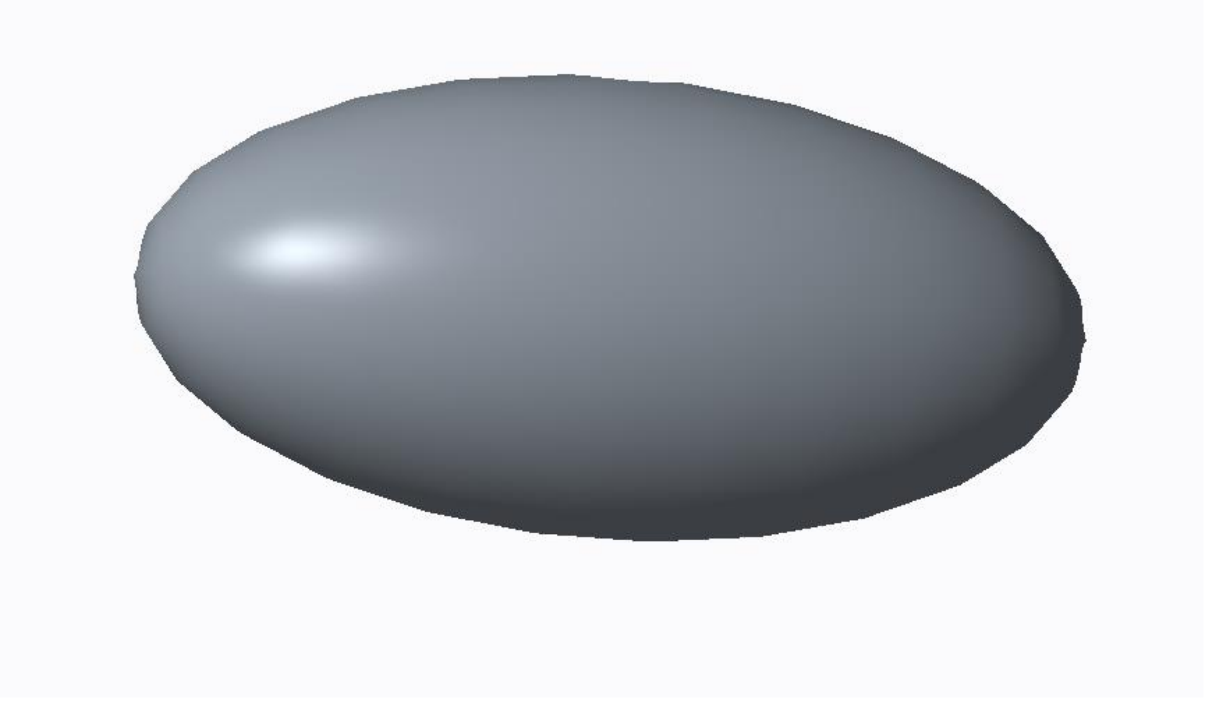


Figure 5.13 Creo Model of Convex Head View 2

Radial Component Design 1

Sketches of the radial component are shown in the figure below;

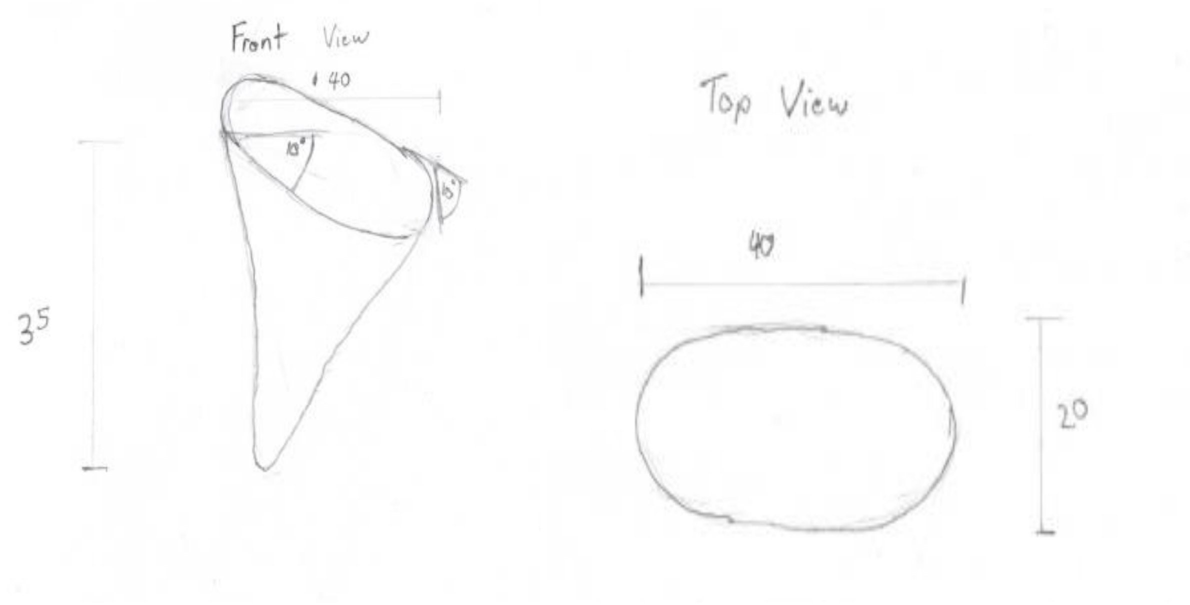


Figure 5.14 Sketches of Radial Component

The sketches were modelled in CREO 3.0 with the resulting model shown below;

Figure 5.15 Creo Model of Radial Component

Fixation Screw Design 1

The sketch for our fixation screw can be seen in the figure below

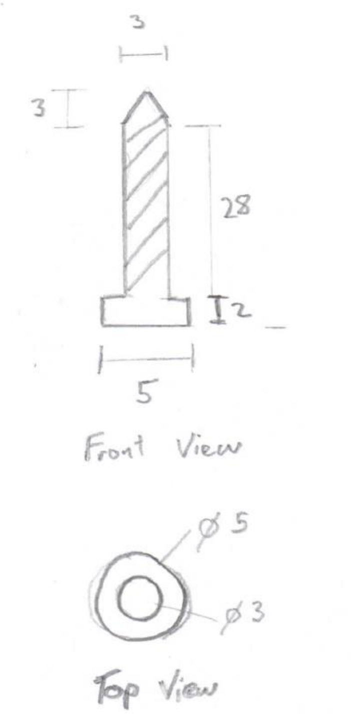


Figure 5.16 Sketch of Fixation Screw

These sketches were used to design the fixation screws in CREO 3.0 with the resulting model shown below;

Figure 5.17 Creo Model of Fixation Screw

Important Features of design

Important features of the above model include

- Central fixation stem that will fixate into the capitate bone of the wrist.

- Two holes either side of the fixation stem for the fixation screws.

- Curved design of the distal plate.

- Threaded central stem that the convex head will screw onto. This fixation stem will have the ability to rotate slightly 10 degrees either direction which will aid in reducing torque experienced by the implant along with aiding the patient in achieving the dart throwers motion in the arthroplasty.

- The distal carpal plate will be manufactured with metal material. This material will have suitable material properties to prevent fracture of the stems of the distal plate but also have Youngs modulus similar to the surrounding bones of the distal carpal row.

- The stem and side in contact with distal row will have cementless fixation technology applied to promote bone ingrowth. The precise technology utilised will be determined in the later design stages of the model

Possible limitations in Design

- The use of a central stem on the distal plate that attaches the convex head could create an area of high stress which could result in the central stem fracturing. This will result in the failure of the wrist arthroplasty design.

- The rotation of the convex head against the distal plate could create friction wear between the two surfaces. This wear would generate particles that could result in osteolysis in surrounding tissue that will eventuate in failure of arthroplasty due to loosening of components.

CHAPTER 6 – CONCLUSION

6.1 Introduction

This dissertation set out to overcome the design limitations of current total wrist arthroplasty. The engineering design process consists of eight steps which are; identification of a need, definition of the problem/specification, search for existing solutions, develop designs, analysis of designs, decision on design, test and verify prototype and communication of results. This dissertation completed the first four steps of the design process to determine a suitable concept design for the total wrist arthroplasty. The remaining steps of the design process will be completed through work with the medical design company 'Field Orthopaedics'. This design process will result in an optimal wrist arthroplasty design with the intention of reducing likelihood of revision surgery relieving the associated financial and emotional burden. This positive impact justifies the need for an improved design for the wrist arthroplasty determined in this dissertation.

6.2 Conclusions

This dissertation determined the need for the total wrist arthroplasty surgical procedure and an improved design. Total wrist arthroplasty (TWA) is an important surgical option for patients suffering late stage pancarpal rheumatoid arthritis wanting to maintain suitable range of motion (ROM). TWA has also been shown that it is the only surgical option available for late stage arthritis for a patient to maintain dart throwers motion. Research has shown that dart throwers motion is an essential ROM for everyday activities. For these reasons TWA is the recommended surgical procedure for patients suffering late stage arthritis wishing to maintain function within the wrist.

Current wrist arthroplasty models have been plagued with complications such as component loosening, fracturing of components and dislocation. Post surgical complication rates have been reported as high as 43% in 1st generation models but have improved to approximately 10% in latest 4th generation models (Lin & Paksima 2017). The result of these complications has been the eventual failure of the arthroplasty necessitating the patient to undergo revision surgery. The high complication rates have reduced the viability of the TWA resulting in the need for an improved TWA design.

Initially the design parameters were determined through the design process steps including definition of design specifications and determining current solutions. These design steps were completed through research into the wrist and a failure analysis of current TWA. Research into the wrist and biomechanics identified several key design points which included; a simple ball and socket design, avoid damage to ligaments (especially scapholunate ligament), facilitate the dart throwers motion and future recommendation to create several sizes for the final TWA. The failure analysis into current TWA identified several key design points which included correct material selection, cementless fixation, curved distal plate, ellipsoid concave head for distal component and large radial stem. These design parameters were applied to formulate an initial concept design for the TWA. The design concept was a screw fixation arthroplasty that utilised a screw thread (that could swivel) to attach the convex head to the distal plate. This design concept adhered to the previously mentioned design parameters which as a result will address current complications in the current TWA designs.

The conceptual design is the starting point for getting a marketable product. The remaining steps of the design process are analysis, decision, testing / verification of prototype and communicating results which will be completed in future research with the company ‘Field Orthopeadics’. The future research will determine a final marketable product that will aim to negate the need for the patient to undergo revision surgery reducing the related negative consequences. These include increased risks, greater odds of complications and financial / emotional burden on the patient (Moussa et al. 2015). The financial impact is quite substantial for the patient with the average cost of a total wrist arthroplasty procedure being priced at $18,478 (Lin & Paksima 2017). On a larger scale, the design will also reduce the burden on the health care system. When a patient is required to undergo surgery, there is a large initial cost but also follow on cost such as post-operative care of patient, follow up appointments and rehabilitation. As it can be seen an improved design for a TWA possess significant advantages to both the patient and health care system.

6.3 Further Research and Recommendations

The conceptual designs devised in this dissertation is a starting point for the company "Field Orthopaedics". There are several further steps in developing the design, these include

5. **Analyses of Designs**
6. **Decision on Design**
7. **Test and Verify Prototype**
8. **Communication of Results**

(Draper 2009)

Analyses of Designs

The design concept determined in this dissertation will be one of the initial designs generated at the company 'Field Orthopaedics'. These initial designs will be further analysed through FEA modelling and evaluation of viability.

Decision on Design

Following the analysis of the concepts there will be a decision on the design to progress. This will be done using a weighted decision matrix which compares the different design against defined criteria that were derived from needs of the patient (Draper 2009). Typical criteria utilised in decision matrix are based on safety, cost and ease of use of product (Draper 2009). Our design will be similar in that the criteria will be based on the ability to withstand stress experienced, address complications typically experienced by patient and cost in developing design.

Test and Verify Prototype

This section will first involve developing the chosen design. This will involve completing the following tasks;

- Finite element analysis will be conducted all the components of the TWA to determine stress experienced by the components. These components will be continually altered utilising the FEA software until optimal designs for the various components are determined

- Material and manufacturing selection will be conducted on all the components in the TWA. The material selected will meet suitable design requirements (for example fracture strength, Young's modulus and wear properties etc) that will be determined in further research. The manufacturing technology utilised in producing the components of the TWA will be selected through further research.

- Conduct research into cementless fixation technologies for TWA to determine optimum cementless fixation technology for our design.

The next step will then be to manufacture design to be tested against typical stress experienced. This will involve sourcing a manufacturer that has suitable material for components, manufacturing capabilities and cementless fixation technology to develop prototype. This prototype will then be tested in line with a developed testing plan. If the prototype passes the testing schedule then the relevant regulations released by FDA in regard to our product will be researched. This research will determine if our design meets the required regulations to determine any alterations that may be required.

Communication of Results

The final step in the process will be to complete 510 (k) submission of final design to get FDA approval to take the product to market. This is where all the information collected during the design process is presented to FDA to justify that the product meets the required standards and is safe for the general public.

It is important that during the design process that when the need necessitates (fail testing, not meeting FDA requirments etc) the designer retracts in the design process to overcome the design issues to ensure an optimal design.

CHAPTER 7 - REFERENCES

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CHAPTER 8 - APPENDICES

8.1 Ligaments of Wrist

Extrinsic Ligaments

Radiocarpal Ligaments

Radio-carpal Ligaments - Radioscaphocapitate, Long Radiolunate (radiotriquetral), Short Radiolunate, Radioscapholunate, Dorsal Radiocarpal

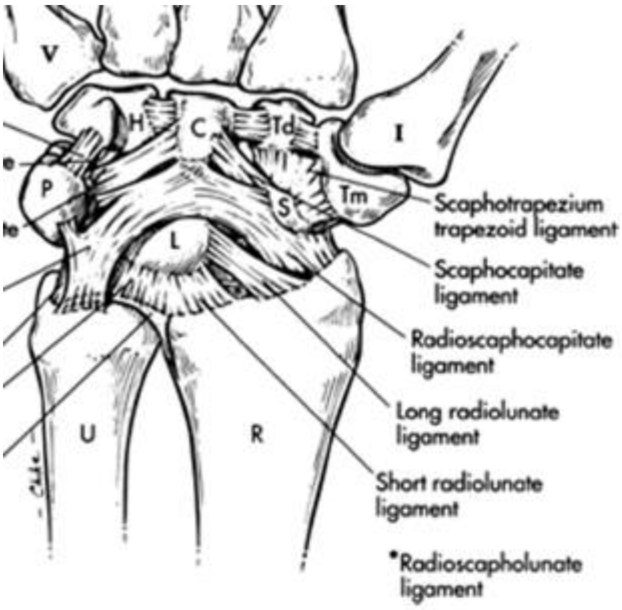


Figure 8.1 Palmer Radiocarpal Ligaments (fisiokinesiterapia, n.d)

Palmar Ligaments

Radioscaphocapitate ligament

The articles by Berger (1996) and Apergis (2013) were paraphrased to form a description of the radioscaphocapitate ligament. This description states the ligament originates proximally from the palmar and radial aspects of the radial styloid process then splits traveling distally and ulnarly which end up attaching to the radial side of the waist of the scaphoid and to the proximal cortex of the distal scaphoid pole. This structure creates a sling like structure that supports the scaphoid. Majority of the fibres of this ligament pass anteriorly under the waist of the scaphoid to form the palmar capsule of the midcarpal joint capsule which supports the head of the capitate.

Apergis (2013) details the dimension, functions and mechanical properties of this ligament. The dimensions of this ligament as approximately 1.4 mm thick, 29.8 mm long, and 5.1 mm wide while its functions include (1) Some of its fibres form a radial collateral ligament (2) provides resistance to passive pronation of the radiocarpal joint (3) along with the other palmar radiocarpal ligaments provides restraint to dorsal translation of the carpus, (4) constrains ulnar translation of the carpus, (5) stabilizes the distal pole of the scaphoid, and (6) acts as a fulcrum around which the scaphoid rotates. Regarding the mechanical properties of this ligament the force required for rupture of the radial collateral region is approximately 100 N, compared with approximately 150 N for rupture of the radiocapitate region. Strain rates at rupture average approximately 125 % and 75 %, respectively. Apergis (2013) also notes that care must be taken during scaphoid excision to avoid damage to this ligament. This is because this ligament acts as a primary stabilizer of the wrist after PRC and prevents ulnar drift.

Regarding the Radioscaphocapitate ligament there is an important division attached to this ligament known as the space of Poirer. The article by Apergis (2013) describes space of Poirer (also known as interligamentous sulcus) that is a deep division that seperates the radioscaphocapitate ligaments from long radiolunate ligament. The articles by fisiokinesiterapia (n.d) and Woon C (n.d) note several key points regarding the space of Poirer. These points include;

- the space of Poirer is a central weak area of the wrist in the floor of the carpal tunnel at the level of the proximal capitate.
- During the biomechanical action of dorsiflexion, the space expands creating a larger weak spot in the wrist while the space disappears during palmar flexion.
- When the wrist is subjected to perilunate dislocation the space of poirer allows the distal carpal row to separate from the lunate while during lunate dislocations the lunate escapes into this space.

Long radiolunate ligament (other names include radiolunotriquetral or volar radiolunate ligament)

Key information from articles by Kijima et al (2009), Woon (n.d) and Apergis (2013) where utilised to form a description of the long radiolunate ligament. This description states the long radiolunate ligament as a large capsular ligament originating from the palmar rim of the scaphoid fossa of the distal radius, just ulnar to the radioscaphocapitate ligament. This ligament courses in several different directions which include obliquely in the distal and ulnar direction passing anterior to the proximal pole of the scaphoid without attaching and anterior to the scapholunate joint overlapping the palmar scapholunate interosseous ligament in the process to end up attaching to the palmar horn of the lunate on the radial and distal edge. The degree of attachment to the lunate varies between individuals

Apergis (2013) notes the dimensions, functions and material property of this ligament. The dimensions are approximately 1.2 mm thick, 16 mm long, and 5.8 mm wide while it functions as a primary restraint to ulnar translocation of the lunate and participates in the formation of the antipronation sling, which is responsible for the control of intracarpal pronation. Regarding material properties, testing has shown that it ruptures at approximately 110 N of applied force, with approximately 125 % strain at rupture.

Short radiolunate ligament

The articles Berger (1996), Kijima et al (2009), Woon (ND) and Apergis (2013) were paraphrased and collaborated to form the following description of the short radiolunate ligament. The short radiolunate ligament originates from ulnopalmar edge of the distal radius attached distally to the lunate at the junction of the proximal articular surface and the nonarticular palmar horn of the lunate. This attachment to the lunate is proximal in location to where the ulnolunate ligament attaches. The orientation of its fibres change during flexion from fan shaped in palmar flexion to longitudinal in dorsiflexion of the lunate.

Apergis (2013) details the dimensions, functional role and deficiency of this ligament. The dimensions of this ligament are approximately 1.2 mm thick, 7.5 mm long, and 10.6 mm wide. Its main functional role is to stabilizes the lunate (and hence the proximal carpal row) and prevents its volar, dorsal, and ulnar translation. The deficiency of the short radiolunate ligament is mainly responsible for the dorsal subluxation of the radiocarpal joint during the dorsal stress test of the wrist and has been considered the primary soft tissue restraint against volar translation of the carpus. Consequently, fracture of the volar radial rim where the short radiolunate ligament is attached, could destabilize the carpus leading to volar subluxation of the wrist.

Radioscapholunate ligament

(Another name: ligament of Testut and Kuentz)

The articles Berger (1996), Kijima et al (2009), Woon (ND) and Apergis (2013) were paraphrased and collaborated to form the following description of the radioscapholunate ligament. The radioscapholunate ligament is located between the long and short radiolunate ligaments and originates from a proximal attachment to the volar edge of the distal radius. This originating attachment is located at the interfossal ridge which is between the scaphoid and lunate articular facets. The ligament propagates vertically branching towards the scaphoid and lunate perforating the palmar joint capsule then inserting into the palmar and proximal aspects of the scapholunate ligament at both the scaphoid and lunate

Apergis (2013) notes the dimensions and mechanical performance of this ligament. The dimensions of the ligament are approximately 0.7-1.2 mm thick, 8.3-9mm long, and 2.5-4.8mm wide with its appearance being described as an intra-articular fat pad. Ligament differs from other radiocarpal ligaments morphologically due to it being a neurovascular mesocapsule with minimal collagen content. This results in poor mechanical performance for this ligament and often not being considered a true ligament. Studies have documented failure of this ligament at approximately 40 N of applied load, but with substantial elastic behaviour and higher strain at failure—approximately 175 %.

