CAN THE WRIST BE EXPLAINED?

THE APPLICATION OF COMPUTER BASED QUANTITATIVE ANALYSIS TO EXPLAIN CARPAL BIOMECHANICS AND IDENTIFY THERAPEUTIC SOLUTIONS FOR WRIST DYSFUNCTION

by

Associate Professor Michael John Sandow

BMBS, FRACS, FAOrthA

Thesis

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Flinders UNIVERSITY
ADELAIDE • SOUTH AUSTRALIA

Associate Professor Michael John Sandow

BMBS, FRACS, FAOrthA

Centre for Orthopaedic & Trauma Research

University of Adelaide, Adelaide, South Australia 5000

and

Wakefield Orthopaedic Clinic

120 Angus Street, Adelaide, SA 5000

Australia

msandow@woc.com.au

Supervisor:

Professor Ruurd L. Jaarsma MD, PhD, FRACS, FAOrthA

Consultant Orthopaedic Surgeon

Head of Orthopaedic and Trauma Services SALHN

Professor of Orthopaedics and Trauma Surgery

Flinders Medical Centre

Flinders Drive, Bedford Park, SA 5042

Australia

Flinders UNIVERSITY
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A general thank you is extended to my many medical colleagues (locally, nationally, and internationally), who politely smiled and developed a glazed affect as I tried to explain my concepts of carpal mechanics - but were always supportive and encouraging. Their trust and loyalty are much appreciated. In particular I wish to highlight the Department of Orthopaedics and Trauma at the Royal Adelaide Hospital, which created (prior to 2016) an environment conducive to research and academic pursuits, led by Professor Don Howie and Professor David Findlay. Professor Findlay has been a persistent encourager and enabler in my studies and investigations on the wrist, and regularly pressed me to carry this work through to a PhD.

All this work within an Orthopaedic Surgeon clinical practice would not have been possible without strong support and tolerance from my clinical administrative team, including Julie Kinter, Michelle Butler and Pauline Chilman and research associates Kirri Riley and Christine Schutz.

I wish to express my gratitude to my supervisor Professor Rudi Jaarsma for his support and guidance in completing the thesis. While it is evident that much of the work was complete before he became involved, his support was critical to align this dissertation with the style and content to comply with the very exacting requirements of a PhD by Prior Publication.

I am also indebted to the Office of Graduate Studies at Flinders University, and in particular the Dean, Professor Tara Brabazon, who made my re-enrolment and return to my alma mater as a Research Higher Degree candidate, a most enjoyable and trouble-free exercise, as well as subsequently awarding me a Research Training Program fee offset, in the form of an Australian Government Research Training Program Scholarship.

I would also like to thank Professor Randall Morton for some sagely advice on thesis style and organisation of content.

Most of all I would like to thank my wife Correne for her love and strong support through this journey, which in reality is only just beginning as this technology opens a whole new approach to understanding and analysing motion systems.

Declarations

The work contained in this thesis represents the original work by Dr Sandow. None of the material has been submitted for any other higher degree. I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Conflict of interest

Michael Sandow acknowledges a commercial interest in the development of the software used in large part to support this research. He was also the co-author and inventor of the subjects of the filed patents and is a shareholder on True Life Anatomy Pty Ltd. No money was received to support this project, although access to the software was made freely available by the company. The company had no direct control over the research performed nor its application.

Terms of Use

Abstract

The wrist remains a challenge with respect to the mechanical controls and biomechanics and has confounded researchers over many years. No standard wrist exists and current attempts to characterise wrist motion or biomechanics have been unsuccessful. The work undertaken as part of this research is part of a larger project to develop a kinetic model of carpal motion and is an extension of Taleisnik's concept of carpal columns and rows (Taleisnik 1976). It expands this basic notion to incorporate the Rules Based Motion concept, which states that a motion system, and in particular the wrist, can be defined and controlled by its 4 basic rules or factors, viz: morphology, constraint, interaction and load.

Rather than utilising the standard empirical study design, this project used a conceptual research strategy to make a limited number of observations on the mechanics of the wrist, and then propose a theory of how the wrist may work. An important early observation was the apparent isometric connection between various regions in the carpus, which underpins the proposed theory of the Stable Central Column of Carpal mechanics.