Although its mechanical contribution is minimal, it may be important to the functional integrity of the wrist. Berger (1996) notes that there is increasing evidence that it plays a role as a mechanoreceptor and is also a likely source for synovial filtration, producing synovial fluid and possibly resorbing metabolic waste.

Dorsal Ligaments

Dorsal Radiocarpal Ligament

The articles Kijima et al (2009) and Apergis (2013) were paraphrased and collaborated to form the following description of the dorsal radiocarpal ligament. The dorsal radiocarpal ligament originates proximally from the ulnar and dorsal portions of the distal end of the radius which is located distal and ulnar to Lister’s tubercle. From this origin, the ligament tracks obliquely in the distal and ulnar direction to attach to the dorsal tubercle of the triquetrum. On this track this ligament splits off to provide osseous attachments onto the distal ulnar aspect of the dorsal lunate and dorsal portion of the lunotriquetral interosseous ligament.

Apergis (2013) details the morphology of this ligament into two distinct components which include a superficial radiotriquetral band and a deep radiolunotriquetral ligament, which intermingles with fibres of the lunotriquetral ligament. The superficial section arises from the distal part of the interosseous border of the radius and tracks obliquely distally and ulnarward, over the distal ulna to attach to the lunate and triquetrum blending with the dorsal radioulnar ligament on its course. The deeper section of this ligament is the radial section which starts from the posterior edge of the distal border of the radius and runs nearly horizontally and ulnarwards to attach to the lunate and triquetrum.

Apergis (2013) details several functions of the dorsal radiocarpal ligament which include

- Cover the dorsal aspect of the proximal scaphoid alongside deltoid fibres which combine to provide dorsal support to the scaphoid
- Help to constrain the ulnar translocation of the carpus
- Acts as a stabiliser and pronator of the wrist
- Provides resistance to passive supination of the radiocarpal joint thus participating as a key component of the antisupination sling.
- Key ligament for the scaphoid and lunate kinematics during dynamic wrist motion
- Attenuation or disruption of this ligament has been implicated in playing a key role in development of instability in the wrist
- Superficial component of ligament plays important role in stabilization of distal radioulnar joint especially in extreme pronation

Ulnocarpal Ligaments

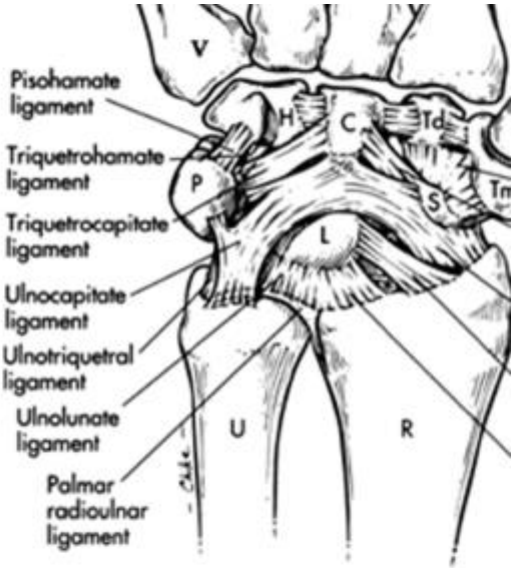


Figure 8.2 Ulnocarpal Ligaments (fisiokinesiterapia, n.d)

Ulnocarpal Ligaments - Ulnolunate, Ulnotriquetral, Ulnocapitate

Apergis (2013) details that the ulnocarpal ligaments form the anterior and ulnar aspects of the ulnocarpal joint capsule and have the following responsibilities;

- Maintaining stability of ulnocarpal joint
- Ensure correct axial alignment between ulna and ulnar side of wrist
- Aid in the atero-posterior stability of the ulnar carpus and restraint of the radiocarpal joint in dorso-palmar translation
- Contribute to stability of the distal radioulnar joint due to being a component of the TFCC
- Rupture or elongation of the ulnocarpal ligaments may lead to supination deformity of the ulnar carpus

Ulnolunate ligament

The articles Berger (1996), Kijima et al (2009) and Apergis (2013) were paraphrased and collaborated to form the following description of the ulnolunate ligament. Ulnolunate ligament originates from the palmar radioulnar ligament which is courses out from distally attaching on the volar edge of the lunate. The track that this ligament takes also means that it parallels the short radiolunate ligament, ulnocapitate ligament and ulnotriquetral with the ulnolunate ligament attachment to the lunate located distally to the short radiolunate ligaments attachment. The origin of the ulnolunate ligament is located radial to the ulnocapitate and ulnotriquetral ligaments at the base of the ulnar styloid process.

Apergis (2013) notes the dimensions and mechanical performance of this ligament. The function of this ligament is to aid the short radiolunate ligament in proximally stabilising the lunate during all phases of wrist motion which it achieves by mirror the short radiolunate ligaments shape changes during dorsiflexion and palmar flexion of the wrist. Dimensions of this ligament are length of 18mm, width of 2.3mm and thickness of 0.7mm. Material properties of the ulnolunate ligaments are failure at 175N of applied load at 125% strain.

Ulnocapitate ligament

The articles Kijima et al (2009) and Apergis (2013) were paraphrased and collaborated to form the following description of the ulnocapitate ligament. Ulnocapitate ligament is unique in that it is the only ligament that originates from the foveal recess of the ulnar head as well originating by attaching proximally to the radioulnar ligament where it attaches to the ulnar styloid process. It then tracks distally across the ulnocarpal joint, partially covering the ulnotriquetral and ulnolunate ligaments ending by attaching to the proximal and volar sides of the capitate. During its path, it integrates with fibres of the palmar region of the lunotriquetral interosseous ligament which ends up attaching to the triquetrum and integrates with fibres of the Radioscaphocapitate ligament. Due to the integration of the fibres of this ligament with other ligaments during its path only about 10% of the ulnocapitate ligaments fibres attach to the capitate. Berger (1996) describes the role of this ligament is to reinforce the ulnocarpal joint capsule and the luno-triquetral joint while also playing a role in the stability of the distal radioulnar joint

Ulnotriquetral ligament

The articles by Berger (1996) and Aspergis (2013) were paraphrased and collaborated to form the following description of the ligament. The ulnotriquetral ligament can be described as originating from the palmar region of the radioulnar ligament and tracks distally to insert into the proximal and palmar surface of the triquetrum. The ulnotriquetral ligament also contains two perforations that can be weak areas for this ligament and could eventually lead to longitudinal split tears in this ligament. One of these perforation is located distally and leads to the pisotriquetral joint (found in more than 70% of adults) and one proximally called the prestyloid recess which communicates with the ulnar styloid process. This ligament is deeply integrated with the ulnolunate ligament with distinction on being visible due to their different distal attachments, Also the border of the Ulnotriquetral ligament has secondary function forming the ulnar and dorsal wall of the ulnocarpal joint.

Midcarpal Ligaments

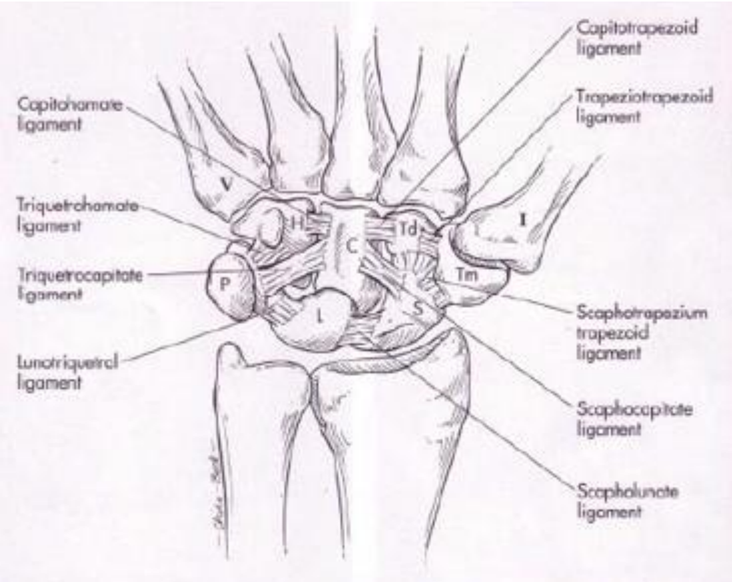


Figure 8.3 Palmer Midcarpal Ligaments (fisiokinesiterapia n.d)

Palmar Ligaments

Scaphotrapezium-trapezoid

The articles Berger (1996) and Apergis (2013) were paraphrased and collaborated to form the following description of the ulnocapitate ligament. The Scaphotrapezium-trapezoid ligament originates from the radiovolar aspect of the scaphoid tubercle (located distal to the attachment of the radioscaphocapitate ligament) tracking out distally into two different bands that attach to the trapezium and trapezoid bones. The radial band (also known as scaphotrapezium) creates a V-shaped structure that attaches to the palmar and radial faces of the trapezium while the ulnar band (also known as the scaphotrapezoid) attaches to palmar face of the trapezoid.

The article by Apergis (2013) notes the function and material properties of the scaphotrapezium-trapezoid. The main function of this ligament is as a stabilizing component of the Scaphotrapezium-trapezoid joint. This ligament is a secondary stabiliser with the distal ligamentous complex of the scaphoid to stabilise the scaphoid. The Scaphotrapezium-trapezoid ligament assist in in maintaining the scaphoid in a palmar-flexed attitude preventing it from lying horizontally (with SL complex intact), while it simultaneously minimizes excessive scaphoid flexion. The material properties of Scaphotrapezium-trapezoid ligament through various studies demonstrated yield strength of approximately 150 N and a strain of failure at approximately 275 %.

Scaphocapitate

The articles Berger (1996), Kijima et al (2009) and Apergis (2013) were paraphrased and collaborated to form the following description of the scaphocapitate ligament. The scaphocapitate ligament originates from the ulnar and volar side of the distal pole of the scaphoid tracking out obliquely on a path that is just distal to the fibres of the radioscaphocapitate ligament and that crosses the palmar midcarpal joint to end attaching to the body of the capitate on the radial and volar side

The article by Apergis (2013) details the functions, dimensions and material properties of the scaphocapitate ligament. The scaphocapitate ligament is the thickest ligament with the largest attachment to the scaphoid which acts as a stabilizer of the distal pole of the scaphoid. The scaphocapitate ligament also forms part of the antipronation sling which constrains the midcarpal pronation. The scaphotrapezium and the scaphocapitate ligaments also function as collateral ligaments of monoaxial articulation, thus consequently are the only ligaments guiding dart-throwing motion. Dimensions of the scaphocapitate ligament are approximately 2.2 mm thick, 14 mm long, and 6.7 mm wide. Studies on the material properties of the scaphocapitate ligament have shown average yield strength of approximately 100 N and a strain of failure at approximately 200 %.

Capitate-Trapezium

The article by Apergis (2013) has the following description of the capitate-trapezium ligament. The capitate-trapezium ligament originates from the radiovolar aspect of the trapezium transerversing out to attach onto the volar waist of the capitate. The development of the capitate-trapezium ligament has been shown to be correlated to the range of scapholunate angle and the prevalence of degenerative changes in the scaphotrapeziotrapezoid joint. The correlation with its development results in its dimensions being highly variable with the widths ranging from 0 to 7.7 mm (average length, 3.3 mm). The capitate-trapezium functions as a labrum for the distal pole of the scaphoid helping to reinforce the palmar aspect of the scaphotrapeziotrapezoid joint.

Triquetrocapitate

The articles Berger (1996) and Apergis (2013) were paraphrased and collaborated to form the following description of the triquetrocapitate ligament. The triquetrocapitate ligament originates from a proximal attachment to the volar and radial edges of the triquetrum tracking out contributing to the upper half of the midcarpal joint capsule then finishing up by attaching to the proximal and ulnar half of the capitate body (Berger RA, 1996), (Apergis E, 2013). The article by Apergis (2013) details the function and mechanical properties of the triquetrocapitate ligament. Key functions of this ligament include aiding in the ulnar and anteromedial midcarpal stability as well as being a key ligament in the formation of the antisupination sling which provides the constraint of midcarpal supination. The yield strength has been estimated at approximately 110 N, with a yield strain at approximately 60 %.

Triquetrohamate

The articles Berger (1996), Kijima et al (2009) and Apergis (2013) were paraphrased and collaborated to form the following description of the triquetrohamate ligament. The triquetrohamate ligament originates distal and radial edge margin of the palmar cortex of the triquetrum tracks out distally to attach to the proximal and volar edge on the palmar cortex of the body of the hamate with no substantial insertion to the proximal pole of the hamate. The fibres of the triquetrocapitate, triquetrohamate and ulnocapitate ligaments often interdigitate together to form the ulnar limb of the arcuate ligament.

The article by Apergis (2013) also goes into detail into the relationship the triquetrohamate and triquetrocapitate ligaments. The anatomical relationship between triquetrocapitate ligament and the triquetrohamate ligament is variable between individuals and is dependent on the type of lunate an individual possess. There are three common classification for the ligaments relationship which are either type A, type B or type C. Type A the triquetrocapitate ligament and the triquetrohamate ligament are separate, type B triquetrocapitate ligament completely overlaps the triquetrohamate ligament and in type C, the triquetrocapitate ligament has an additional ligament from the triquetrum to the proximal pole of the hamate. Studies on the relationship between the type of lunate and ligaments relationships have shown 82% type 1 lunates are associated with a type A ligament relationship and 96% of type II lunates associated with type C relationship

Palmar scaphotriquetral ligament

The article by Apergis (2013) describes the palmar scaphotriquetral ligament as well as behaviour and function of this ligament. The palmar scaphotriquetral ligament originates with a substantial attachment to the triquetrum that lies between the attachment of the triquetralcapitate ligament and the lunotriquetral ligament. It tracks out horizontally from this attachment spanning the entire midcarpal joint finishing up by inserting into the scaphoid in a fan like attachment with fibres interdigitating with those of the radioscaphocapitate ligament on the scaphoid attachment. The palmar scaphotriquetral ligament is an integral ligament of the midcarpal arcuate ligament which is formed in combination with the radioscaphocapitate and ulnocapitate ligaments. Behaviour of the palmar scaphotriquetral ligament is that during dorsiflexion it tightens while during palmarflexion it slackens and during radioulnar deviation it neither tightens or slackens. Researchers have postulated that a key function of this ligaments is to support the head of the capitate during dorsiflexion of the wrist, acting as volar labrum for the lunocapitate joint. Another theory speculated by researchers is that the that widening of the scapholunate joint during dorsiflexion of the wrist, may only be possible when the palmar scaphotriquetral ligament is torn.

Dorsal Midcarpal Ligaments

There are 2 dorsal midcarpal ligaments which are the dorsal intercarpal ligament and the dorsal scaphotriquetral

Dorsal intercarpal ligament

The articles Kijima et al (2009) and Apergis (2013) were paraphrased and collaborated to form the following description of the scaphocapitate ligament and the important functions it plays in the wrist. The dorsal intercarpal ligament originates by proximally attaching onto the distal and radial aspect of the dorsal tubercle of the triquetrum then tracks radially overlapping the dorsal portion of the scapholunate interosseous ligament and interdigitating with fibre of the dorsal radiocarpal ligament. Towards the end of the ligament it splits into two sections with the thicker portion inserting into the dorsal groove of the scaphoid while the thinner arm inserts into the dorsal components of the trapezium and trapezoid. The interdigitating of the dorsal intercarpal and dorsal radiocarpal ligaments creates a lateral V configuration which have some important functions of providing indirect dorsal stability to the scapholunate complex during wrist motion, maintaining carpal stability and alignment and play an important role in preventing the development of dorsal intercalated segment instability (DISI) and volar intercalated segment instability (VISI) deformities. The article by Apergis (2013) also details the dimensions and mechanical strength of this ligament. The dimension of the dorsal intercarpal ligament are approximately 1.2 mm thick, 32.6 mm long, and 6.3 mm wide. The mechanical strength of the dorsal intercarpal ligament is 115 +/- 57.2N.

Dorsal scaphotriquetral

The article by Apergis (2013) provides a description of the dorsal scaphotriquetral ligament as well as describing the function it has in the wrist. The thicker branch of the dorsal intercarpal ligament augments the dorsal regions of scapholunate and lunotriquetral interosseous ligaments while also having osseous attachments to the dorsal lunate and scaphoid. This creates a proximal thick band that is called dorsal scaphotriquetral ligament. The dimensions of the dorsal scaphotriquetral ligament are often inconstant which often causing it to be confused with the dorsal intercarpal ligament. The role of the dorsal scaphotriquetral ligament is to provide transverse stability of the proximal carpal row. The dorsal scaphotriquetral ligament also has secondary functions of creating a labrum for the head of the capitate and the proximal pole of the hamate dorsally thereby deepening the midcarpal joint.

Distal Radioulnar Joint

Triangular fibrocartilage complex (TFC)

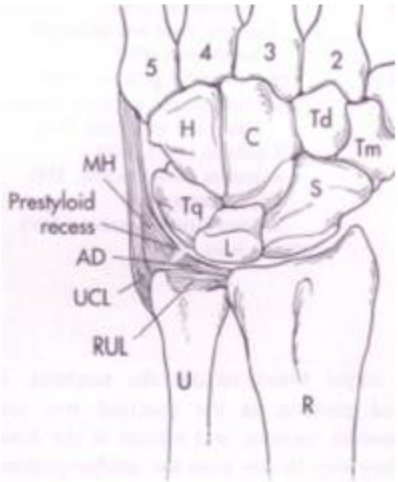


Figure 8.4 Triangular Fibrocartilage Complex (fisiokinesiterapia, n.d)

The article by Apergis (2013) provides a description of the triangular fibrocartilage complex (TFC), details the components of the TFC and describes the function it serves in the wrist. The triangular fibrocartilage complex (TFC) is a term invented by Palmer and Werner to describe a collection of ligaments that separates the DRUJ from the radiocarpal joint. The TFC originates from the distal rim of the radial sigmoid notch and inserts on the fovea of the ulnar head and the base of the ulnar styloid. The components of the complex include: the articular disk which is a fibrocartilaginous biconcave structure with varying thickness of between 1-2mm that is interposed between the ulnar dome and the ulnaraspect of the carpus, the dorsal and palmar radioulnar ligaments, the meniscus homologue (MH), and the extensor carpi ulnaris sheath (the floor of which is often called the ulnar collateral ligament). The functions of the TFC include:

(1) The articular disk component acts as a supporting cushion for the ulnar carpus which can carry up to 20% of the load the forearm is subjected to
(2) The peripheral component of the TFC is the major stabilizer of the dorsal radioulnar joint
(3) The ulnocarpal ligaments and the sheath of the extensor carpi ulnaris contribute to the stability between the ulnar head and the ulnar carpus

Radioulnar Ligament

The article by Apergis (2013) provides the following description of the radioulnar ligament as well describing the dorsal / volar components and deep/ superficial of this ligament. The radioulnar ligament is composed of longitudinally oriented bundles of collagen fibres and can be split into dorsal and palmer sections. The dorsal and palmar sections are similar in that they both consist of superficial components inserting directly onto the ulna styloid and deep components inserting more lateral, into the fovea adjacent to the articular surface of the pole of the distal ulna. The radioulnar ligaments have a spiral configuration as they insert into a surface area, not one single point, on the ulnar head. The helicoidal bundles, in conjunction with the combined centric and epicentric insertions of the deep and superficial radioulnar portions respectively, lead to a continuous shift in the tension of various portions of the ligaments. This continuous shift in tension and compression constitutes to the stability of the dorsal radioulnar joint. The dorsal section contributes to the formation of the extensor carpi ulnaris subsheath. The dorsal radioulnar ligament component has additional ligamentous fibres that originate from the ulnar aspect of the distal radius which reinforce the ligament. These additional reinforcement fibres are often described as separate ligaments which are called dorsal radial metaphyseal arcuate ligament, a component of the dorsal radiocarpal ligament, or part of the interosseous ligament of the forearm. The palmar section contributes to the formation of the ulnocarpal ligament complex. The superficial component fibres of the radioulnar ligament often form an acute angle as they converge on the ulna styloid which results in the superficial triangular fibrocartilage complex exhibiting poor mechanical strength thus provides limited help in guiding the radio-carpal unit through an arc of pronosupination. The deep components (also known as Ligamentum subcruentum) on the other hand form an obtuse angle of attachment which provides much higher mechanical strength which provides the stabilisation required during the rotation of the radius around the fixed ulna. Also, the superficial and deep components of the radioulnar ligaments have different roles in forearm pronation. The dorsal superficial fibres of the radioulnar ligament must tighten for stability, as do the deep palmar fibres of the Ligamentum subcruentum. Conversely, in supination, the palmar superficial radioulnar fibres (to the ulna styloid) tighten, as do the deep dorsal fibres of the Ligamentum subcruentum.