This theory defines a stable central column and this has been applied to address the pathological disruptions within the carpus. Past repairs have been largely unsuccessful in predictably restoring mechanics of the wrist. The paper published by Drs Sandow and Fisher (Anatomical Volar and Dorsal Reconstruction (ANAFAB) for Scapho-lunate dissociation in Journal of Hand Surgery (European) (Sandow and Fisher 2019)) represents the culmination of over 20 years work to create a process of reverse engineering, using quantitative 3D analysis, to better characterise the normal wrist biomechanics and then extrapolate this to the delivery of a successful reconstructive solution to address wrist dysfunction.

The journey to identify the critical biomechanical restraints of the wrist, by using a reverse engineering technology and then identifying a means of restoring them to the pathologically injured wrist, would appear to have achieved its goal, at least in one part of the wrist. In the case of scapho-lunate diastasis and collapse of the central column, applying a logic based reconstructive volar and dorsal surgical solution (ANAFAB - Sandow and Fisher 2019), carpal function has been successfully restored in the majority of this group of patients, and constitutes at the very least a proof of concept.

The application of computer based quantitative analysis appear to be able to characterise carpal biomechanics and identify therapeutic solutions for wrist dysfunction – and to this extent, explain the wrist.

Contents

List of Figures

(Excluding figures in chapters 1-7)

Reference citations:

References are cited as lead author and year of publication, and are included in the bibliography from page 191 to 194, apart from those citations in chapters 1 to 7 where they are cited in the style of the actual prior publications and are not included in the main bibliography.

List of Abbreviations

(Does not include journal names, academic degrees and place names)

3D	– Three dimensional
AAOS	– American Academy of Orthopaedic Surgeons
AOA	– Australian Orthopaedic Association
AHSS	– Australian Hand Surgery Society
ASM	– Annual Scientific Meeting
ASSH	– American Society for Surgery of the Hand
CID	– Carpal instability dissociated
CIND	– Carpal instability non-dissociated
COMET	– Commercialising Emerging Technologies grant
CT	– Computed Axial Tomography
DCSS	– Dorsal capsulo-scapholunate septum
DIC	– Dorsal intercarpal ligament
DIC-L	– Dorsal intercarpal ligament-lunate connection
DICOM	– Digital Imaging and Communications in Medicine
DISI	– Dorsal intercalated segmental instability
IT	– Information technology
MRI	– Magnetic resonance Imaging
q.v.	– (" quad vide") translates literally as "which see," indicating "for which, see elsewhere."
RACS	– Royal Australasian College of Surgeons
RBM	– Rules Based Motion.
RD	– Radial deviation
SCCT	– Stable Central Column Theory of Carpal mechanics
UD	– Ulnar deviation
VISI	– Volar intercalated segmental instability

Glossary

(The definitions of the various terms are drawn from a wide range of sources and many remain controversial)

ANAFAB

Published surgical technique to address scapho-lunate dissociation utilising an anatomical front and back wrist reconstruction

Animation Technology

This is a process that creates motion of the digitally created 3D models within a graphics environment. Once the pathways of the 3D object are defined, the motion sequence is rendered and exported as a video with the transitions between key frames "smoothed" using tweening or morphing. This is distinct from stop motion techniques such as step frame animation where the apparent motion is created by frame -by-frame animation of 2D illustrations.

Concept

Concept is a widely-used term synonymous with "Idea." Typically, the context of a concept has had time to be more organized than an idea. Concepts can be broad or specific, experiential or imaginary, abstract, detailed or explicit.

Conceptual Research

Conceptual research focuses on using limited observational data to develop the concept or theory that explains or describes the phenomenon being studied. Hypotheses are then proposed that can be tested to refute, enrich or validate the described theory on the basis of the outcome or results predicted by the proposed theory.

Empirical

Based on, concerned with, or verifiable by observation or experience rather than theory or pure logic.

Empirical research

Empirical research is based on observed and measured phenomena and derives knowledge from actual repeated measurements rather than from initially proposing a theory and then undertaking observations to specifically test hypotheses.

Proof of Concept

A realization of a certain method or idea in order to demonstrate its feasibility, or a demonstration in principle with the aim of verifying that some concept or theory has practical potential. A proof of concept is usually small and may or may not be complete. The concept is further developed over time from a simple proof stage to a more formalised theory and ultimately to a law or other validated explanation.

Rule(s)

A defined phenomenon that comprise the parts of a larger system. In the case of the wrist, the rules are 1. the bone morphology, 2. the constraints between the bones, 3. the interaction or friction between the various bones, and 4. the load applied by the various tendon, external or gravitational forces.