Meniscus homologue

The article by Apergis (2013) provides the following description of the meniscus homologue. The meniscus homologue is a triangular soft tissue structure emerging from the space between the medioproximal aspect of the triquetrum and the ulnar styloid process and the articular disk. This structure is formed by well vascularized, loose connective tissue with its inner surface being lined by synovial cells. The meniscus homologue has three anatomic variations which include; narrow opening observed in 74 % of specimens, the wide opening type observed 11 %, and the no opening observed in 15 %. (Apergis E, 2013)

Intrinsic Ligaments

Proximal-row Interosseous Ligaments

Scapholunate ligament

Apergis (2013) describes the scapholunate ligament as linking the scaphoid and lunate through bone insertions on only the most proximal and superior parts of the articular surfaces of these bones. While Kijima et al (2009) describes that the overall main function of the scapholunate ligament is to provide the primary stabilisation of the scapholunate joint during the joints articulation. The articles by Woon (n.d) and Apergis (2013) also notes that disruption of this ligament can have disastrous consequence to the wrist. This is because any disruption to this ligament results in the destabilisation of the scapholunate joint which results the scaphoid and lunate kinematics being altered which ultimately leads to dorsal intercalated segment instability (DISI) and/ or scapholunate advanced collapse (SLAC).

The article by Apergis (2013) describes the scapholunate ligament as being composed of three section which include a volar portion, a proximal portion, and a dorsal portion which are described in more detail in the following paragraphs. The articles Kijima et al (2009), Berger (1996) and Apergis (2013) where analysed with relevant information utilised to come up with following definitions of the proximal, dorsal and volar components.

The proximal scapholunate ligament is the thinnest section of the ligament but still can make some contributions to the rotational stability of the scapholunate joint. This section extends into the scapholunate joint space with a triangular cross section like a knee meniscus. It appears histologically as a fibrocartilaginous structure being able to withstand compression and shear loads between 25-50N before failure. Dimensions of this section are approximately 1 mm thick, 4 mm long, and 11 mm wide

The dorsal scapholunate interosseous ligament is regarded as the thickest, strongest, and most critical of the scapholunate stabilizers requiring up to 250N of force to fail. It is a true ligament with a trapezoidal shape and is composed of transversely oriented collagen fibres surrounded by connective tissue which course vascular and nerve bundles. Dimensions of the dorsal section measure approximately 5–6 mm in proximal—distal length, 3–5 mm long, and 2–4 mm thick. The dorsal section is the most critical section restraint to palmar–dorsal translation, torsional and distraction moments.

The volar scapholunate ligament is not as strong as the dorsal section but stronger than the proximal section typically requiring 125N – 150N of force to fail. The volar section is considered a true capsular ligament with its fibres obliquely oriented from the palmar rim of the proximal scaphoid to the palmar rim of the palmar horn of the lunate. The dimensions of the palmar region vary between 1 and 2 mm in thickness, 3–5 mm in length, and 4–7 mm in width. Volar section is the most critical section in the controlling of rotation of the scapholunate joint.

Lunotriquetral ligament

Apergis (2013) describes the lunotriquetral ligament joins the lunate and triquetrum along the proximal edge of the joint surface. The lunotriquetral interosseous ligament is also described as a 3-part structure with a volar portion, a proximal portion, and a dorsal portion. The article by Kijima et al (2009) co-citates an article by Nagao et al. that states the lunotriquetral ligament should be considered a part of the radiotriquetral ligament. Woon (n.d) states that any disruption of this ligament can have negative conseqeunces to the wrist as it can lead to lunate flexion when the scaphoid is normally aligned which creates a volar intercalated segment instability (VISI) deformity (in combination with rupture of dorsal radiotriquetral rupture).

The articles by Berger (1996) and Aspergis (2013) details the appearance, dimensions, function and mechanical properties of the dorsal, volar and proximal regions of this ligament. The composition of the different regions the volar and dorsal regions are considered true ligaments composed of collagen perifascicular spaces, small blood vessels, and nerves while the proximal region is different being composed of avascular fibrocartilage. In regards to dimensions, the volar region has the thickest dimension of 2.3 ± 0.3 mm followed by the dorsal region of 1.4 ± 0.2 mm and the proximal region being the thinnest with thickness of 1.0 ± 0.2 mm. The volar region is often reinforced with fibres from the ulnocapitate ligament and has the greatest strength of all the regions failing at force of 301 ± 36 N. The key function of the volar region in constraining mutual translation of the lunate and triquetrum. The dorsal region is reinforced with fibres of the dorsal radiocarpal ligament and dorsal scaphotriquetral ligaments and can withstand forces of up to 121 ± 4 2 N. The key function of the dorsal region is to provide rotational constraint for the lunate-triquetrum joint. The proximal appearance resembles that of a knee meniscus is weakest of all the regions failing at 64N – 25N due to its fibrocartilaginous composition.

Distal-row Ligaments

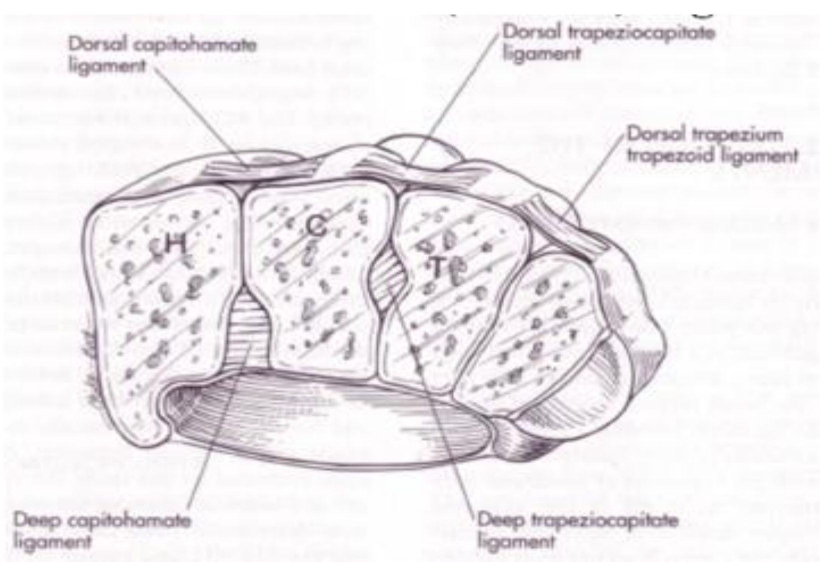


Figure 8.5 Palmer Midcarpal Ligaments (fisiokinesiterapia, n.d)

Distal Row Interosseous- Trapezium trapezoid (Dorsal & Palmar), Trapeziocapitate (Deep, Dorsal, Palmar) Capitohamate- (Deep, Dorsal & Palmer)

The article by Apergis (2013) provides the following overview of the distal row ligaments. The four bones that compose the distal carpal row is held together by three ligaments which are trapezium trapezoid, trapeziocapitate, capitohamate. These ligaments have dorsal and palmar regions don't span the entire proximal–distal dimension of the joints in the carpal row but instead interdigitate with fibres from the adjacent carpometacarpal joints. The trapeziocapitate and capitohamate ligaments have deep regions that are shorter and stronger than the dorsal and palmar regions which provides mechanical stability to these ligaments. The function of these ligaments is crucial in providing transverse carpal stability.

Trapezium Trapezoid

The trapezium trapezoid ligament originates from the ulnar edge of the trapezium tracking ulnarly to the radial edge of the trapezoid which results in it being completely encapsulated in the trapeziotrapezoid joint (Kijima Y and Viegas SF, 2009). The trapezium trapezoid ligament is composed of two regions which are the dorsal and palmar regions. The dimensions of the two regions are the same with thickness of approximately 1-2mm and a width of up to 5mm wide in the proximal–distal direction. The dorsal region of this ligament also has function in forming the floor of the extensor carpi radialis longus tendon. The properties of the regions through various studies have shown yield strength of 150N for the dorsal regions and 125N for the palmar region (Apergis E, 2013).

Trapeziocapitate (also known as Capitotrapezoid)

Kijima et al (2009) states that the trapeziocapitate interosseous ligament originates from the center of the ulnar edge of the trapezoid then tracks ulnarly to the distal, radial edge of the capitate. The article by Apergis (2013) and Berger (1996) describe the trapeziocapitate ligament being composed of three regions which are the dorsal, volar, and deep regions and provides the following information on these regions. The dorsal and volar regions take the appearance of flat sheets with dimensions 1-2mm thick and 3-5mm wide spanning between the trapezoid and capitate. The deep region on the other hand has a cylindrical shape which covers the ‘‘notch’’ created in the articular surface of the trapezoid and capitate. The deep region provides the structural integrity of the ligament with greater mechanical strength typically failing around 300N while the dorsal and palmar region failing at lower stress of approximately 125 N individually.

Capitohamate

The articles by Apergis (2013) and Kijima et al (2009) were paraphrased and collaborated to provide the description of the capitohamate ligament and to define the volar, dorsal and deep regions of this ligament. The capitohamate originates from the ulnar edge of the capitate and attaches to the radial edge of the hamate. The capitohamate ligament is divided into three regions which are dorsal, volar and deep. The dorsal region is further subdivided into distal and proximal sections. The proximal part has been shown to be is devoid of ligamentous connections. The dorsal region has a thickness which ranges from 1-2mm and is transversely orientated. The function of the dorsal region is the principal stabilizing structure for volar rotation/translation and proximal and distal translation of the capitate relative to the hamate. The dorsal region is the weakest of the three sections failing at 133N. The volar region is different in that it has been shown to be more continuous with the other palmar interosseous ligaments. The volar region is stronger than the dorsal region failing at 171N. The deep region is short and the strongest of the three regions failing at 289N. Because of this strength and central location, it acts as a pivot point for rotation of the capitohamate joint. The deep region plays an important role in constraining dorsal rotation and dorsal translation of the capitate relative to the hamate. As described above the volar and deep region exhibit greatest strength which contributes substantially to the transverse stability of the distal row.

8.2 Wrist Kinematic Theories

Navarro 3 Column Theory

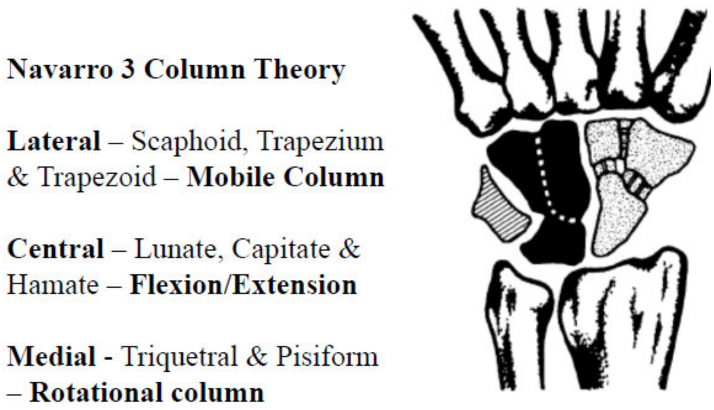


Figure 8.6 Navarro 3 Column Theory (Woon N.D)

Relevant information on the Navarro 3 Column Theory from the articles by Woon (n.d), Freeland & Geissler (2005) and Rainbow et al. (2015) were collaborated to form the following description of the theory. The Navarro 3 column theory was first described by Navarro in 1921. The theory is a column theory were the wrist is made up by three independent columns which include the lateral/radial column (scaphoid, trapezium and trapezoid), central column (lunate, capitate and hamate) and the medial/ulnar column (triquetrum, pisform and distal carpal row). The role of the lateral column is to support the thumb and transfer load between carpal rows. The scaphoid in the lateral column is mobile in this theory and plays a role along with the triquetrum of the medial/ulnar column in controlling the radial and ulnar deviations of the wrist that occurs around the central column. The flexion/extension of the wrist also occurs through luno-capitate articulations in the central column in this theory. The medial/ulnar column plays a role in controlling the rotation of the wrist in this theory.

Foundational Row Theory

Rainbow et al (2015) describes how the foundational row theory goes about describing wrist kinematics as well as some of the positive and negative aspect of this theory. The Foundational Row Theory was first described by researchers Bryce and Destot during the year 1926 explaining the wrist as consisting of two rows. The distal row consisting trapezium, trapezoid, capitate and hamate which acts a single unit due to the constraining of bones by the metacarpal ligaments. The proximal row (also known as intercalated segment) consists of the scaphoid, lunate and triquetrum. The theory utilised radiographic evidence to state that head of the capitate was the centre of wrist motion while the scaphoid was an external pillar that stabilised the wrist in flexion/extension. Researchers into this theory also stated that the midcarpal joint was responsible for transmitting force between the rows in flexion / extension while the articulation of the ulnar and radial deviation of the wrist is controlled by scaphoid in conjunction with the radius of radiocarpal joint.

This theory was a good starting point as it was the first theory to describe the importance of the radiocarpal and midcarpal joint working together to control wrist motion, provided a good organisational model of the carpus of the wrist into two distinct rows and provided insight into compressive force transmission in the carpus. Even though it was a good starting point it was not suitable theory to describe wrist biomechanics. This is because the theory oversimplified the kinematics of the wrist and the fact it described several bones as not having a role in wrist motion which have since been shown to be vital

Screw-Vice Theory

The screw-vice theory states that bones of the wrist exhibit characteristic of both screw and a vice to achieve the wrist kinematics. Rainbow et al (2015) provides the following description of this theory. The screw-vice model was first detailed by MacConaill in 1941. This theory states that the mechanism of wrist occurs through the scaphoid which acts as the jaws of the vice becoming fixed to the distal carpal row that acts as the base of the vice while the hamate acts as a screw that pins the lunate and triquetrum against the scaphoid. The force responsible for deviation of the wrist occurs from transmission of muscular forces from forearm bones to proximal carpal row. In this theory, the triquetrum is the most mobile bone followed by the lunate and the scaphoid is the least mobile bone.

The article by Rainbow et al (2015) describes some of the strengths and weakness of the screw vice theory. Strengths of this theory exist in the explanation of the alteration of the carpal position with wrist extensions. The theory has strength in that it reiterates that the scaphoid has a key role as a connecting rod between the proximal carpal row and distal carpal row. Although this theory has the above strengths there are weakness that exist in the theory. The theory fails to address wrist flexion/extension in adequate detail which limits its overall applicability of the theory.

Link Theory

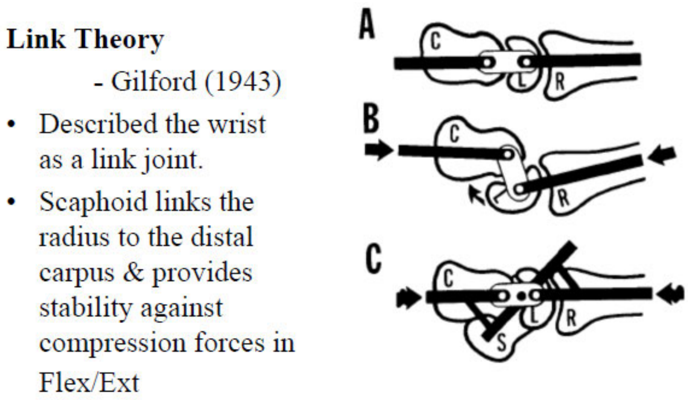


Figure 8.7 Link Theory (Woon N.D)

The link theory as the name suggest describes the wrist acting as a link joint during wrist kinematic motion. Woon (ND) describes in the link concept the radius, lunate and capitate acts as three links in a chain that work together to provide the motion in the wrist. The wrist motion occurs over two joints in the wrist. Rainbow et al (2015) describes the links of the wrist spanning the lunocapitate and radiolunate joint with the extension of the wrist occurring at the radiolunate joint and flexion occurring the lunocapitate joint.

The motion of these links also has a unique pattern. Woon (ND) describes the motion of these links in regards to the bones as the head of the capitate acts as the center of rotation while both the distal and proximal row act as single units with the proximal row is also an intercalated segment with no direct tendon attachments. Garcia-Elias (2013) describes that the link system tends to collapse in a zigzag pattern (concertina effect) with the scaphoid preventing the concertina effect. This concertina effect can be explained that when the carpus is axially loaded the lunate tends to rotate into extension while the capitate translates dorsally.

Regarding the stability of the wrist this theory states that the scaphoid, triquetrum and TFCC all play a role. Rainbow et al (2015) describes that in the ulnar direction the triquetrum and TFCC act as hinges that stabilise the wrist while radially the scaphoid acts as a bridge to stabilise the links. Garcia-Elias (2013 describes the role of the scaphoid in the stability of the wrist. The intercalated scaphoid with proximal and distal links to the dorsum of the lunate and palmar edge of the capitate that provides the elastic stability that eliminates the risk of carpal collapse.

As with all theories that describes wrist kinematics there are strengths that justify the credability of the theory. Rainbow et al (2015) describes some of the strengths of the link theory. Strengths of this theory include; it provides justification on how the carpus can flex/extend over a greater arc than any of the bones that comprise it and provides a sound explanation for the concertina effect that occurs in the wrist.

There is weakness of this theory which makes it not a valid theory anymore. Rainbow et al (2015) states that one weakness of this theory is that it doesn't explain radial and ulnar deviation. Garcia-Elias (2013) explains some of the weakness in the theory that any alteration of carpal alignment was the result of intracarpal pathology which is not always the case as can sometimes be an adaption to something wrong outside the carpus. This theory also states that the scaphoid was the key to normal carpal alignment which is not a valid theory.

Modified Column Theory

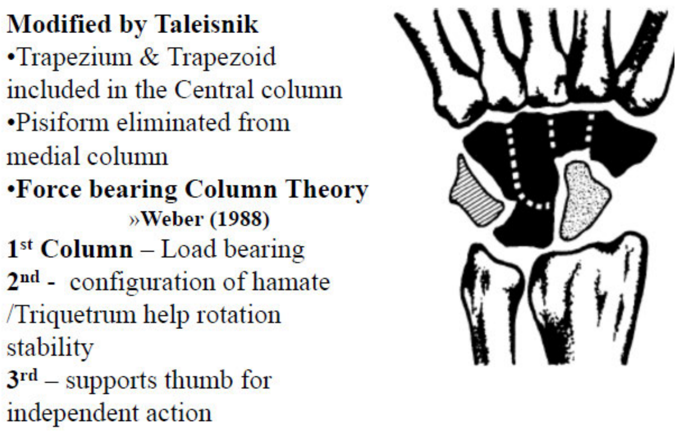


Figure 8.8 Modified Column Theory (Woon N.D)

The modified column theory modifies the original column theory proposed by Navarro. Freeland et al (2005) describe the modified column theory as a modification of the column theory where the distal carpal row as a single unit that acts as part of the central column while the pisform bone is ignored as doesn't form an integral part of the carpal motion. Garcia-Elias (2013) states the central column is controlled by the scaphoid on the lateral side and the triquetrum on the medial side. When the wrist is subjected to an axial load the supporting bones of scaphoid and triquetrum act in particular patterns.

Garcia-Elias (2013) describes that when the wrist is subjected under axial load the obliquely orientated scaphoid rotates in flexion while in contrast the triquetrum is pulled into extension by the palmar hamotriquetral ligament.

The theory stresses the importance of the ligaments in providing stability to the wrist. Gatcia-Elias (2013) highlights that when the ligaments connecting the bones are intact the proximal row is dynamically stable. The article also notes that the equilibrium of the wrist depends on the ligaments to stabilise the opposing moments produced by the scaphoid and the triquetrum. Ligaments of particular importance in providing this stability include the dorsal scapholunate ligament which prevents scaphoid flexion and palmar lunotriquetral ligament that prevents extension of the triquetrum.

Longitudinal Chain Theory

The longitudinal chain theory describes the wrist as three parallel chains. Rainbow et al (2015) describes the longitudinal chain theory. The wrist being composed of three parallel and interdependent chains. The motion in the wrist occurs as the scaphoid rotates faster on the radius than the lunate. In the flexion motion the wrist moves as the scaphoid rotates palmarly and shifts proximally with respect to the lunate and the capitates while in extension the scaphoid rotates dorsally and shifts distally.

The longitudinal chain theory has it strengths as a theory. These strengths are described by Rainbow et al (2015) which states the theory accounts why the wrist can move simultaneously at the midcarpal and radiocarpal joints simultaneously, describes the role of the interosseous ligaments in intercarpal stability and relates the morphology of the carpal bones to their kinematic profile. The theory also has its weakness as a model of the wrist. Rainbow et al (2015) states the weakness of this model is that the scaphoid and lunate are the primary focus of the model with the rest of the carpus not being address by the model

Oval Ring Theory

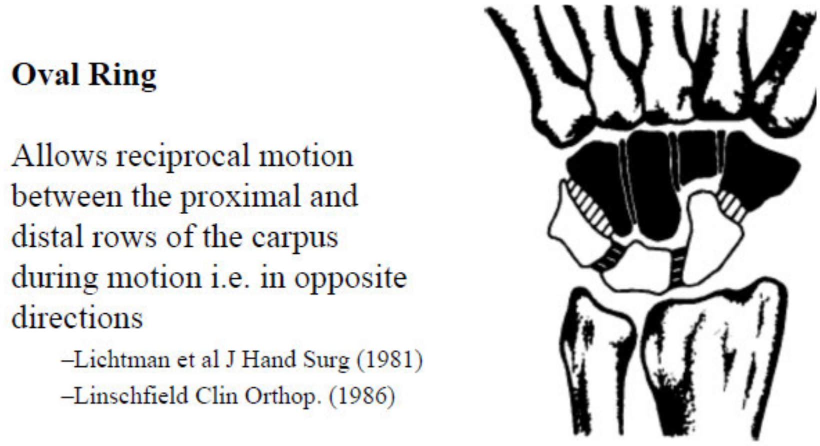


Figure 8.9 Oval Ring Theory (Woon N.D)

The Oval Ring theory takes a unique approach in that it describes the wrist as a ring instead of rows and columns that previous theories utilised. Freeland et al (2005) describes the oval ring theory. The bones of the wrist form an oval ring that are comprised of four segments (distal carpal row, scaphoid, lunate and triquetrum) with ligaments attaching each segment attached to adjacent segment. The ligaments are continuous throughout the oval of the wrist which assures synchronous synergetic wrist motion during wrist kinematics. This also means that any disruptions to the ligaments result in instability of the wrist. There are two forms of instability described in this theory. Rainbow et al (2015) describes these forms of instability as radial disruption leading to instability in the scaphoid – lunate – capitate articulation while ulnar disruption leads to midcarpal instability.

There are strengths and weakness for the oval ring theory. Some of strength described by Rainbow et al (2015) include the theory provides an explanation on how carpal instability doesn't always occur longitudinally as well as describing how the intercarpal ligaments allow the proximal row to rotate as one functional unit. The main drawback of this theory is that a cadaveric study conducted by Lichtman where the dorsal triquetrohamate ligament was divided didn't induce midcarpal instability which would be expected to occur per the theory.

Triquetrum- Hamate Articulation Theory

The triquetrum-hamate articulation theory describes the wrist as three longitudinal columns each with a different role in the kinematics of the wrist. Rainbow et al (2015) provides the following description for the theory. The carpus of the wrist is comprised of three longitudinal columns (central force bearing column, ulnar control column and a radial thumb-axis column). The extension / ulnar deviation of the wrist is achieved by the palmar displacement of the lunate which then compresses the capitate that results in the elevation of the distal pole of the scaphoid that causes in the scaphoid extending. The above occurs in reverse for flexion and radial deviation of the wrist. During the flexion/extension or radial/ulnar motion of the wrist the triquetrum translates on the slope of the hamate.

As with all theories there are strengths and weakness to the triquetrum – hamate articulation theory. Rainbow et al (2015) states some of the strengths of this theory include that it provides explanation to all four wrist motions (flexion, extension, radial and ulnar deviation) also the theory provides foundation for understanding of the pathological conditions of DISI that can progress to SLAC and tears of lunotriquetral ligament. There are weakness in the theory which are described by Rainbow et al (2015) which include the fact the theory state the triquetrohamate joint is the major point of control for wrist kinematics which is contradictory to other theories that state the scaphoid as a bone that spans both rows of the wrist and is the main stabilising structure of the wrist.

Carpal Stability through Balanced Moments applied to Lunate Theory

This theory describes the carpus of wrist being stabilised in four mechanism areas. Rainbow et al (2015) describes that four mechanism of carpal stabilisation work together to provide the kinematics of the wrist. These mechanisms include the proximal row stabilization, distal row stabilisation, midcarpal stabilisation and the radiocarpal stabilisation. In this theory, the lunate is held in position by the scaphoid and the triquetrum. Rainbow et al (2015) states that the position of the lunate is maintained through the tendency of the scaphoid to flex while the triquetrum tends to extend. This theory also stresses the importance of two key ligaments in the prevention of VISI and DISI. Rainbow et al (2015) states that in this theory the disruption of the scapholunate ligament results in DISI occurring when the scaphoid subluxes dorsally that produces an extension/supination moment on the lunate. The second important ligament is the lunitriquetrum ligament which any disruption can eventuate in VISI occurring when the lunate follows the scaphoid into a flexion/pronation moment.

This theory like the others has it strengths and weakness. Rainbow et al (2015) describes some of the strengths of the theory. The main strength of this theory is that it doesn't describe the wrist with one model. Instead the theory divides the wrist into four separate segments and assessing the kinematics of each sections of the wrist separately in a systematic manner. Another strength of this theory is its simplicity in that describes the balance of the wrist as a simply balance of forces. Like all the previous theories there are weakness that questions its validity as a theory. Rainbow et al (2015) describes that the main weakness of this theory is that it doesn't allow the wrist to be conceptualised due the treatment of the wrist as four independent systems. This can result in the reader question the practical applicability of the theory.

Central Column Theory

The central column theory sets about defining the wrist corpus as a large central column that is controlled by the surrounding bones. Rainbow et al (2015) states that the theory describes the carpus functions as a stable central column (formed by unite and distal carpal row) which is controlled by the surrounding bones that act like a four-bar linkage system. In this theory, the scaphoid comprises a lateral column that supports the central column, the triquetrum functions as a restraint against ulnar translation while the trapezoid functions to rotate the central column in the dart throwers motion axis.

This theory used a different approach in its creation which provides credibility to the theory. Rainbow et al (2015) describes that the theory was derived from analysis of 3D generated models of the wrist which is different to previous theories which are first proposed subjectively then later supported with subjective data. Although this theory seems promising to describe the wrist kinematics it is still in the process of being justified. Rainbow et al (2015) sates that the theory has not been tested and validated for all wrist motion and functional tasks for a large cohort of patients and controls. This testing to justify the theory is important as the theory did find differences to previously established theories. Rainbow et al (2015) states that the theory found no isometric constraints between the hamate and the triquetrum that doesn't agree with previous theories. The theory is also unique in that it attempts to reconstruct the courses of the ligaments using an isometric lengthening assumption which could lead to insight into the subtle nuances of carpal mechanics.

The previous section detailed several of the theories that described the wrist kinematics showing how the understanding of wrist kinematics has evolved over the last century. At present, there is no unifying theory for explaining wrist mechanics. Rainbow et al (2015) describes that the discovery of a unifying theory for carpal kinematics is still elusive to researchers due to the wide variability in wrist ligament laxity, anatomic variability and bone morphology. Although there is no unifying theory there are a general understanding on the kinematics of the wrist which will be explained in the next section.

8.3 LITERATURE REVIEW

Literature review was conducted to source credible information that could be useful for the completion of this dissertation. This systematic process extracted the relevant information required for the dissertation while simultaneously evaluating the source of the information. The result of the literature review is shown below;

Paper 1

Categories about the paper

Name of Paper: Arthritis of the Wrist

Authors of Paper: Jacob W Brubacher (MD), Charles D Jennings

Databased that article was sourced from: Google

Date: 21st March 2017

Search term: Arthritis of the wrist

Reference: Brubacher JW & Jennings CD, 2016, Arthritis of the Wrist, Ortho Info, American Academy of Orthopaedic Surgeons, retrieved 21st March 2017, http://orthoinfo.aaos.org/topic.cfm?topic=A00218

Evaluating Information

Credibility of authors: Both the authors are medical doctors which adds to the credibility of the paper

Credibility of paper: The main limitation of the source of information is that it is not from a peer reviewed journal article. Although the information is from American academy of surgeons which is a large academic organisation which provides credibility to the information

Evaluation of relevance: The information on the different forms of arthritis will be useful in the cause of wrist failure section of the dissertation

Useful information for dissertation: Information on the rheumatoid arthritis, osteoarthritis, posttraumatic arthritis and Kienbocks disease would be useful for this dissertation.

Paper 2

<u>Categories about the paper</u>

Name of Paper: Osteoarthritis and Rheumatoid Arthritis 2012: Pathophysiology, Diagnosis and Treatment

Authors of Paper: Kori A Dewing (DNP, FNP, ARNP), Stephen M Setter (PharmD, DVM, CDE, CGP, FASCP) and Barbara A Slusher (MSW, PA-C)

Databased that article was sourced from: Google

Date: 22nd March 2017

Search term: Osteoarthritis

Reference: - Dewing KA, Setter SM, Slusher BA, 2012, "Osteoarthritis and Rheumatoid -Arthritis 2012: Pathophysiology, Diagnosis, and Treatment", *Clinical Advisor*, Nurse Practitioner Healthcare Foundation, viewed 22nd March 2017, http://www.clinicaladvisor.com/features/osteoarthritis-and-rheumatoid-arthritis-2012-pathophysiology-diagnosis-and-treatment/article/265549/2/

<u>Evaluating Information</u>

Credibility of authors: Examining the abbreviations following the authors names the following was discovered. Kori A Dewing is a registered nurse practitioner, Stephen M Setter is a pharmacist graduate and Barbara is a holder of both a physician's assistant and masters of social work qualifications. These qualifications of the various authors add to the credibility of the paper

Credibility of paper: The main limitation of the source of information is that it is not from a peer reviewed journal article. Although the information is from a credible source in the clinical advisor paper which is a monthly paper for nurses and physician which is run by the nurse practitioner healthcare foundation through funding by Horizon Pharma.

Evaluation of relevance: The information is relevant for the cause of wrist failure section of the dissertation.

Useful information for dissertation: Information used in dissertation from the article will be the information on rheumatoid arthritis.

Paper 3

Categories about the paper

Name of Paper: Wrist arthroplasty: Bone fixation, clinical development and mid to long term results

Authors of Paper: Ole Reigstad

Databased that article was sourced from: National Center for Biotechology Information

Date: 26 April 2017

Search term: Wrist Arthroplasty

Reference: Reigstad O (2014) ‘Wrist arthroplasty: Bone fixation, clinical development and mid to long term results’, Acta Orthopaedica, .85, 1-46,

Evaluating Information

Credibility of authors: Research on Ole Reigstad found that he works at the Oslo University Hospital. He has his medical doctorate and also his PHD. He is also the author of 23 research articles with the majority being on wrist arthroplasty based topics. From the above research, it can be seen that the author is highly credible source of information

Credibility of paper: The paper was written by a highly qualified author and is featured in a peer reviewed journal article so there are no limitations on the credibility of the paper

Evaluation of relevance: The paper is highly relevant as it examines the history of the total wrist arthroplasty, the forms of wrist failure and surgical options which are all topics examined the dissertation.

Useful information for dissertation: There were several topics in which information was sourced from this paper including, total wrist fusion, total wrist arthroplasty, failure analysis of total wrist arthroplasty, biomechanics of the wrist, Kienbocks disease, scapholunate advanced collapse and scaphoid non-union advanced collapse.

Paper 4

Categories about the paper

Name of Paper: Functional kinematics of the wrist

Authors of Paper: Michael J Rainbow, Aviva Wolff, Joseph J Crisco & Scott W Wolfe

Databased that article was sourced from: ResearchGate

Date: 12th April 2017

Search term: Biomechanics of the Wrist

Reference: - Rainbow MJ, Wolff A, Crisco JJ & Wolfe SW, 2015, 'Functional kinematics of the wrist', Journal of Hand Surgery, Vo.41, Issue 1, pp.1-15, viewed at https://www.researchgate.net/publication/283886122_Functional_kinematics_of_the_wrist

Evaluating Information

Credability of authors: The authors worked for various universities and hospitals including Queen's University, Brown University and the Hospital for Special Surgery. The various authors have also multiple publications to their names ranging from 29 to 274 publications. The above information shows that the authors of this paper are highly credible

Credability of study: The paper was written by highly qualified authors and is featured in a peer reviewed journal article so there are no limitations on the credibility of the paper.

Evaluation of relevance: The article is relevant for the biomechanics of the wrist section in the dissertation

Useful information for dissertation: The information on the evolution of wrist kinematic theories, current understanding of wrist kinematics and information on the dart throwers motion were used in the dissertation

Paper 5

Categories about the paper

Name of Paper: Scaphoid excision and four-corner fusion in the SLAC/SNAC wrist

Authors of Paper: Robert P. Lyons (MD) and Arnold-Peter C. Weiss (MD)

Databased that article was sourced from: Science Direct

Date: 24th April 2017

Search term: Four corner fusion

Reference: Lyons RP & Weiss AP, 2003, 'Scaphoid Excision and Four-Corner Fusion in the SLAC/SNAC Wrist', Operative Techniques in Orthopeadics, Vol. 13, Issue 1, pp. 34-41

Evaluating Information

Credibility of authors: Both of the authors are medical doctors who are currently employed at Department of Orthopaedic Surgery at Brown Medical School in Rhode Island. Their employment as medical doctors at a prestigious medical school provides credibility to the paper.

Credibility of paper: The paper was written by highly qualified authors (medical doctors) and is featured in a peer reviewed journal article (Operative Techniques in Orthopeadics) so there are no limitations on the credibility of the paper.

Evaluation of relevance: The article is relevant for the surgical treatment section in the dissertation

Useful information for dissertation: The information regarding the four corner fusion surgical treatment and the arthritis condition of scapholunate advanced collapse was utilised in this dissertation

Paper 6

<u>Categories about the paper</u>

Name of Paper: Scapholunate Advanced Collapse: Four-Corner Fusion and Proximal Row Carpectomy

Authors of Paper: Ryan Miller (MD) and Phillipp N. Streubel (MD)

Databased that article was sourced from: Science Direct

Date: 29th May 2017

Search term: Proximal row Carpectomy

Reference: - Miller R & Streubel PN, 2016, 'Scapholunate Advanced Collapse: Four-Corner Fusion and Proximal Row Carpectomy, Operative Technique in Sports Medicine, Vol. 24, pp. 117-122

<u>Evaluating Information</u>

Credibility of authors: Both of the authors are medical doctors who are currently employed at Department of Orthopaedic Surgery and Rehabilitation at University of Nebraska Medical Center. Their employment as medical doctors at a prestigious medical school provides credibility to the paper.

Credibility of paper: The paper was written by highly qualified authors (medical doctors) and is featured in a peer reviewed journal article (Operative Techniques in Sports Medicine) so there are no limitations on the credibility of the paper.

Evaluation of relevance: The article is relevant for the surgical treatment section in the dissertation

Useful information for dissertation: The information regarding the four corner fusion and proximal row carpectomy surgical treatment along with the information on the arthritis condition of scapholunate advanced collapse was utilised in this dissertation

Paper 7

Categories about the paper

Name of Paper: Total wrist arthroplasty

Authors of Paper: Lawler EA & Paksima N

Databased that article was sourced from: National Center of Biotechnology Information

Date: 7th July 2017

Search term: Total Wrist Arthroplasty

Reference: Lawler EA & Paksima N, 2006, 'Total Wrist Arthroplasty', Bulletin of New York University Hospital for Joint Diseases, Vol. 64, No. 3 & 4, viewed 7th July 2017

Evaluating Information

Credibility of authors: Both the authors have numerous research articles to their names which adds to their credibility as authors

Credibility of paper: The paper was written by highly qualified authors and is featured in a peer reviewed journal article (Bulletin of New York University Hospital for Joint Diseases) so there are no limitations on the credibility of the paper.

Evaluation of relevance: Information from this paper was utilised in the failure analysis and surgical treatments sections of the dissertation

Useful information for dissertation: Information of study results on failure of previous arthroplasty designs from this paper was used in the failure analysis section of this dissertation. There was also information relevant to patient selection for the total wrist arthroplasty used in this dissertation.

Paper 8

Categories about the paper

Name of Paper: The arthritic wrist. II--the degenerative wrist: indications for different surgical treatments

Authors of Paper: Laulan J, Bacle G, De Bodman CD, Najihi N, Richou J, Simon E, Saint-Cast Y, Obert L, Saraux A, Bellemere P, Dreano T, Le Bourg M, Le Nen D

Databased that article was sourced from: National Center of Biotechnology Information

Date: 16th June 2017

Search term: Surgical Selection of arthritic wrist

Reference: Laulan J, Bacle G, De Bodman CD, Najihi N, Richou J, Simon E, Saint-Cast Y, Obert L, Saraux A, Bellemere P, Dreano T, Le Bourg M, Le Nen D, 2011, 'The arthritic wrist. II - The degenerative wrist: Indications for different surgical treatments', Orthopaedics & Traumatology: Surgery & Research, Vol. 97, pp. 37-41

Evaluating Information

Credibility of authors: The authors of the paper have numerous research articles to their names ranging from as little as 6 to as many as 1456 articles. This varying experience amongst the authors adds to the credibility of the paper

Credibility of paper: The paper was written by highly qualified authors and is featured in a peer reviewed journal article (Orthopaedics & Traumatology: Surgery & Research) so there are no limitations on the credibility of the paper.

Evaluation of relevance: The article is relevant for the surgical treatment section in the dissertation

Useful information for dissertation: The information on surgical selection for patients, denervation, proximal row carpectomy, four corner fusion and total wrist fusion was utilised in this dissertation

Paper 9

<u>Categories about the paper</u>

Name of Paper: Proximal row carpectomy: Long-term results

Authors of Paper: Richou J, Chuinard C, Moineau G, Hanouz N, Hu W, Nen DL

Databased that article was sourced from: National Center of Biotechnology Information

Date: 29th May 2017

Search term: Proximal Row Carpectomy

Reference: Richou J, Chuinard C, Moineau G, Hanouz N, Hu W, Nen DL, 2010, Proximal row carpectomy: Long-term results', Chirurgie de la main, Vol. 29, pp. 10-15

<u>Evaluating Information</u>

Credibility of authors: The authors of the paper have numerous research articles to their names ranging from as little as 7 to as many as 6822 articles. This varying experience amongst the authors adds to the credibility of the paper

Credibility of paper: The paper was written by highly qualified authors and is featured in a peer reviewed journal article (Chirurgie de la main) so there are no limitations on the credibility of the paper.

Evaluation of relevance: The article is relevant for the surgical treatment section in the dissertation

Useful information for dissertation: The information on surgical selection for patients and proximal row carpectomy was utilised in this dissertation

Paper 10

Categories about the paper

Name of Paper: Effects of proximal row carpectomy on wrist biomechanics: A cadaveric study

Authors of Paper: Sobczak S, Rotsaert P, Vancabeke M, Jan SVS, Salvia P & Feipel V

Databased that article was sourced from: National Center of Biotechnology Information

Date: 18th June 2017

Search term: Proximal Row Carpectomy

Reference: Sobczak S, Rotsaert P, Vancabeke M, Jan SVS, Salvia P & Feipel V, 2011, 'Effects of proximal row carpectomy on wrist biomechanics: A cadaveric study', Clinical Biomechanics, Vol. 26, pp. 718-724,

Evaluating Information

Credibility of authors: The authors of the paper have numerous research articles to their names ranging from as little as 5 to as many as 73 articles. This varying experience amongst the authors adds to the credibility of the paper

Credibility of paper: The paper was written by highly qualified authors and is featured in a peer reviewed journal article (Clinical Biomechanics) so there are no limitations on the credibility of the paper.

Evaluation of relevance: The article is relevant for the surgical treatment section in the dissertation

Useful information for dissertation: The information on surgical selection for patients and proximal row carpectomy was utilised in this dissertation

Paper 11

Categories about the paper

Name of Paper: Total wrist arthroplasty for rheumatoid arthritis

Authors of Paper: Brian D. Adams

Databased that article was sourced from: Science Direct

Date: 3rd July 2017

Search term: Total Wrist Arthroplasty

Reference: Adams BD, 2006, 'Total wrist arthroplasty for rheumatoid arthritis', International Congress Series, Vol. 1295, pp. 83-93, viewed 3rd July 2017

Evaluating Information

Credibility of authors: The author has credibility as they work at the University of Iowa Hospitial in the Department of Orthopaedics and Rehabilitation. They also have several other articles to their name.

Credibility of paper: The paper was written by highly qualified authors and is featured in a peer reviewed journal article (International Congress Series) so there are no limitations on the credibility of the paper.