Rules Based Motion (RBM)

The interplay of various rules that may each individually vary, but the product of all the rules create a consistent or generic outcome. RBM can be used to create one of three basic forms of animation, viz. **freeform animation** (where the 3D artist creates a 3D motion sequence, independent of an existing system, phenomena or example), **simulation animation** (where the 3D artist attempts to replicate a new 3D motion sequence, based on an existing or known phenomena, such as overlaying a dinosaur image over a stick frame animation of an elephant) and **RBM animation** (where the resultant motion is due to the rigid body interaction of the various system components acted on and upon the various other rules or phenomena within the defined 3D environment). The resultant motion is the product of the interaction of the rules in that defined environment. Each of the rules can vary, but a compensatory variation must occur in the other rules to achieve the required net generic or specific outcome. In a virtual surgical environment, by deliberately varying one of the rules a “what if” scenario could be created to test (for example) various surgical interventions on an individual wrist, with its own specific Rules.

Scientific Law

Scientific laws or laws of science are statements, based on repeated experiments or observations, that describe or predict a range of natural phenomena. The term law has diverse usage in many cases across all fields of natural science.

Stable Central Column Theory of Carpal mechanics

Theory to explain the phenomenon of the stable, yet mobile wrist that is able to achieve a wide range of functional task. The SCCT is based on a combination of RBM and the application of quantitively based 3D analysis.

Surface (mesh) rendered

A three-dimensional object on a computer, generally based on thresholding of the interface between different materials or tissues of the scanned object, comprising a surface mesh made up of nodes, vertices and polygons.

Theory

A clarification or description in an attempt to explain a system or process. A good theory must provide a description of a mechanical system based on a limited number of observations, must be testable, cannot be proven and most importantly be predictive.

Two Gear Four Bar linkage

This is a complex mechanical linkage that attempts to reconcile the situation where one of the bars in a four bar linkage changes in length. This is achieved by one of the bars containing a gear or hinge that can change the separation of the ends of the respective bar. (q.v. Chapter 4, and ref: Zhenying 2011)

Volume rendered

Construction or creation of an apparent 3D image using ray casting. More like a projected shadow of the scanned object, and not an actual 3D object. Presented not as a 3D object, but as projected and captured 2D screen views.

“What if”

This refers to the option to apply some sort of variation of a mathematical algorithm or Rule modification to assess the outcome of such a change. This is a process to trial operations on a mathematical model of a motion system, and to try out various operative interventions on a virtual model of the actual patient injury.

Contextual Statement / Background

Research Statement

The wrist is a complicated structure and a consistent explanation for how it works and reliable means to address dysfunction has been elusive. In large part the research approach to the wrist has been through empirical observation. This involves the extensive measuring of both static and dynamic aspects of the wrist and then attempting to identify patterns, from which a theory of function can be developed. This has been problematic as there is no standard or normal wrist, and even basic relationships between components of the wrist can vary between individuals.

The approach in this project however, which is part of a larger study to define a kinetic model of the wrist, is to use a conceptual approach to theory development, and then apply hypotheses and testing to refine, enrich or reject the proposed theory.

This is a fundamentally different approach to existing research, which is heavily based on cadaveric analysis. The approach of reverse engineering the dynamic system, then the development of a Rules Based Motion concept to allow forward engineering re-animation, and even "What if" analysis, has not been used previously - and this claim is supported by the successful filing of patents on the subject.

The requirement to find more effective solutions was created by the inability to offer patients reliable solutions to their wrist dysfunction and while many proposed reconstructive procedures were available, none was able to provide consistent functional restoration.

The need for an alternate approach was inspired by the inability to characterise wrist function and apply reliable solutions, as well as an inability of recognised specialists in the field to present cogent and consistent arguments to explain wrist form and dysfunction.

The pre-planned research journey covered in this thesis was therefore to define carpal biomechanics using 3D (three dimensional) analysis software, identify deficits that may lead to wrist dysfunction and identify solutions to address such dysfunction. This was to be achieved using a conceptual theory development process rather than the typical empirical approach.