Evaluation of relevance: The article is relevant for the surgical treatment and failure analysis sections in the dissertation

Useful information for dissertation: The information on total wrist arthroplasty and outcomes of different wrist arthroplasty designs was utilised in this dissertation

Paper 12

<u>Categories about the paper</u>

Name of Paper: Total wrist arthroplasty: A review

Authors of Paper: Indranil Chakrabarti

Databased that article was sourced from: National Center of Biotechnology Information

Date: 3rd July 2017

Search term: Total Wrist Arthroplasty

Reference: Chakrabarti I, 2009, 'Total wrist arthroplasty: A review', Journal of Hand Microsurgery, Vol. 1, pp. 72-75, viewed 3rd July 2017

<u>Evaluating Information</u>

Credibility of authors: The author has credibility as they work at the University of Sheffield Medical School. They also have 66 other research articles to their name.

Credibility of paper: The paper was written by highly qualified authors and is featured in a peer reviewed journal article (Journal of Hand Microsurgery) so there are no limitations on the credibility of the paper.

Evaluation of relevance: The article is relevant for the surgical treatment and failure analysis sections in the dissertation

Useful information for dissertation: The information on total wrist arthroplasty and outcomes of different wrist arthroplasty designs was utilised in this dissertation

Paper 13

Categories about the paper

Name of Paper: Denervation of the radiocarpal joint: A FOLLOW-UP STUDY IN 22 PATIENTS

Authors of Paper: W Grechenig, M Mahring & Hans Gunther Clement

Databased that article was sourced from: ResearchGate

Date: 27th June 2017

Search term: Denervation

Reference: Grechenig W, Mahring M & Clement HG, 1998, 'Denervation of the radiocarpal joint: A FOLLOW-UP STUDY IN 22 PATIENTS', The Journal of Bone & Joint Surgery, Vol 80, pp. 504-507, viewed 27th June 2017, http://www.boneandjoint.org.uk/content/jbjsbr/80-B/3/504.full.pdf

Evaluating Information

Credibility of authors: The authors has credibility as they have 356 research articles experience collectively

Credibility of paper: The paper was written by highly qualified authors and is featured in a peer reviewed journal article (The Journal of Bone & Joint Surgery) so there are no limitations on the credibility of the paper.

Evaluation of relevance: The article is relevant for the surgical treatment

Useful information for dissertation: The information on denervation surgery was used in this dissertation

Paper 14

Categories about the paper

Name of Paper: Total Wrist Fusion

Authors of Paper: Tomilinson J

Databased that article was sourced from: Google

Date: 28th June 2018

Search term: Total Wrist Fusion

Reference: Tomilinson J, 2012, 'Total Wrist Fusion', Melbourne Hand Surgery, Richmond, Victoria, viewed 28th June 2018, http://www.melbournehandsurgery.com/hand-a-wrist-arthritis/32-hands/arthritis/174-total-wrist-fusion

Evaluating Information

Credibility of authors: The author has credibility as they work at the author is a qualified orthopaedic surgeon.

Credibility of paper: The paper was written by highly qualified authors and is sourced from a website for an orthopaedic surgeon based in Melbourne. The only limitation for this article is it wasn't sourced from a peer reviewed journal article which would make the article more credible.

Evaluation of relevance: The article is relevant for the surgical treatment section of the dissertation

Useful information for dissertation: The information on total wrist fusion surgical procedure was utilised in this dissertation.

Paper 15

Categories about the paper

Name of Paper: The Anatomy and Basic Biomechanics of the Wrist Joint

Authors of Paper: Richard A. Berger (MD, PHD)

Databased that article was sourced from: Science Direct

Date: 5th December 2016

Search term: Anatomy of the wrist

Reference: Berger RA, 1996, 'The Anatomy and Basic Biomechanics of the Wrist Joint', Journal of Hand Therapy, Vol. 9, Issue 2, pp. 84 - 93, viewed 5th December 2016, http://www.sciencedirect.com.ezproxy.usq.edu.au/science/article/pii/S0894113096800664

Evaluating Information

Credibility of authors: The author has credibility as they work at the Mayo Clinc which is a respected orthopaedic research laboratory based in Minnesota, United States of America. They also have their PHD and medical doctorate degree qualifications.

Credibility of paper: The paper was written by highly qualified authors and is featured in a peer reviewed journal article (Journal of Hand Therapy) so there are no limitations on the credibility of the paper.

Evaluation of relevance: The article is relevant for the anatomy and biomechanics section of the dissertation

Useful information for dissertation: The information on anatomy of wrist including information on the bones, joints and ligaments of the wrist. Also, information on the biomechanics of the wrist was included in this dissertation.

Paper 16

Categories about the paper

Name of Paper: Wrist Anatomy and Biomechanics

Authors of Paper: Yasumu Kijima (MD), Steven F. Viegas (MD, PHD)

Databased that article was sourced from: Science Direct

Date: 10th December 2016

Search term: Wrist anatomy

Reference: Kijima Y and Viegas SF, 2009, 'Wrist Anatomy and Biomechanics', Journal of Hand Surgery, Vol. 34, pp. 1555-1563, viewed 10th December 2016

Evaluating Information

Credibility of authors: The authors work at the Department of Orthopaedic Surgery, Graduate School of Biomedical Sciences, Hiroshima University, Japan and the Department of Orthopaedic Surgery and Rehabilitation, The University of Texas Medical Branch, Galveston, TX. They also have qualifications of medical doctorate for Yasumu and medical doctorate / PHD for Steven

Credibility of paper: The paper was written by highly qualified authors and is featured in a peer reviewed journal article (Journal of Hand Surgery) so there are no limitations on the credibility of the paper.

Evaluation of relevance: The article is relevant for the anatomy section of the dissertation

Useful information for dissertation: The information on anatomy of wrist including information on the bones, joints and ligaments of the wrist.

Paper 17

Categories about the paper

Name of Paper: Wrist Anatomy

Authors of Paper: Emmanuel Apergis

Databased that article was sourced from: Research Gate

Date: 24th March 2017

Search term: Wrist Anatomy

Reference: Apergis E, 2013, 'Wrist Anatomy', Fracture-Dislocations of the Wrist, pp.7-41, viewed 24th of March 2017, https://www.researchgate.net/publication/278704900_Wrist_Anatomy

Evaluating Information

Credibility of authors: The author has credibility as they are the director at the Red Cross Hospital at Athens. They also have 27 research publications to their name

Credibility of paper: The paper was written by highly qualified authors and is featured in a peer reviewed journal article (Fracture-Dislocations of the Wrist) so there are no limitations on the credibility of the paper.

Evaluation of relevance: The article is relevant for the anatomy section of the dissertation

Useful information for dissertation: The information on anatomy of wrist including information on the bones, joints and ligaments of the wrist.

Paper 18

Categories about the paper

Name of Paper: Wrist Ligaments and Biomechanics

Authors of Paper: Colin Woon (MD)

Databased that article was sourced from: Google

Date: 16th January 2017

Search term: Wrist ligaments

Reference: Woon C, ND, Wrist Ligaments and Biomechanics, Orthobullets, viewed 16th January 2017, http://www.orthobullets.com/hand/6005/wrist-ligaments-and-biomechanics

Evaluating Information

Credibility of authors: The author has a medical doctorate qualifications

Credibility of paper: The paper was written by highly qualified authors and is featured on a non-peer reviewed site which retracts from the credability of the information

Evaluation of relevance: The article is relevant for the anatomy and biomechanics section of the dissertation

Useful information for dissertation: The information on anatomy of wrist including information on the bones, joints and ligaments of the wrist. Also, information on the biomechanics of the wrist was included in this dissertation.

Paper 19

Categories about the paper

Name of Paper: Kinematics and Pathophysiology of Carpal Instability

Authors of Paper: Alan E. Freeland & William B. Geissler

Databased that article was sourced from: Google scholar

Date: 16th March 2017

Search term: Wrist Biomechanics

Reference: Freeland AE & Geissler WB, 2005, 'Kinematics and Pathophysiology of Carpal Instability' Wrist Arthroscopy, pp.72 - 86, https://books.google.com.au/books?id=K3xJFFOpaSsC&pg=PA72&lpg=PA72&dq=navarro+central+column+theory+wrist&source=bl&ots=BsGFr6SY-y&sig=D4hq7AbhzpdJfRpDnGzUaYwkkdg&hl=en&sa=X&ved=0ahUKEwjDouCb8bzTAhWEJJQKHQOfADoQ6AEIKzAB#v=onepage&q=navarro%20central%20column%20theory%20wrist&f=false

Evaluating Information

Credibility of authors: Research into the authors found that they are both orthopaedic surgeons based in Jackson, Mississippi USA which provides credability to their paper

Credibility of paper: The paper was written by highly qualified authors and is featured in a peer reviewed journal article (Wrist Arthroplasty) so there are no limitations on the credibility of the paper.

Evaluation of relevance: The article is relevant for the Biomechanics section of the dissertation

Useful information for dissertation: The information on evolution of wrist kinematic theories was utilised in this dissertation

Paper 20

Categories about the paper

Name of Paper: Understanding of Wrist Mechanics: A Long and Winding Road

Authors of Paper: Marc Garcia-Elias (PHD)

Databased that article was sourced from: National Center of Biotechnology Information

Date: 24th April 2017

Search term: Biomechanics of the Wrist

Reference: Garcia-Elias M, 2013, 'Understanding of Wrist Mechanics: A Long and Winding Road', Journal of Wrist Surgery, Vol. 2, Issue 1, pp.5 - 12, viewed 24th April 2017, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3656573/

Evaluating Information

Credibility of authors: The author has credibility as they work at the Institut Kaplan in the Department of Hand and Upper Extremity at Barcelona, Spain. They also have their PHD qualification and have 101 other research articles to their name.

Credibility of paper: The paper was written by highly qualified authors and is featured in a peer reviewed journal article (Journal of Wrist Surgery) so there are no limitations on the credibility of the paper.

Evaluation of relevance: The article is relevant for the Biomechanics section of the dissertation

Useful information for dissertation: The information on evolution of wrist kinematic theories was utilised in this dissertation

8.4 PROJECT SPECIFICATION

ENG4111/4112 Research Project

Project Specification

For: Paul Johnstone

Title: Optimization of Distal Carpal Component

Major: Mechanical Engineering

Supervisor: Dr. Steven Goh, Senior Lecturer USQ
Dr. Chris Jefferys, CEO Field Orthopaedics

Sponsorship: Field Orthopaedics

Enrolment: ENG4111 – EXT S1, 2017
ENG4112 – EXT S2, 2017

Project Aim: The aim of the dissertation is to determine an initial conceptual design for a total wrist arthroplasty that will address the high complication rates present in current commercially available wrist arthroplasty designs

Programme: Version 5, 16th September 2017

The dissertation will optimise the total wrist components that will address the high complication rates in current designs. The key learning objective for the dissertation are outlined below

Key Learning Objectives

Through the completion of these dissertation several key learning objectives will be obtained which include the following

1. Research the anatomy and biomechanics of the wrist.

2. Research the various forms of arthritis that can cause the wrist to fail along with surgical treatments available to the patient.

3. Complete a detailed failure analysis on the previous designs.

4. Determine key design parameters.

5. Apply the design parameters to conceptualise an initial design.

This dissertation will be completed in eight stages.

1. Determine methodology utilised in completing dissertation
2. Research into cause of wrist failure
3. Research into surgical treatment options available to patient
4. Research into wrist anatomy and biomechanics
5. Failure analysis of the total wrist arthroplasty
6. Determine key design parameters from information collected
7. Design conceptual design of total wrist arthroplasty using design parameters
8. Write up phase

Further details of the above stages looking at the steps required in detail are provided in table 10.1

Stage 1	**METHDODOLOGY**
1A	Dissertation Methodology – Outline the key steps that will be followed in the completion of the dissertation.
1B	Research Methodology – Outline the research tools that will be utilised in completing certain stage of the dissertation which will include systematic literature review methodology and failure analysis methodology.
Stage 2	**IDENTIFICATION OF NEED**
2A	Cause of Wrist Failure – Determine the causes of the failure of the wrist (arthritis) and its various forms.
2B	Surgical Treatments – Detailed examination of the different surgical treatments available to the patient and how a surgeon will select the right treatment for a patient
Stage 3	**DETERMINING DESIGN PARAMETERS**
3A	Anatomy of the Wrist – Research into the various components of the wrist including the bones, joint and ligaments.
3B	Biomechanics of the Wrist – Research into theories of wrist kinematics.
3C	Failure analysis of the Total Wrist Arthroplasty – Detailed examination of all the previous designs of total wrist arthroplasty designs looking at the key components of the design and the results of studies conducted on the various designs.
3D	Determine Key Design Parameters – Determine key design parameters from information collected in the dissertation
Stage 5	**CONCEPTUAL DESIGN**
5A	Outline design parameters – Outline the design parameters and how they are going to be instrumental in the design
5B	Conceptual Design – Draw up a conceptual design utilising design parameters as guides for the design. The design will be formulated in CREO program.
Stage 6	**WRITE UP PHASE**
6A	Draft dissertation – prepare draft dissertation for supervisors to review and provide feedback
6B	Final dissertation – make amendments to draft based on supervisor feedback and then finalise dissertation.

Table 8.1 Further description of Project Stages

8.5 Progress Report

University of Southern Queensland

Faculty of Health, Engineering and Sciences

ENG4111/ENG4112 Research Project

OPTIMIZATION OF DISTAL CARPAL COMPONENT

Progress Report

Student: Paul Johnstone

Student number: 1021121

Due date: 24th May 2017

Table of Contents

Content	Page
1.0 INTRODUCTION	3
2.0 STATEMENT OF AIM AND OBJECTIVES	5
3.0 LITERATURE REVIEW	
3.1 Anatomy of the Wrist	6
3.2 Biomechanics of the Wrist	9
3.3 Total Wrist Arthroplasty	10
3.4 Failure Analysis	16
4.0 CONSEQUENCE/ ETHICS	22
5.0 METHODOLOGY	
5.1 Project Outline	25
5.2 Research Methodology	27
6.0 RISK ASSESSMENT	33
7.0 RESOURCE PLANNING	35
8.0 PROJECT SCHEDULE	36
9.0 REFERENCES	37
10.0 APPENDIX	40

1.0 INTRODUCTION

The design of components with long term life expectancy is important as many patients live many years after receiving the implant and the consequences on the patient when a revision is required can be quite high. Moussa et al (2017) explains that the loosening of distal carpal component is important consideration as the many patient undergoing total wrist arthroplasty have a life expectancy of over 25 years. The article also notes that the effects of the patient requiring revision surgery can be great as there are increased risks, greater odds of complications and financial / emotional burden experienced by the patient. Improved design of distal carpal component to reduce loosening is vital due to the long-life expectancy of the patient and negative consequence patient experiences when an implant revision is required.

Distal carpal component loosening is a major problem in total wrist arthroplasty that are current available in the market. This problem is illustrated in study by Sagerfors et al (2015) who examined a surgical centre over a five-year period looking at the results of 219 cases. Loosening of the distal carpal is the major cause of implant failures in this study collectively accounting for 54% of all implant failures. This study illustrates the need for the creation of a distal carpal component conductive to implant fixation through reducing stress shielding and alternative fixation techniques.

Stress shielding is a major contributing factor to the loosening of the distal carpal component. Moussa et al (2017) defines stress shielding as the presence of the distal carpal component reduces the normal load experienced by the wrist. This reduction of load experienced by the surrounding bone results in periprosthetic bone resorption, bone loss, cortical bone thinning and joint prosthesis failure. The physiological dynamic response of the bone results in mechanical loosening of the implant is one of the main factors affecting long term survivability of the implant. As such the control of the stress shielding of the bone surrounding the implant is an important design consideration that needs to be investigated.

Osteolysis of surrounding bone is another contributing factor where the wear particles generated by the articulation of joint cause inflammation/deterioration of the surrounding tissue. Gallo, J et al (2013) and Dattani R (2006) describe the process that particles biological react inflame the surrounding the tissue that creates cells (e.g osteoclasts) that resorb the surrounding bone. This reabsorbing of the bone creates a condition that is conductive to the distal carpal component becoming loose.

Poor fixation due to cement etc….

Consequential failure of the wrist implant also has negative aspects for the patient. Loosening of the distal carpal component is one of the most common failure mechanism for the wrist implant. The underlying causes of the distal carpal loosening is stress shielding and wear particle induced osteolysis. As such the distal carpal component needs to be designed with reducing the likelihood of stress shielding occurring to improve the survival of the wrist implant

This dissertation will aim to determine optimal design and materials to improve the long-term survivability of wrist arthroplasty. The distal carpal component will be designed to reduces stress shielding while maintaining the mechanical strength of the component. While the polyethylene cap will be design to improve the wear characteristics. Optimal porous design will be investigate for the fixation of the implant. This design will then result in the optimal combination of materials and design features to reduce the loosening of the distal carpal component.

A review of literature for this research will investigate several key topics. The first topic will be a clear understanding of the anatomy of the wrist and failure mechanism of the wrist. The next topic will determine the progression of the total wrist arthroplasty and the required mechanical properties of the distal carpal component via conducting a failure analysis. The literature review will be determining how to reduce the likelihood of stress shielding and osteolysis through material selections.

The research is expected to show the optimal combination of metal and polyethylene that will reduce the occurrence of loosening of the distal carpal component. These components will also have the required mechanical strength to avoid the component failing during everyday activities. The research will also determine how to design the implant and the porous fixation to reduce loosening of components. The outcome of this study will be used by Field Orthopaedics who are considering materials for their total wrist arthroplasty. The results will determine how the materials will reduce the prevalence of the distal carpal component loosening. This dissertation will thus be an invaluable resource to the company Field Orthopaedics in determining the suitability of materials in the creation of their total wrist arthroplasty design

2.0 STATEMENT OF AIM AND OBJECTIVES

AIM

The aim of the dissertation is to determine how to improve the total wrist arthroplasty design to prevent the loosening of the distal carpal component. This improvement will be achieved through material selection of articulating components, optimising fixation through porous fixation and research into design to improve stress distribution.

SPECIFIC OBJECTIVES

There will be a set of learning objectives that will need to be completed to achieve the aim of the dissertation. These objectives include the following;

7. Understand the wrist, how the wrist fails (arthritis) and the various surgical treatments available
8. Investigate total wrist arthroplasty including; history and when they are used, failure analysis of total wrist arthroplasty and identify the main failure mechanism.
9. Determine the optimal materials for the articulating surface to reduce stress shielding and wear particles
10. Determine optimal porous coating structure to improve fixation
11. Investigate the design of the various components that aid to better stress distribution and long term survival of the total wrist arthroplasty

The scope of this project will also need to be controlled to make sure that the workload will be able to be completed before the deadline. This will be controlled by the following steps;

- The required FEA modelling of the total wrist prosthesis will be sourced through reviewing literature. This was decided upon as the scope of topics is quite large and conducting FEA modelling of implants will make achieving the dissertation deadline unachievable.
- In research of design of implants the section will be limited to just discussing the key points to improve stress distribution. The implants will not be redesigned by the author in this dissertation due to the increased workload jeopardize the author finish the dissertation by the due date.

3.0 LITERATURE REVIEW

A literature review was undertaken to further develop the idea towards a research project. The purpose of the review was to gather relevant information about:

- Background research into the Wrist
- Total Wrist Arthroplasty
- Failure Analysis

3.1 Anatomy of the Wrist

The wrist is a collection of bones, ligaments and muscle are working together to provide motion to a complex joint. Berger (1996) describes the wrist as a joint comprised of an assortment of bones, muscles and ligaments that work together to allow the classic, or cardinal, motions of flexion, extension, radial deviation, and ulnar deviation, but also for limited longitudinal rotation, combined motions. Each component of the wrist (bones, ligaments etc) plays a vital role in the kinematic motion.

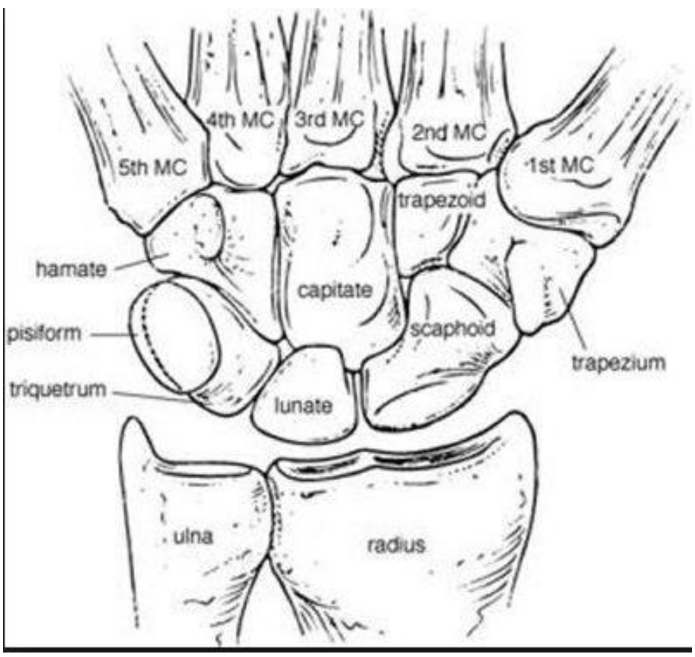


Figure 8.10 Bone Anatomy of the Wrist (Wordpress, 2013)

Berger (1996) and Kijima et al (2009) describe the bones of the wrist as including the distal radius and the ulna bones that join from the forearm, the carpal bones which are divided into the distal and proximal row and the bases of the metacarpals. The carpal bones are classified as either proximal or distal row based on their kinematic behaviour during global wrist motion. The proximal carpal row is composed of (from radial to ulnar) the scaphoid, lunate, and triquetrum while the distal carpal row is comprised of (from radial to ulnar) the trapezium, trapezoid, capitate, and hamate. The metacarpals are numerically labelled beginning from the thumb metacarpal which is named the first metacarpal finishing with the fifth metacarpal that is on the other side of the wrist.