Medical Background

Assoc. Professor Michael Sandow BMBS, FRACS, FAOrthA

I am an Orthopaedic Hand and Upper Limb surgeon, and did my basic medical degree at Flinders University, graduating in 1980. I did my basic and advanced surgical training in Adelaide and received my fellowship of the RACS (Royal Australasian College of Surgeons) in 1988. I then completed a post training orthopaedic fellowship at Duke University, North Carolina in Hand and Microsurgery.

I am currently a Clinical Associate Professor in the University of Adelaide and in Private Orthopaedic practice at Wakefield Orthopaedic Clinic.

I have been a member of the Shoulder and Elbow Society of Australia since 1991, and am a past President. I have been an Associate Editor of the Journal of Shoulder and Elbow Surgery since 2000, and have been a member of the American Shoulder and Elbow surgeons since 2006. I was previously State Chairman of South Australian Branch of the AOA (Australian Orthopaedic Association) and a member of the AOA Board, as well as on the Board of Australian Society of Orthopaedic Surgeons and AHSS (Australian Hand Surgery Society) (and currently President).

I have published numerous articles on hand and upper limb disorders and continue an active research program, with a number of new devices and techniques under development and undergoing clinical review. Particular projects are in wrist biomechanics and reconstruction, porous metal arthroplasty wedges, a new type of rotator cuff anchor for osteoporotic bone, and an integrated 3D templating and virtual surgery system.

Publications and IP held included in Appendix 1.

Publication Metrics: (as at 29th December 2019)

- RG index – 26.16
- h-number – 16
- Citations (ResearchGate) – 1,182

Prior Publications to be included as part of the Thesis

Contribution Declaration

For all studies included in this thesis I:

- singly conceived the studies and then sought support from specialists in the area of patent filing, grant writing, project management or animation technology.
- was centrally involved in the conception, funding and functionality defining of the 3D animation software (True Life Anatomy).
- personally, developed and wrote the submissions for all Ethics committee applications.
- conducted and performed all treatments on patients included in the clinical studies.
- coordinated and supervised the clinical databases used in the clinical studies.
- wrote the initial manuscript drafts for all papers.
- led the editing of all manuscripts prior to submission for publication, and oversaw the publication process as senior and corresponding author.

For most of the work, I either published alone, or engaged one or two colleagues to assist with the specialist aspects such as animation technology or Mechanical Engineering, or to engage a junior colleague to assist in analyzing the data.

The concepts, drive and clinical focus was virtually entirely by me, and the entire project was self-funded, either directly, or as part of a matching funding arrangement with various Government support grants.

The core technology software (True life Anatomy) that has facilitated the analysis and 3D representations is owned by a private company (True Life Anatomy Pty Ltd) and I am the Sole Director and majority shareholder and more importantly the major debtor.

Peer Reviewed Publications

1. Australian patent - 2001237138 Animation technology -
   Applicant: Macropace Products Pty Ltd; True Life Creations (SA) Pty Ltd
   Inventors: Papas, Sam; Sandow, Michael John
   Priority date: AUPQ6001A – 03-3-2000
   Patent granted: 05-03-2001
   https://patents.google.com/patent/AU3713801A/en (accessed 19th September 2019)

2. United States Patent 7,236,817-B2 Granted: 26th June 2007
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Invited Presentations

1. Sandow MJ, Fisher TJ. Proximal Carpal Row Controls Midcarpal Alignment and Motion – The Offset Unitary Motion of the Rows Creates a Stable Carpus. Journal of Wrist Surgery. 2015; 04 - A021 DOI: 10.1055/s-0035-1545659
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5. Sandow MJ. Why I do it this way and how I do it with technique video - ANAFAB Reconstruction. American Society for Surgery of the Hand,
PRE-COURSE 05: Carpal Instability
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6. Sandow MJ. Does the Stable Central Column Theory offer anything useful? It explains how the wrist works!! Instructional Course: IC11: The 2019 Linscheid-Dobyns Instructional Course Lecture: The Critical Stabilizers of the Intercalated Segment. The stable central column and the critical ligamentous stabilizers.
http://assh.force.com/annualmeeting/servlet/servlet.FileDownload?file=00P0a00000mMoDLEA0
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Citations of Prior Publications to be included in this thesis

(as per Google Scholar)

Animation Technology Patents (q.v. Chapter 1)

S Papas, MJ Sandow Animation technology- US Patent 7,236,817, 2007 - Google Patents