The wrist can be split into three joint segments which are the radiocarpal joint, ….midcarpal joint. These joints are….

Two or three paragraphs on joints of wrist

Berger (1996) describes ligaments as being made up of parallel collagen fasicicles that are bound together by perifascicular loose connective tissue. On the joint surface of these ligaments, a synovial lamina, composed of cuboidal synoviocytes, forms a complete layer, while the superficial surface is covered by a fibrous lamina. The synovial and fibrous laminae together completely encircle the collagen fascicles to form the epiligamentous sheath. In the wrist, the ligaments serve several roles which include and are not limited to constraining displacement, guiding motion, and perhaps providing afferent neural input regarding the mechanical status of the joint. The ligaments in the wrist also have different mechanical properties throughout the wrist due to the different functions they perform in the wrist actions.

Fisiokinesiterapia (n.d) details how the ligaments in the wrist are grouped as either extrinsic or intrinsic. Extrinsic ligaments are defined as crossing the radio-carpal joint, the midcarpal joint or both while the Intrinsic Ligaments are defined as being located between the bones of either the proximal or distal carpal rows. The article by Kijima et al (2009) also describes how ligaments are further sub classified into several groups which include distal radioulnar, palmar radiocarpal, dorsal radiocarpal, ulnocarpal, palmar midcarpal, dorsal midcarpal. Within the groups ligaments are further subdivided into volar and dorsal ligaments groups. Volar ligaments are secondary stabilizers of the scaphoid and are stronger than dorsal ligaments while the dorsal ligaments converge on the triquetrum. Below is a table that summarises the various extrinsic and intrinsic ligaments that can be found in the wrist.

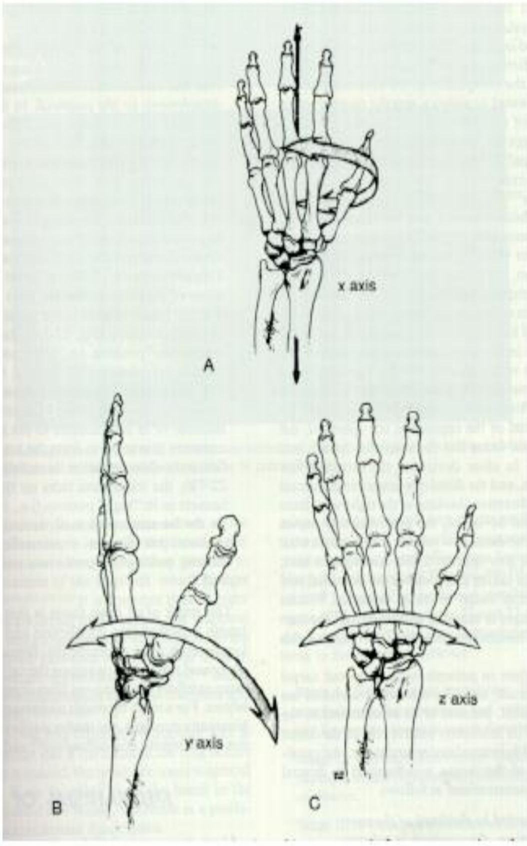
Extrinsic Ligaments	Intrinsic Ligaments
Radiocarpal Ligaments **Palmer** - Radioscaphocapitate - Long Radiolunate - Short Radiolunate - Radioscapholunate **Dorsal** - Dorsal Radiocarpal	Proximal carpal row - scapholunate (dorsal, volar and proximal) - lunotriquetral (dorsal, volar and proximal)
Ulnocarpal ligaments - ulnotriquetral - ulnolunate - ulnocapitate	Distal carpal row - trapeziotrapezoid ligament - trapeziocapitate ligament - capitohamate ligament
Midcarpal **Palmar** - scaphotrapeziotrapezoid - scaphocapitate - triquetralcapitate - triquetralhamate - Capitate Trapezium - Palmer scaphotriquetral **Dorsal** - Dorsal Intercarpal - Dorsal scaphotriquetral	
Distal Radioulnar Joint - Triangular fibrocartilage complex (TFFC) - Dorsal radioulnar - Palmar radioulnar - Meniscus homologue	

(Apergis E, 2013)

Table 8.2 Ligaments of the Wrist

3.2 Biomechanics of the Wrist

In regard to the biomechanics of the wrist there are three motions that is common in the motion of the wrist which include Flexion – Extension Motion (90 – 70 degrees), Radial – Ulnar Deviation (20 – 50 degrees), Pronation Supination Movement (90 – 90 degrees), (fisiokinesiterapia, n.d). These motions are illustrated in figure 2 … below.



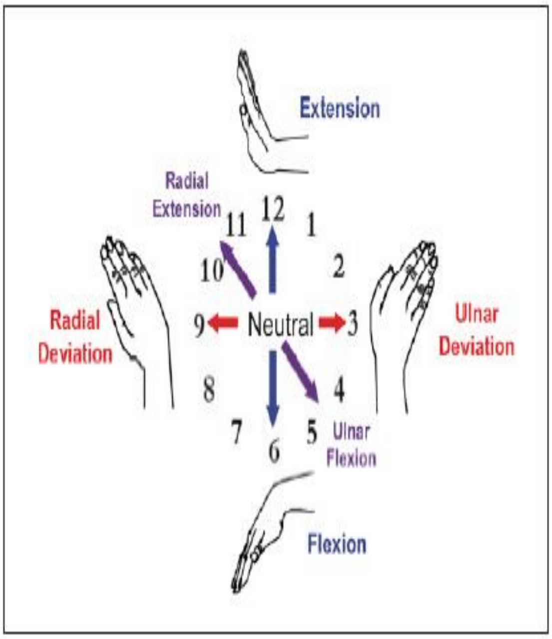


Figure 8.11 Motions of the Human Wrist (fisiokinesiterapia, n.d) Figure 2… (Rainbow MJ et al, 2015)

The theory of wrist mechanics has evolved over the years from…..

<u>Dart Throwers Motion</u>

One key understanding of wrist kinematics that has been discovered over the last century of research is the existence of the dart throwers motion that occurs in the wrist.

Wrist Kinematics

The previous mentioned theories give insight to how the understanding of the wrist kinematics has been constantly evolving. The research has also shown that wrist motion is extremely complex with knowledge of the wrist constantly being discovered. The theories also show that it is hard to summarises the wrist in a simple model.

3.3 Total Wrist Arthroplasty

2.21 The cause of wrist failure and treatments available

Arthritis is a chronic disease that severely affects the patient's quality of life. Brubacher et al (2016) details arthritis as the inflammation of the joint that causes pain / stiffness in the individual making the completion of daily activities difficult to complete. Brubacher et al (2016) explains the process of arthritis as the deterioration of the articular cartilage that surrounds the bones of the wrist that provides the smooth surface for bones in the wrist to glide past each other. The article then went on to explain that the deterioration of the cartilage eventually results in the bones of the wrist rubbing against each other which can cause irreparable wrist joint damage. There are two main types of arthritis that affect the wrist which are osteoarthritis and rheumatoid arthritis.

Osteoarthritis is an irreparable disease caused by cartilage wear in the wrist and causes pain to the patient. Brubacher et al (2016) defines the cyclic nature of osteoarthritis in the deterioration of the wrist. Osteoarthritis develops due to wear of the smooth articular cartilage that covers the bone which is unable to repair itself due to its limited blood supply. Cartilage wear then creates a rough surface that decrease the space between the bones that then results in the bones rubbing against each other. This rubbing of the bone surfaces results in enhanced deterioration of the remaining cartilage. The above process of osteoarthritis described by Brubacher et al (2016) shows that osteoarthritis progressively degrades the cartilage surrounding the bones at increasing pace until the wrist fails.

Osteoarthritis creates pain and stiffness in the wrist often ending in irreparable wrist joint damage. The article by University of Washington (2017) details that patients suffering from osteoarthritis have wrist joint that is stiff and swollen with the pain and stiffness being localised in nature. Another sentence or two on pain

Osteoarthritis has several causes for the disease to develop. University of Washington (2017) noted that the causes of osteoarthritis can include endocrine and metabolic disorders, nutritional deficits, and genetic lack of protection for cartilage. Brubacher et al (2016) details that osteoarthritis may also develop from Kienböck's disease which is caused by blood supply to the lunate being disrupted, causing the bone to die and slowly collapse. This collapse progressively eventuates in arthritis to develop in the joints around the lunate. Kienbock's disease, endocrine/metabolic disorders, nutritional defects and genetic predisposition are all common reasons for the osteoarthritis disease to develop.

There several risk factors that predispose the individual as a higher risk to develop osteoarthritis. The age of the individual is a risk factor for osteoarthritis. Dewing et al (2012) details that the older generation are at higher risk due to the combination of impact on the cartilage extracellular matrix structure and components as well as declining chondrocyte function and response rate to stimuli that occur due to the aging process. Another risk factor is being a woman often developing this disease in the wrist at an earlier age then men. University of Washington (2017) notes that studies have shown nearly 40% of women over the age of 60 have developed osteoarthritis in hand or wrist. Obesity and previous trauma to the wrist place a patient at a higher risk to develop osteoarthritis due to the damage these conditions have placed on the cartilage. Dewing et al (2012) notes that obesity and previous injury and trauma can also place an individual in higher risk category for this form of arthritis. Age, gender, obesity and previous trauma all increase the likelihood of an individual developing osteoarthritis in the wrist

Individuals with previous trauma develop a specific type of arthritis known as scapholunate advanced collapse (SLAC) wrist arthritis. Rainbow et al (2015) notes that if the proximal row of the wrist is disrupted the individual will progressively start to develop SLAC wrist arthritis which is responsible for 55% of cases of degenerative wrist arthritis. Lyons et al (2003) also details that the SLAC is caused by misalignment at the radioscaphoid articulation which leads to concentrated wear at the edges of the scaphoid fossa which leads to abnormal wear patterns cause articular destruction of the joint. Lyons et al (2003) details all the underlying causes of this arthritic disease as observed after distal radius fracture involving the radioscaphoid fossa, Preiser's disease, uncollapsed Kienbock's disease, chronic symptomatic scapholunate ligament incompetency and calcium pyrophosphate dihydrate deposition disease.

SLAC wrist arthritis first develops at the radiocarpal joint between the scaphoid and the radius eventually progressing to the midcarpal joint. Lyons et al (2003) details the SLAC is the most common form of arthritis around the scaphoid while 95% of degenerative wrist arthritis is around the scaphoid of the wrist. There are three stages in the development of SLAC. Lyons et al (2003) describes stage I as only involving the radial styloid-scaphoid joint, stage II encompasses the whole radioscaphoid joint and stage III encompasses capito--lunate degeneration. SLAC is the main form of arthritis in the wrist that progresses throughout the wrist causing its eventual failure

Rheumatoid is different to osteoarthritis in that is occurs due to the immune system of the body attackingthe cartilage of the wrist. Brubacher et al (2016) and Dewing et al (2012) define rheumatoid arthritis as an autoimmune disease that typically affects the radius and ulna bones of the wrist. The body’s defences that typically protect it from infection instead attack the wrist tissue such as ligaments and cartilage while also softening the bone. The disease begins with an initial immune response being triggered which causes the cells of the immune system to produce autoantibodies and inflammatory cytokines. These autoantibodies and inflammatory cytokines then create a cascade of inflammation resulting in the formation of pannus which then invades and destroys the surrounding cartilage and bone. The above description shows that rheumatoid arthritis is a contradictory disease in that body’s defences are damaging the wrist until its eventual failure.

Unlike osteoarthritis little is known about the cause of rheumatoid arthritis. Brubacher et al (2016) details that the cause of rheumatoid arthritis is unknown with some researchers suggesting its development is associated with bacteria and/or virus which is contracted from the surrounding environment. While University of Washington (2017) notes that some researchers believe that some individuals can be genetically predisposed to have this form of arthritis with the disease often seen running in families. There is much debate on the cause of osteoarthritis which is either genetic or bacterial in nature but what can be certain is that certain factors put an individual at a higher risk to contract the disease

These factors that put an individual in a higher risk category. The articles by University of Washington (2017) and Dewing et al (2017) outline these risk factors as including family history (risk doubles with first degree relative having rheumatoid arthritis), old age, women (3.6% compared to 1.7% for men), high rates disease onset associated during pregnancy, cigarette smoking (can increase risk more than 2-fold and is the strongest risk factor) and presence of the human leukocyte antigen. When a patient does have these risk factors in their life they are much more likely to contract the rheumatoid arthritis disease and start to exhibit symptoms

The symptoms the patient with rheumatoid arthritis exhibit can range from mild to debilitating and impact on the patient’s quality of life. University of Washington (2017) describes that individuals exhibiting rheumatoid arthritis have stiffness and swelling in the wrist, fatigue that ranges from mild to debilitating and ulnar drift of the fingers which is where the fingers drift at the knuckles towards the small fingers. Brubacher et al (2016) also mentions that the inflammation caused by rheumatoid arthritis can result in the tendons eroding which then results in the fingers drooping which is known as extensor lag. The tendons at the back of the hands and fingers which are known as the extensors tendons are most vulnerable to erosion due to inflammation. University of Washington (2107) also recognised that if left untreated rheumatoid arthritis it can leave the patient with permanent damage to bone/cartilage as well as surrounding soft tissue and could also result in the rupture of tendons in the hand and wrist causing loss of normal function of the hand. The above symptoms show that rheumatoid arthritis results in impacting the patient’s quality of life leaving the patient with irreversible damage.

Rheumatoid arthritis and osteoarthritis result in the patient exhibiting severe pain, swelling of the wrist and limited range of movement. Brubacher et al (2016) details that patient’s treatment options are thus to try to mitigate this disease thus slowing its progression through drug therapy etc. Although the may be slowed in some individuals the disease may have progressed to far with the painful symptoms resulting in the individual living with a poor quality of life whereby surgical treatment may be the only option. There are three surgical options typically available to a patient of arthritis in their wrist. These options are ablative surgery, arthrodesis, or arthroplasty.

Ablative Surgery

The removal of the arthritic section of the wrist is one surgical option available to the patient. Rainbow et al (2015) explains that the ablative surgical procedure is where the pain generating segment of the arthritic wrist is removed. Rainbow et al (2015) also explains that the patient has relief from the pain post-surgery with the arthritic degeneration being slowed but still progressing to failure. Regarding ablative procedures there are several options available to the patient. Rainbow et al (2015) lists the most common ablative procedures as proximal row carpectomy (PRC)

Proximal row carpectomy

Proximal row carpectomy is a surgical procedure that is utilised for stage II scaphoid nonunion collapse. Sobczak et al (2011) describes proximal row carpectomy as the creation of a joint between the head of the capitate and the lunate fossa of the radius by removing the scaphoid, lunate and triquetrum bones. Richou et al (2010) describes advantages of this procedure when compared to arthrodesis procedure as lower risk of infection, no implant related complications, simplicity of procedure and shorter rehabilitation. Proximal row carpectomy also provides relief to the pain suffered by the patient. Sobczak et al (2011) reports that literature studies have shown that PRC results in pain relief experienced in 83% of cases and Richou et al (2010) described the 83% of patients were satisfied with the procedure. High level of patient satisfaction and pain relief to a patient makes it a viable option for surgery to an arthritic wrist.

Proximal row carpectomy is a significant alteration of the wrist. Sobczak et al (2011) notes that after the surgery the wrist joint is changed from a universal cardan joint to more of a ball-and-socket joint with the axis of motion being closer together. This change of the wrist structure does not have a significant affect the wrist range of motion. Sobczak (2011) and Richou et al (2010) describes the range of motion relatively well preserved to 76° in dorso-palmar flexion and 45° during radioulnar deviation. Even though the range of motion is preserved there are negative aspects that need to be considered. Richou et al (2010) details that patient after PRC report pain in extreme wrist rotations and weakness with repeated movements. This is due to the radiocarpal ligament being removed in the PRC and rotational instability being common in wrist kinematics. Although the patient can have pain in extreme rotations the available range of motion should allow them to complete everyday functional activities.

Proximal row carpectomy surgery affect reduces the capacity of the muscles of the wrist. Sobczak et al (2011) notes that after PRC the mean moment arms of the muscle are significantly decreased effectively reducing the moment generating capacity of these muscle. Richou et al (2010) describes the reduction in the moment arms due to height of the carpus being reduced and the relatively lengthening of the tendons. This reduction in mean moment arms of the muscles could explain the decrease in grip strength of the patient. Sobczak et al (2011) notes that the grip strength decrease after PRC to between 60 – 90% of normal hand. Sobczak et al (2011) the APL and EU are the principal dynamic stabilizing muscles of the wrist during dorso-palmar flexion motion. The reduction of the moment arms of these muscles results in limited capacity of the APL and EU muscles which means the dynamically stability of the wrist in dorso-palmar flexion motion is partially preserved.

There are certain circumstances that remove proximal row carpectomy from being a viable surgical option. Richou et al (2010) describes certain individuals as poor candidates for PRC which include patients with inflammatory arthritis, patients with large cartilage lesions and heavy manual laborer. Sobczak et al (2011) notes that poorer outcomes are observed in patients who have PRC surgery when severe cartilage degeneration is present around the radiocapitate joint and remove them as possible patients. Richou et al (2010) reaffirms that attempting proximal row carpectomy on patients with arthritic wrist will often accelerate the arthritis. Heavy manual laborer is poor candidate as during their job they require extreme wrist position and repeated wrist motion which will cause pain in the wrist. Proximal row carpectomy has promising results in preserving wrist kinematics but reduced grip strength, reduced dynamic stability in dorso-flexion, pain in extreme rotations/weakness in repeated movement could remove it as a viable option for certain patients

Arthrodesis Surgery

Arthrodesis is another surgical option to provide pain relief and stability. In this surgical procedure, certain sections of the wrist are fused together to provide function back to the wrist. There are several available procedures available to the patient which include radioscapholunate arthrodesis, midcarpal arthrodesis and four corner fusion.

Watson Procedure

Dernervation/ Total Wrist Fusion

Arthroplasty

Open with what TWA and partial TWA.

- Explain why not used / shortcomings – specific patient criteria, high failure rates, low load capability etc /Comparison with other surgical procedures

- Finish with statement how constantly changing and survivability constantly improving thus will overcome shortcomings and be surgery of choice etc.

At this point in time, total wrist arthroplasty is typically reserved for the low-demand rheumatoid wrist.

Comparison surgical procedures

The article by Rainbow MJ et al cites a study by Wolff et al which examined how the ablative surgical procedure of PRC and the arthrodesis procedure of 4CF affected patients motion and their ability to perform everyday tasks such as…

PRC is generally only indicated in stage II SLAC where the capitate head and lunate fossa cartilage are intact. Scaphoid excision and 4CF may be performed for stage II SLAC and is the procedure of choice for stage III SLAC wrist when capitolunate degeneration precludes PRC.

2.22 History of Wrist Implant

Understanding of the historical evolution of the wrist implant gives a perception on the progress of the wrist implant over the last century. The wrist implant has

Expand section

3.4 Failure Analysis

3.4.1 Causes of Total Wrist Arthroplasty Failure

Understanding why current wrist implant is vital in designing an optimal distal carpal component of the wrist implant. This failure analysis of the wrist implant was investigated in several steps. The first step in the process was an extensive literature review on the failure of wrist implants. This was done completed by…

Examining the failure of the wrist prosthesis it is important to note the survivability of the implant and the effect that the distal carpal plays in this failure. The study conducted by Cooney W et al (2012) examined three different wrist prosthesis models which included Remotion, Universal 2 and Biaxial looking at the survivability of these models. The main findings from this study is that re-sectional based model (Biaxial) had a much larger failure rate in the study (50%) compared to the resurfacing based models (Universal 2 (0%) and Remotion (20%)). Another point from the study is that in total 9 implants failed and of the 9 implants 7 of them failed by distal loosening.

The study by krukhuag et al (2011) also examined three models (Biax, Elos and Gibbon) by utilising the Norwegian Arthroplasty Register to determine the survivability of the implants and the cause of failure. The study concluded that the overall survivability of the wrist prosthesis was 78% (95% CI: 70–85) for 5-year survival and 71% (CI: 59–80) for the 10-year survival of the implant. The study also highlighted the main causes of failure which are highlighted in the table below.

Reasons for revision (more than one reason could be given)

Brand	Biax	Elos	Gibbon	Total
Loosening of proximal component	3	2		5
Loosening of distal component	8	8	5	21
Dislocation	2	—	—	2
Instability	3	—	—	3
Axis problems	7	—	1	8
Deep infection	1	—	3	4
Pain	7	1	2	10
Wear of liner	1	—	—	1
Total number of revisions	18	10	11	39

Table 8.3 Causes of Failure – Table 1 krukhuag et al (2011)

The above table shows that the loosening of the distal component, dislocation, instability and wear of the bearing surface as major causes of revision for all the models of wrist implants. The likelihood of occurrence of the different failure mechanism are directly dependent on the mechanical properties of wrist implant which will be discussed later in this section.

Study by Gaspar MP et al (2016) looked at a medical institutes results for reasons for the failure of partial and total wrist arthroplasty (TWA). The study retrospectively reviewed 105 wrist surgeries in 100 patients who underwent surgery with prosthetic replacement of the distal radius, the proximal carpus, or both at a single institution. The results for reasons for revision are shown below

TABLE 2. Type and Rates of Complications Occurring Based on Type of Arthroplasty Performed	TWA n (%)	DRH n (%)	CH n (%)	All Surgeries n (%)	P Value*
Minor Complications					
Contracture	7 (15)	11 (21)	3 (50)	21 (20)	.56
DRUJ disease/progression	6 (13)	-	2 (33)	8 (8)	-
Erosion into opposing bone	NA	4 (8)	2 (33)	6 (6)	-
Soft tissue imbalance	4 (9)	-	2 (33)	6 (6)	-
Infection (superficial)	3 (6)	2 (4)	-	5 (5)	.37
Nerve compression in CT or Guyon canal syndrome	3 (6)	2 (4)	-	5 (5)	.37
Tendon rupture	3 (6)	-	-	3 (3)	-
HO formation	2 (4)	-	-	2 (2)	-
Hypertrophic scar	-	-	2 (33)	2 (2)	-
Major Complications					
Failure of DR component	2 (4)	5 (10)	NA	7 (7)	.11
Failure of carpal component	5 (11)	NA	1 (17)	6 (6)	
Failure of both components	3 (6)	NA	NA	3 (3)	
Infection (deep)	2 (4)	1 (2)	-	3 (3)	.47
Instability	2 (4)	-	1 (17)	3 (3)	-
CRPS type I	-	1 (2)	-	1 (1)	-
Total Surgeries Performed	47	52	6	105	

CRPS, complex regional pain syndrome; CT, carpal tunnel; DR, distal radius; DRUJ, distal radioulnar joint; HO, heterotopic ossification.
**P* values denote comparisons between TWA and DRH groups only.

Table 8.4 Causes of Failure – Table 2 Gaspar MP et al (2016)

From the above table the study identified several causes for the failure of the TWA which include failure of the component, infection, instability, tendon rupture, contracture, erosion of bone and HO formation.

Harlingen DV et al (2011) examined the survivability and failure outcomes of the Biaxial prosthesis which is a third generation wrist implant for 5 – 8 year timeframe. The results from the study can be seen below.

Table 2. Complications. The numbers in parentheses indicate the number of prostheses

Complication	Solution	Further complications	Need for revision
Intraoperative (4)			
Severe soft bone tissue (1)	Prostheses cemented		
Difficulty in wound closure (1)	Soft tissue patch		
Breakout distal component (2)	14 days splint immobilization	Limited ROM (1) [a]	
Postoperative (27)			
Dislocations (7)			
Direct postoperative (2)	14 days of immobilization		
Late (4)	Reposition, expectative		
Ulnar instability (1)	Flexor carpi ulnar transposition		
Infections (3)			
Superficial (1)	Antibiotics (1)	Limited ROM + loosening (1)	
Deep (2)	Removal of prosthesis (2)		Deep infections (2)
Limited range of motion (7)	Operative release of capsule (3)		
	Manipulation under anesthetic (4)		
Nerve damage (3)			
CTS (2)	CTS release (2)		
Sensible disorder ulnar nerve (1)	Expectative (1)		
Ulnar pain (1)	Further resection ulna		
Wound dehiscence (1)	Operative debridement		
Need for revision (5)	Removal prosthesis (5)	Not available	
Loosening (3)			Loosening (3)
Malpositioning (1)			Malpositioning (1)
Breakout of distal component (1)			Breakout of distal component (1)

[a] One patient had a superficial infection, limited range of motion, and loosening (in order of appearance). This loosening is one of the three mentioned under "Need for revision".

Table 8.5 Causes of Failure – Table 3 Harlingen DV et al (2011)

Table 3. Revisions

Case	Months in situ	Reason for revision	Age at operation	Larsen pre-operatively	Dominant side (–/+)
1	22	Loosening	39	I	–
2	9	Malpositioning	23	III	–
3	66	Loosening	63	I	+
4	18	Infection	66	V	+
5 [a]	71	Breakout of distal component	63	II	–
6 [a]	8	Infection	64	IV	+
7	59	Loosening	61	III	+

[a] 5 and 6 are the same patient with bilateral total wrist arthroplasty.

Table 8.6 Causes of Failure – Table 4 Harlingen DV et al (2011)

The reasons cited by the study for the failure include loosening, infection, dislocation, breakout of distal component, limited range of motion, pain and nerve damage.

Looking at the previous discussed studies there seems to be common failure mechanisms for total wrist arthroplasty. The table below summarises these common failure mechanisms.

Failure mechanism	Varieties of failure mechanisms	Studies mentioned mechanism	Probabilities of occurance
Loosening	Loosening of proximal component, Loosening distal component	Harlingen DV et al (2011), krukhuag et al (2011)	3 out of 7 revision cases (Biaxial), 11 out of 18 (Biax), 8 out of 10 (Elos) and 5 out 11 (Gibbon)
Infection	Deep, superficial	Harlingen DV et al (2011), Gaspar MP et (2016), krukhuag et al (2011)	3 out of 34 cases (Biaxial), 5 out of 47 cases (Gaspar study),
Failure of the components	Failure of DR component, failure of carpal components, failure of both components	Gaspar MP et al (2016)	10 out of 47 cases
Breakout of distal component	Can occur intraoperative and post operatively	Harlingen DV et al (2011)	1 out of 7 revision cases,
Nerve damage	Nerve compression in Carpal tunnel, Guyon canal syndrome, sensible disorder ulnar nerve	Gaspar MP et al (2016), Harlingen DV et al (2011)	3 out of 34 cases (Biaxial), 3 out of 47 cases
Instability		Harlingen DV et al (2011), Gaspar MP et (2016), krukhuag et al (2011)	1 out of 27 cases postoperatively (Harlingen study), 2 out of 47 cases (Gaspar study), 3 of 39 cases (krukhaug study)

Dislocation	Ulnar instability, Late, Direct postoperatively	Harlingen DV et al (2011), krukhuag et al (2011)	7 out of 27 cases postoperatively (Harlingen study), 2 of 39 cases (krukhaug study)
Limited range of motion	----------	Harlingen DV et al (2011)	7 out of 27 cases postoperatively (Harlingen study)
Contracture	-----------	Gaspar MP et al (2016)	7 out of 47 cases (Gaspar study),
HO formation	----------	Gaspar MP et al (2016)	2 out of 47 cases (Gaspar study),

Table 8.7 Failure Mechanism Table

3.4.2 Underlying Causes of Failure

The most common form of failure outlined in the failure analysis was the loosening of the distal carpal component. The studies by Harlingen DV et al (2011) and krukhuag et al (2011) both mentioned this failure mechanism as the primary cause of failure. Results from these studies for the implants are 3 out of 7 revision cases (Biaxial), 11 out of 18 (Biax), 8 out of 10 (Elos) and 5 out 11 (Gibbon). Understanding the underlying causes of loosening of the distal carpal component is imperative in the design process. Harlingen DV et al (2011) cited that prosthesis that gradually loosened was because of the progressive loss of bone stock surrounding the implant. The study mentioned that to control this loosening it was important to closely monitor the patient to diagnose the radiographic loosening while sufficient bone stick remain to perform a revision. Osteolysis and stress shielding are the two common underlying causes of the distal carpal component becoming loose.

Loosening of the component is usually predated by peri prosthetic osteolysis where the bone surrounding the implant is deteriorated by a combination of mechanical and biological causes. Gallo, J et al (2013) highlights that mechanical causes of wear occurs due to the frictional forces occurring between two contacting surfaces in motion in the prosthetic. The article describes that smaller, more biologically active particles are usually created by rolling/ sliding and rotational motion due to adhesive/ abrasion wear while larger particles occur due to surface fatigue by delamination wear. Gallo, J et al (2013) and Dattani R (2006) also describe how these particles biological react inflame the surrounding the tissue that creates cells (e.g osteoclasts) that resorb the surrounding bone. This resorbing of the bone creates cavity in the bone. This cavity also creates an area where additional fluid and particles can pool creating conditions where hydrodynamic forces are likely to generate causing damage to the spongy bone surface surrounding the implant and the increased particles causing increase bone resorption in the area. This results in the cavity to become larger and result in large localised bone loss occurring in the area. The studies also outline that the degree of osteolysis occur is patient specific with some patients exhibiting greater susceptibility to the osteolysis. Hypersensitivity of metal ions also results in the cycle of osteolysis being accelerated in the patient when metal prosthesis being used and premature failure of the implant.

The weight of the patient and the condition of the surrounding muscles determine the likelihood of them developing osteolysis. Gallo, J et al (2013) outlines that obese patients could be highly susceptible to osteolysis and aspectic loosening due to high loading due to excess weight but also younger active males also at high risk due to the high cyclic loading experienced by these patients (up to 3.2 million steps per year). Gallo, J et al (2013) also highlights that the condition of the surrounding muscles could be a decisive factor in the likelihood of osteolysis occurring with muscles being in optimal condition helping to shield the stresses being experienced by the prosthesis.

Gallo, J et al (2013) highlights that instability of the prosthesis is caused by accuracy of surgical technique, the degree the implant fixates to surrounding bone bed and factors that influence bone vitality and remodelling such as osteolysis. When the implant is misaligned and poorly fixated there is increase wear, damage to surrounding bone and degradation to surround bone-cement interface. So there is a deadly cycle that occurs in the prosthesis that the wear and poor fixation results in the implant becoming more unstable and thus increasing the wear.

Gallo, J et al (2013) and Dattani, R (2006) also explains the importance in have good fixation of the prosthesis. The prosthesis-bone interface is usually weak point that shear stress can occur thus causing the surrounding bone to fail. Voids that surround a poorly fixated device provides location for the formation of fibrous tissue which is susceptible to be infiltrated by pathogens and cells that participate in the advancement of osteolysis. Thus, optimal fixation of the prosthesis with the surrounding bone will be a key parameter in the material selection and design of the prosthesis

Stress Shielding

Stress shielding is the deterioration of the surrounding bone….

Expand section on what is stress shielding, prevelance of stress shielding in components, how to prevent stress shielding, detail importance of material properties to prevent stress shielding

Failure of Component

Detail different ways component fail such as compressive failure etc

Outline studies where implants have been modelled to determine stress experience which lead to failure.

Determine material properties required

Multiple Surgeries

Deep tissue infection was a major cause of failure of TWA. Gaspar MP et al (2016) discussed that deep infection is associated with morbidity and prolonged course of treatment on the patient. In the study three patients developed deep infection with the common features of these patients receiving multiple surgeries before or after the infection. One patient who ended up having four revision to address failure in their wrist replacement before developing a deep infection

4.0 Consequences / Ethics

The consequence of the dissertation is that the results will be used by the medical implant design company Field Orthopaedics as part of the design process for their total wrist arthroplasty design. Thus the information will steer the design path of their implant as such incorrect information could put the company on the wrong path costing them time and money. Worst still if verification testing is not done on sample from dissertation recommendations it could place the patient at risk. This is why it is important to source information from credible sources (peer reviewed academic journal articles) and that there is a statement at the start detailing the dissertation as an academic exercise.

The ethical responsibility that will need to be adhered to will be based on the ethical responsibilities of an engineer outlined by Engineers Australia that can be found in the appendix of this dissertation. The relevant ethical considerations in relation to this dissertation are outlined below with an explanation on how these ethical considerations will be handled

1.2 Be honest and trustworthy

a) accept, as well as give, honest and fair criticism

Throughout this dissertation feedback will be given by my supervisors and course examiners. This dissertation will also be assessed at several stages throughout its completion. As a student, it will be up to me to take the criticism on board to make the necessary changes while learning from any criticism that is bestowed upon me.

b) be prepared to explain your work and reasoning

In the course of completing the dissertation the course of the academic work will constantly be questioned. This dissertation has already been altered several times to get a clear direction. In fact a major change was instated recently to give the dissertation a clear purpose and direction. Although this resulted in the stagnation of my progression at the time, it was more important to get make sure the dissertation had a clear direction. This was an important lesson to learn and also showed that as an engineer it is always important to understand the purpose of the work.

c) give proper credit to those to whom proper credit is due

All academic work from outside sources will be referenced correctly throughout the dissertation. This references will be done through the use of the Harvard referencing style.

e) respect confidentiality obligations express or implied

Any confidential sensitive information will be used carefully with appropriate disclaimers attached. The original version did have confidentiality sensitive images of the Field Orthopaedic Wrist Implant design but a disclaimer was attached informing the reader of the confidentiality sensitive information and how it was not to be disclosed to external parties for commercial gains. The latest version of the dissertation has taken a new direction and as such there is no confidentiality sensitive information attached.

2.1 Maintain and develop knowledge and skills

a) continue to develop relevant knowledge and expertise

In completing this dissertation my knowledge into the field of biomechanics and implant development will be constantly expanding. This will include developing my understanding of how the wrist works, different surgical options available for wrist failure, how the wrist implant has developed, why the current wrist implants fail and how implants can be designed better to improve survivability.

c) seek peer review

Throughout the course of completing this dissertation I will constantly seek review from the project supervisors. This will be important as they will be instrumental in providing guidance if the dissertation is on the correct course and will help to assure there are no major flaws in the dissertation that I might have missed. Recently the academic supervisor Steven Goh and myself have agreed upon a communications plan in that I will update my progression on the dissertation every fortnight via sending him an email.

2.2 Represent areas of competence objectively

a) practise within areas of competence

Biomechanics is within the field of mechanical engineering that specialises in developing implant that are suitable to withstand the forces in the human body while also being aware of how the human body reacts to these foreign objects. Basic principles used throughout this dissertation stem from the field of mechanical engineering. These principles include material selection, failure analysis and FEA force analysis.

4.1 Engage responsibly with the community and other stakeholders

b) inform employers or clients of the likely consequences of proposed activities on the community and the environment.

The company Field Orthopaedics that will be interested in the results of the dissertation will be informed that this dissertation should only be used as a preliminary document for their design process. Any information from this dissertation that could be used in their design process should be verified from other sources to cross check the credibility with external testing should be also be conducted to verify their design. This is important as the final implant design will be used on patients so any failures of the design will result in emotional and physical damage to the patient

5.0 METHODOLOGY

5.1 Project Outline

This dissertation will be completed in eight stages.

1. Background research into wrist

2. Literature Review of total wrist arthroplasty

3. Failure analysis of the total wrist arthroplasty

4. Research methodology for key points

5. Material selection for articulating components

6. Porous design to improve fixation

7. Design to improve stress distribution

8. Write up phase

Further details of the above stages looking at the steps required in detail are provided in table 3.1

Stage 1	**Background research into Wrist**
1A	Anatomy of the Wrist – research into the various components of the wrist such as the bones, ligaments etc
1B	Biomechanics of the Wrist – research into theories of wrist kinematics
Stage 2	**Literature review of Total Wrist Arthroplasty**
2A	Cause of Wrist Failure and Treatments – Determine the primary causes of the failure of the wrist (arthritis) and the different surgical treatments available
2B	History of Total Wrist Arthroplasty – Detail the history of the total wrist arthroplasty
Stage 3	**Failure analysis of the Total Wrist Arthroplasty**
3A	Cause of Total Wrist Arthroplasty Failure – determine the primary causes of failure of the total wrist arthroplasty
3B	Underlying Causes of Failure – in depth research into the underlying failure mechanism
Stage 4	**Research Methodology for key points**

4A	Methodology for Material Selection – Approach utilised to determine the optimal material for components will be discussed in this section
4B	Research Methodology- Highlight approach that will be used to conduct research into the design of implant to improve porous design for optimal fixation and how to design the implant to improve stress distribution.
Stage 5	**Material Selection for articulating components**
5A	Material Selection for Polyethylene Cap – Material selection for the polyethylene cap of the radial stem will be conducted.
5B	Material Selection for Distal Carpal Component – Material selection for the distal carpal component to determine the optimal metal
Stage 6	**Porous Design to Improve Fixation**
6A	Parameters to improve Fixation – Various methods that are currently utilised to improve implant fixation will be discussed
6B	Research on Key Parameters – Methods that are utilised in cementless fixation will be explored in more detail
Stage 7	**Design to improve Stress Distribution**
7A	Current models with Improved Design – This section will detail how the latest total wrist arthroplasty have improved the design to improve stress distribution
7B	Key Parameters for Improved Design – The key parameters in regard to improving the design will be explored in more detail in this section
Stage 8	**Write up phase**
8A	Draft dissertation – prepare draft dissertation for supervisors to review and provide feedback
8B	Final dissertation – make amendments to draft based on supervisor feedback and then finalise dissertation.

Table 8.8 Further description of Project Stages

a. Research Methodology

In researching to optimise the design of the total wrist arthroplasty there are several types of review strategies that can be employed. University of Southern Australia n.d cites several review strategies that are available to the reader include Cochrane review, Systematic Review, Scoping Review, Integrative Review and Narrative Review. Elsevier n.d. also cites several research strategies which include systematic review, best evidence synthesis, narrative review, integrative research review, theoretical review, methodological review, thematic review, state of the art review and historical review. Each strategy has advantages/ disadvantages that make it ideal for certain research projects.

The available literature reviews can be categorised into three broad categories. These categories include Traditional/ narrative, Systematic / quantitative and Meta- Analysis (Pickering, n.d). Each category has it strengths and weakness which are detailed in table …below.

Table 5.2 Different Methodologies for Literature Review

	Traditional/ narrative	Systematic/ quantitative	Meta-Analysis
Description	Narrative review utilises a less rigorous approach. The literature is qualitative analysed with no formal attempt to rate the papers credability. The author contrasts the papers in narrative fashion comparing the papers when required	Systematic review answer a set of research objectives utilising a systematic process to review the available literature. The literature is selected by a predefined selection criteria with a wide selection of research investigated to ensure all relevant research is considered which minimises bias in research.	Meta-Analysis summarises the results of systematic literature review using statistical methods to formulate a conclusion
Who utilises review methodology	Experts and University students	University Student	Team of Experts
How are papers selected and compiled	Rarely systematic	Systematic	Systematic

Comparing papers	Expert evaluation	Quantitative or expert evaluation	Expert Evaluation
Statistical Analysis	No	If you want to	Yes
Structure of paper	Narrative	Standard	Standard
Ease of updating	Limited	Easy	Statistical Analysis will have to be redone

(Pickering, n.d), (Elsevier, n.d), (University of Southern Australia, n.d)

Table 8.9 Different Research Methodologies

This dissertation will utilise Systematic literature review approach as is best suited for the following reasons;

- The systematic literature is often utilised by university students due to the fact it suits the style of the dissertation.
- The systematic literature review allows the use of quantitative analysis to compare papers and doesn't necessary require the expert evaluation that the other methodologies require
- Systematic literature review doesn't require expert knowledge that is required in the other review methodologies. The process of the systematic literature review helps the student to improve the knowledge on the research topic
- The systematic literature review is easier to update then the other methodology techniques
- The systematic literature review is not as in-depth and convoluted as the meta-analysis which can take large number of researchers to complete. Thus, the meta- anlaysis process will make the dissertation workload too large to complete by the due date.
- The Systematic literature review is more structured and analytical then the narrative approach which is better suited to the dissertation topic

The systematic literature review uses a systematic approach to collect and evaluate literature papers. The methodology is the same regardless of the topic and is outlined below.