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1. X Bi, J McLaughlin, J Weikel… Method and system for analyzing bone conditions using DICOM compliant bone radiographic image - US Patent App. 10 …, 2005 - Google Patents
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This study was part of a larger project to develop a (kinetic) theory of carpal motion based on computationally derived isometric constraints. Three-dimensional models were created from computed tomography scans of the wrists of ten normal subjects and carpal spatial …

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    A virtual biofeedback system is provided. The virtual biofeedback system provides visualization animation related to parts of the human body subject to one or more predetermined conditions, wherein the visualization animations are adapted to assist an …

Stable Central column paper (q.v. Chapter 2)

MJ Sandow, TJ Fisher, CQ Howard ,S Papas… - Unifying model of carpal mechanics based on computationally derived isometric constraints and rules-based motion–the stable central column theory Journal of Hand surgery (European) 2014 - journals.sagepub.com

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5. HP Gould, RA Berger, SW Wolfe The origin and meaning of "intercalated segment" Journal of Hand Surgery, 2015 - jhandsurg.org
THE TERM AND CONCEPT "INTERCALATED segment" appears widely in the medical literature. In the context of wrist mechanics, this concept emphasizes how little direct control is exerted over the proximal carpal row. Rather, the motion of these bones is governed by a …

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Knowledge gained from the scientific literature over the past decade has allowed for a better understanding of individual carpal bone motions in 3-dimensional (3D) space, 1-7 load dynamics through the wrist, 8-10 relative motion within the different joint spaces in the wrist …

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Computer-generated 3D modeling, prototyping, and custom jig fabrication have gained popularity in a short space of time in hand and wrist surgery. Currently used applications include custom jig fabrication for the correction of malunion and other deformities …

8. M Sandow - The why, what, how and where of 3D imaging 2014 - journals.sagepub.com
The 'WHAT' is a more difficult problem, and is at the core of the confusion over 3D imaging. There are essentially two distinct forms of 3D imaging or more specifically 3D

data presentation. These are Volume Rendering (VR) and Surface Rendering (SR). The image …

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Introduction The standard therapy of intra-articular and extra-articular distal radius fractures consists of open reduction and stabilization using palmar osteosynthesis with an angularly stable plate. The integrity of the flexor pollicis longus tendon (FPLT) may be mechanically …

12. M Sandow, T Fisher Anatomical anterior and posterior reconstruction for scapholunate dissociation: preliminary outcome in ten patients - Journal of Hand Surgery (European …, 2019 - journals.sagepub.com
This study reviews the efficacy of a reconstruction to address scapholunate dissociation using an anterior and posterior approach with a hybrid synthetic tape/tendon weave between the trapezium, scaphoid, lunate and radius: an anatomical front and back …

13. EQ Pang, N Douglass, A Behn, M Winterton… Tensile and Torsional Structural Properties of the Native Scapholunate Ligament - The Journal of hand …, 2018 - Elsevier
Purpose The ideal material for reconstruction of the scapholunate interosseous ligament (SLIL) should replicate the mechanical properties of the native SLIL to recreate normal kinematics and prevent posttraumatic arthritis. The purpose of our study was to evaluate the …

14. AJ Pérez, RG Jethanandani, ES Vutescu, KN Meyers… - Role of Ligament Stabilizers of the Proximal Carpal Row in Preventing Dorsal Intercalated Segment Instability: A Cadaveric Study JBJS, 2019 - journals.lww.com
Background: Isolated injuries of the scapholunate interosseous ligament (SLIL) are insufficient to produce dorsal intercalated segment instability. There is no consensus about which additional ligamentous stabilizers are critical determinants of dorsal intercalated …

15. PA Rust, LM Manojlovich… A comparison of dart thrower's range of motion following radioscapholunate fusion, four-corner fusion and proximal row carpectomy - Journal of Hand Surgery …, 2018 - journals.sagepub.com
Dart thrower's motion is the functional coupled movement of the wrist from radial extension to ulnar flexion. The aim of this study was to evaluate dart thrower's motion following three surgeries: radioscapholunate fusion, four-corner fusion and proximal row carpectomy. Six …

16. BH Foster, CB Shaw, RD Boutin, AA Joshi… A principal component analysis-based framework for statistical modeling of bone displacement during wrist maneuvers- Journal of …, 2019 - Elsevier
We present a method for the statistical modeling of the displacements of wrist bones during the performance of coordinated maneuvers, such as radial-ulnar deviation (RUD). In our approach, we decompose bone displacement via a set of basic functions, identified via …