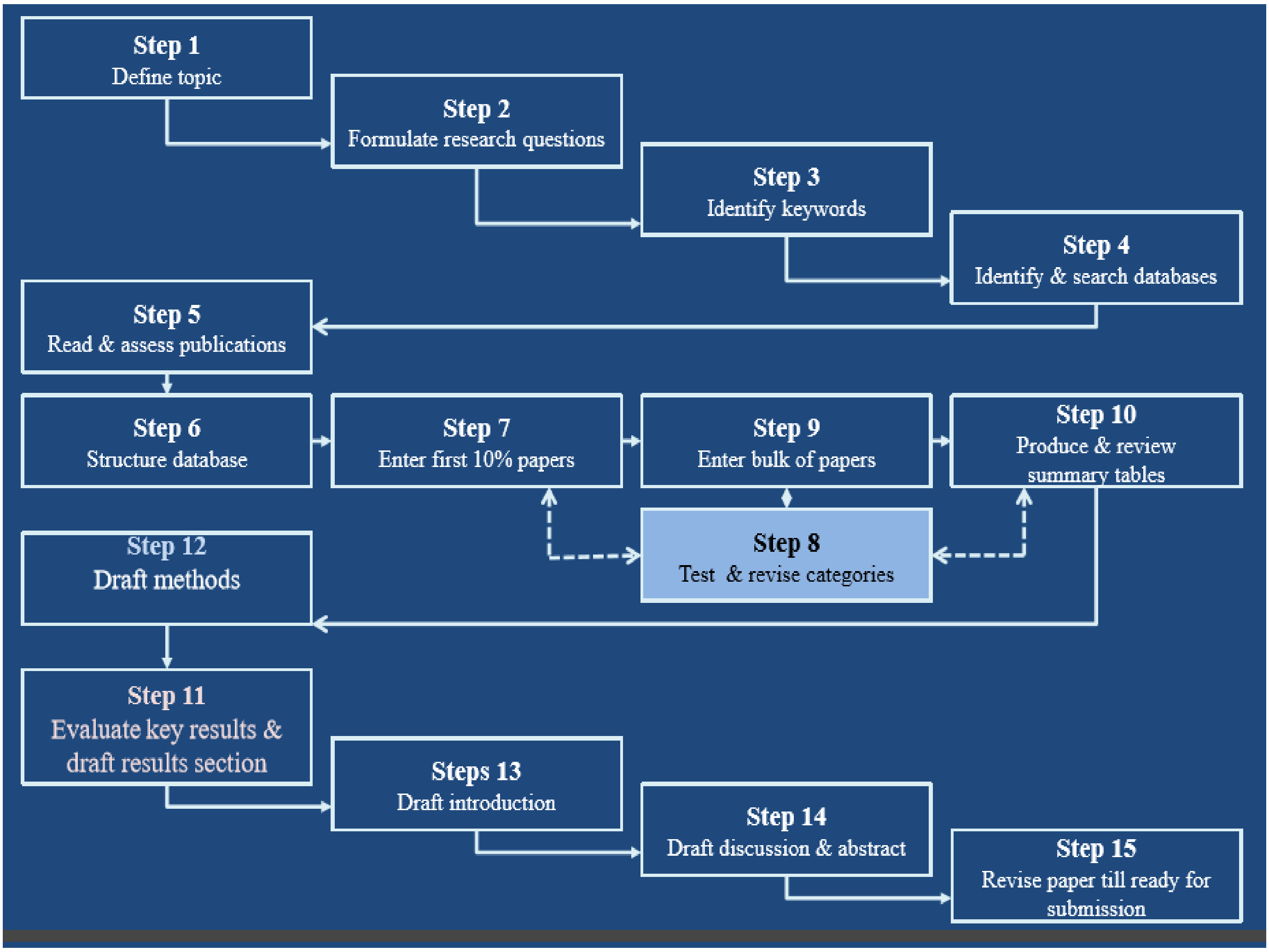


Figure 8.12 Systematic Literature Review Process (Pickering, n.d)

The first steps in the systematic review process is to define a topic which specific research questions/keywords will be defined. The literature review in section 3.0 of this progress report completes steps 1-3 of the literature review process. In the literature review it was shown that the major cause of total wrist arthroplasty failures is the loosening/dislocation of the distal carpal component. Thus, the topic of the dissertation is to research how to reduce the likelihood of the loosening/dislocation of the distal carpal component through design.

The research into the loosening of the distal carpal component and total wrist arthroplasty generated four research question. These research questions were focused on how to optimise the design to reduce the occurrence of distal carpal component loosening. These research question are

4. What metal material for the metal distal carpal component should be selected to reduce distal carpal component loosening while still delivering the required mechanical performance
5. What polyethylene component should be selected for the radial stem to reduce wear particles while still delivering the required mechanical performance
6. What porous design will improve the fixation of the distal carpal component
7. What key design principles are required in the distal carpal component to improve stress distribution.

The third step of the process will be to determine key search words that will be researched in the various online databases. Each of the four research questions will have several search keywords that were determined from the preliminary literature review on the topic. These keywords are outlined below and will be the preliminary search terms used. Additional search terms will also be generated during the systematic review process.

Metal Material Research

- TiAI6V4
- Cobalt Chromium
- Stress shielding
- Fatigue resistance
- Compression strength

Polyethylene component research

- PEEK
- UHMWPE
- Crosslinked
- Vitamin E
- Wear particles
- Biological response
- Uni-directional loading
- Multidirectional loading
- Radiation sterilisation
- Oxidation resistance

- Fatigue properties
- Chemical sterilisation

Porous Design

- Porous lattice
- Lattice structure
- Roughened surface
- Pore size
- Bone ingrowth

Stress distribution

- Remotion arthroplasty
- Uniform stress distribution
- Edge loading

The search terms will be utilised on the *Science Direct database*, *National Centre for Biotechnology Information Database* and the *University of Southern Queensland library journal article access*. These databases were selected due to the articles generated from the databases from credible sources and are peer reviewed.

The fifth step in the process will be read and assess the journal articles. This will involve defining a clear set of exclusion and inclusion criteria to determine what articles are relevant to the research questions. The inclusion and exclusion criteria that will be utilised in the dissertation are outlined below

Inclusion criteria

- Peer reviewed
- Quantitative analysis
- Experimental studies
- Reductive manufacturing
- FEA diagrams

Exclusion criteria

- Qualitative analysis

- New experimental materials
- Additive manufacturing
- Theoretical case studies
- Studies in other language where translation cannot be sourced

The steps 6 - 9 in the process will be to structure / refine categories to analyses the literature articles that make the inclusion criteria to form a information database. This will involve determining initial categories to collect information and analyse the chosen articles. Then the first 10 % of the articles will be reviewed with the initial categories. The effectiveness the categories will then be critiqued and any alterations to the categories will be conducted if required. This process will be repeated until the categories are suitable then the rest of the papers will be analysed. The categories can be altered at any stage during this stage of the dissertation. The initial categories that will be used in this dissertation include the following;

- Categories about paper- databased that article was sourced from, date, search term, reference,
- Categories about experiment – experimental method utilised, results of experiment and controls utilised in experiment
- Categories that on study- authors of study and credability of authors, limitation of study and evaluation of relevance and useful information for dissertation

These categories will be the initial categories that will change throughout the course of the dissertation. The literature for the research questions will be reviewed using the categories that are refined during the literature review process. The information collected during the literature review process will be collaborated into summary tables in the tenth step of the process. This will check that the information collected in the database for any errors while determining what results from the review is important for the dissertation.

The important information from summary tables will be used to draft the results of the dissertation. The results will answer the research questions that were outlined earlier in this section. Answering the research questions will then determine the various design properties required to reduce the distal loosening fulfilling the topic of the dissertation.

6.0 RISK ASSESSMENT

Risk assessment will be carried out on the dissertation using the risk assessment table in Table 4.1. The first risk assessment that was conducted in Table 4.4 will be to discuss potential situations that may arise which could potential delay the completion of the project on time. This will involve analysing every aspect of each step of the project and think of potential problem that may arise and rate the risk and hazard using Table 4.1. This time the risk is not to personal safety but rather the non-completion of the project.This risk assessment will also involve the step of discussing suggestion to mitigate the risk of each potential problem and the revaluation of the mitigated risk

Likelihood	Consequence Rating				
	1. Insignificant	2. Minor	3. Moderate	4. Major	5. Catastrophic
A.. Almost Certain	Low	Medium	High	Extreme	Extreme
B. Likely	Low	Medium	High	Extreme	Extreme
C. Possible	Low	Low	Medium	High	Extreme
D. Unlikely	Low	Low	Medium	High	High
E. Rare	Low	Low	Low	Medium	High

Table 8.10 Risk Assessment Table (C, Gray, 2013)

Consequence	Risk Assessment
Catastrophic	Result in project not being completed and failure of project
Major	Project be substantially affected and questionable if project will be completed. Mark will likely be only just a pass due to problem
Moderate	Project will be set back by several weeks due to *- problem. Project will still likely to be finished but mark will likely to be severely affected by the problem
Minor	Project will be put back by a couple of days but will still be completed
Insignificant	No affect to completion of project

Table 8.11 Possible Consequences Table

Task	Hazard	Risk	Mitigation of Risk	Revised Risk

5A-7B	Final design recommendations are used for design of implants without performance verification testing	4D - High	Start dissertation with clause recommending that work be taken as an academic exercise only	4E – medium
1A – 8B	Information used is not from credible sources resulting in misguiding dissertation for implant company	3C - Medium	Collect information used in dissertation from credible sources	3E - Low
5A-5B	Material selection performed on only a small group of materials thus missing a potential superior material that is commercially available	3C – Medium	Explore all commercially utilised materials that are currently utilised in implants to make sure all materials are explored	3D - Unlikely

Table 8.12 Risk Assessment of Information used in Design of Implant

Task	Hazard	Risk	Mitigation of Risk	Revised Risk
5A-7B	Try to complete sections without a clear plan which results in work being unorganised and taking a lot longer to complete	3B - High	Outline a methodology on how the complete sections 5A – 7B so have clear direction in completing sections	3D - Unlikely
8A	Leave writing up the draft dissertation to the very end rather than completing through the term. Results in large workload at end of dissertation	3C - Medium	Completing drafting up the dissertation through the year	3E - Low
7A-7B	Try to conduct extensive modelling to improve the design of a total wrist arthroplasty. This creates to much workload to complete and then therefore fail to draft up final dissertation	4C - High	Refrain from conducting any modelling and instead collect FEA from relevant studies on the internet	4E - Medium

Table 8.13 Risk Assessment on Completion of Project

7.0 RESOURCE PLANNING

The resource requirements for this project is outlined in table … below. Resources will be sourced through either USQ or through the student own resources.

Task	Item	Amount	Source	Cost
1A – 2B, 3A – 3C	Microsoft Word software	One (1)	Student	free
2C	Computer	One (1)	Student	free
4B	Access to database of journal articles	NCBI and USQ database	Google and USQ	Free
4C	Laptop	One (1)	Student	free

Table 8.14 Resource Planning

8.0 PROGRESS SCHEDULE

The planned project schedule is given in figure 4.2 below and include the following key features

- Project will start on Week 1 of Semester 1 2017 and will end Week 15 of Semester 2 (Project Week 35
- Two milestone reviews will be conducted by the academic supervisor which include; 1) review at week 13 were a decision will be made if a contingence plan needs to be put into place to salvage the assignment, 2) Week 29 where a partial dissertation will be handed to supervisor for feedback
- ENG4903 conference and seminar activities have been included in the schedule
- The dissertation will be planned to be written up throughout the course of the project as information becomes available from research.

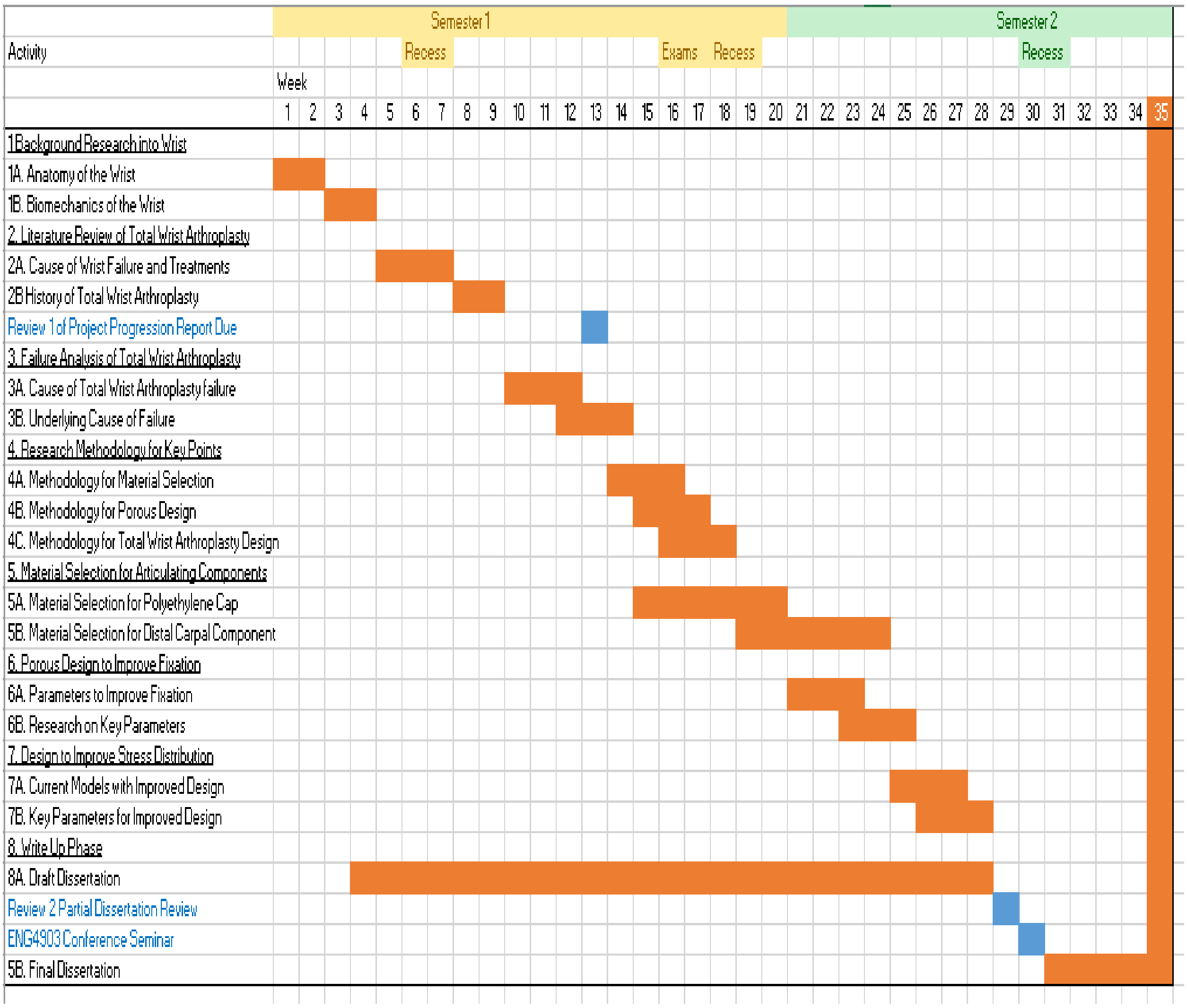


Figure 8.13 Progress schedule

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10.0 APPENDIX

Engineers Australia Code of Ethics

The Engineers Australia have a guideline on the ethical values that every engineer should strive to adhere to in their professional career. These guidelines were obtained from Engineers Australia (n.d) and are outlined below

The Guidelines on Professional Conduct

The Guidelines on Professional Conduct provide a framework for members of Engineers Australia to use when exercising their judgment in the practice of engineering.

The Guidelines are not intended to be, nor should they be interpreted as, a full or exhaustive list of the situations and circumstances which may comprise compliance and non compliance with the Code of Ethics. If called upon to do so, members are expected to justify any departure from both the provisions and spirit of the Code.

Ethical engineering practice requires judgment, interpretation and balanced decision-making in context.

Engineers Australia recognises that, while our ethical values and principles are enduring, standards of acceptable conduct are not permanently fixed. Community standards and the requirements and aspirations of engineering practice will develop and change over time. Within limits, what constitutes acceptable conduct may also depend on the nature of individual circumstances.

Allegations of non-compliance will be evaluated on a case-by-case basis and administered in accordance with Engineers Australia's General Regulations 2013.

1. DEMONSTRATE INTEGRITY

1.1 Act on the basis of a well-informed conscience

a) be discerning and do what you think is right
b) act impartially and objectively
c) act appropriately, and in a professional manner, when you perceive something to be wrong
d) give due weight to all legal, contractual and employment obligations

1.2 Be honest and trustworthy

a) accept, as well as give, honest and fair criticism
b) be prepared to explain your work and reasoning
c) give proper credit to those to whom proper credit is due
d) in managing perceived conflicts of interest, ensure that those conflicts are disclosed to relevant parties
e) respect confidentiality obligations, express or implied
f) do not engage in fraudulent, corrupt, or criminal conduct

1.3 Respect the dignity of all persons

a) treat others with courtesy and without discrimination
or harassment
b) apply knowledge and skills without bias in respect of race, religion, gender, age, sexual orientation, marital or family status, national origin, or mental or physical handicaps

2. PRACTISE COMPETENTLY

2.1 Maintain and develop knowledge and skills

a) continue to develop relevant knowledge and expertise
b) act in a careful and diligent manner
c) seek peer review
d) support the ongoing development of others

2.2 Represent areas of competence objectively

a) practise within areas of competence
b) neither falsify nor misrepresent qualifications, grades of membership, experience or prior responsibilities

2.3 Act on the basis of adequate knowledge

a) practise in accordance with legal and statutory requirements, and with the commonly accepted standards of the day
b) inform employers or clients if a task requires qualifications and experience outside your areas of competence

3. EXERCISE LEADERSHIP

3.1 Uphold the reputation and trustworthiness of the practice of engineering

a) advocate and support the extension of ethical practice
b) engage responsibly in public debate and deliberation 3.2 Support and encourage diversity
a) select, and provide opportunities for, all engineering practitioners on the basis of merit
b) promote diversity in engineering leadership

3.3 Communicate honestly and effectively, taking into account the reliance of others on engineering expertise

a) provide clear and timely communications on issues such as engineering services, costs, outcomes and risks

4. PROMOTE SUSTAINABILITY

4.1 Engage responsibly with the community and other stakeholders

a) be sensitive to public concerns
b) inform employers or clients of the likely consequences of proposed activities on the community and the environment
c) promote the involvement of all stakeholders and the community in decisions and processes that may impact upon them and the environment

4.2 Practise engineering to foster the health, safety and wellbeing of the community and the environment

a) incorporate social, cultural, health, safety, environmental and economic considerations into the engineering task

4.3 Balance the needs of the present with the needs of future generations

a) in identifying sustainable outcomes consider all options in terms of their economic, environmental and social consequences
b) aim to deliver outcomes that do not compromise the ability of future life to enjoy the same or better environment, health, wellbeing and safety as currently enjoyed

Our Code of Ethics

As engineering practitioners, we use our knowledge and skills for the benefit of the community to create engineering solutions for a sustainable future. In doing so, we strive to serve the community ahead of other personal or sectional interests.

Our **Code of Ethics** defines the values and principles that shape the decisions we make in engineering practice.

The related Guidelines on Professional Conduct provide a framework for members of Engineers Australia to use when exercising their judgment in the practice of engineering.

As members of Engineers Australia, we commit to practise in accordance with the Code of Ethics and accept that we will be held accountable for our conduct under Engineers Australia's General Regulations 2013.

In the course of engineering practice we will:

1. DEMONSTRATE INTEGRITY

1.1 Act on the basis of a well-informed conscience
1.2 Be honest and trustworthy
1.3 Respect the dignity of all persons

2. PRACTISE COMPETENTLY

2.1 Maintain and develop knowledge and skills
2.2 Represent areas of competence objectively
2.3 Act on the basis of adequate knowledge

3. EXERCISE LEADERSHIP

3.1 Uphold the reputation and trustworthiness of the practice of engineering
3.2 Support and encourage diversity
3.3 Communicate honestly and effectively, taking into account the reliance of others on engineering expertise

4. PROMOTE SUSTAINABILITY

4.1 Engage responsibly with the community and other stakeholders
4.2 Practise engineering to foster the health, safety and wellbeing of the community and the environment
4.3 Balance the needs of the present with the needs of future generations