17. B Akhbari, DC Moore, DH Laidlaw… - Predicting Carpal Bone Kinematics Using an Expanded Digital Database of Wrist Carpal Bone Anatomy and Kinematics Journal of …, 2019 - Wiley Online Library
The wrist can be considered a 2 degrees-of-freedom joint with all movements reflecting the combination of flexion–extension and radial–ulnar deviation. Wrist motions are accomplished by the kinematic reduction of the 42 degrees-of-freedom of the individual …

The why, what, how and where of 3D imaging (q.v. Chapter 3)

M Sandow - 2014The why, what, how and where of 3D imaging - journals.sagepub.com

Citations (2)

1. SG Xing, YR Chen, RG Xie, JB Tang In vivo contact characteristics of distal radioulnar joint with malunited distal radius during wrist motion- The Journal of hand surgery, 2015 - Elsevier
   Purpose To determine whether distal radioulnar joint (DRUJ) contact characteristics were altered in patients with malunited distal radius fractures. Methods We obtained computed tomography scans at 5 positions of both wrists of 6 patients who had unilateral malunited …

2. J Chen, J Tan, JB Tang Length changes of scapholunate interosseous ligament at different wrist positions: an in vivo 3-dimension image study- Surgical and Radiologic Anatomy, 2015 - Springer
   Purpose The scapholunate interossous ligament (SLIL) has a critical role in maintaining the proper kinematic relationship between the scaphoid and the lunate. We hypothesize that the length of SLIL changes significantly at wrist full extension and during forearm rotation. The …

3D dynamic analysis of the wrist (q.v. Chapter 4)

MJ Sandow 3D dynamic analysis of the wrist - Hand Surgery, 2015 - World Scientific

Citations (1)

1. [A Wolff PDF] Clinical relevance commentary in response to: Force transmission through the wrist during performance of push-ups on a hyperextended and a neutral wrist Journal of Hand Therapy, 2018 - researchgate.net
   Patients recovering from wrist injury commonly express the desire to return to activities that require loading the wrist in extension, such as push-ups, planks, and various yoga and pilates positions. 1-3 These activities are fundamental to many fitness programs and have …

Computer modelling of Wrist Biomechanics (q.v. Chapter 5)

MJ Sandow - Computer Modelling Of Wrist Biomechanics-Translation Into Specific Tasks. Current rheumatology reviews, 2019 - europepmc.org

No Citations – Recently Published

Anatomical anterior and posterior reconstruction for scapholunate dissociation: preliminary outcome in ten patients (ANAFAB) (q.v. Chapter 6)

M Sandow, T Fisher -Anatomical anterior and posterior reconstruction for scapholunate dissociation: preliminary outcome in ten patients Journal of Hand Surgery (European …, 2019 - journals.sagepub.com

No Citations – Currently in Print

Translational Impact and Commentary

In 2016, Rainbow and colleagues (Rainbow et al 2016) published a detailed overview entitled “Functional kinematics of the wrist” of carpal mechanics and I was asked to review the initial submission. This had been an invited review article and my comments on the initial submission are presented in the Introduction section (q.v. Preamble, Introduction). My review recommended reject and re-submit.

In their revision they substantially improved the paper, largely in line with my suggestion, but more importantly included our work on the Stable central Column theory of Carpal Mechanics published in 2014 (Sandow et al 2014).

They reviewed existing theories and descriptions of carpal mechanics, and with respect to our work, these were the comments included in the summary table. Italic have been added to emphasize that this is a direct copy of the published text.

> *“Supporting Evidence:*
>
> *As yet, no subsequent investigations have examined this theory, likely due to its recent publication and novel computational methods.*
>
> *Strengths*
>
> *Sandow’s theory is derived directly from 3D computer generated models; by definition, it is therefore more organic than most other theories, which are first proposed subjectively and later supported with objective data.*
>
> *Weaknesses*
>
> *Sandow’s study found no isometric constraint between hamate and triquetrum; this conclusion fails to reconcile with the established work of others (originally Weber, and later Kamal). The two-gear four bar linkage model has not been tested for all wrist motions.” (Rainbow et al 2015)*

In the discussion, they further referred to our work, and in particular the potential benefits of computational modelling.

> *“Computational modelling is a promising approach that can overcome this limitation by estimating these forces, but most studies to date have focused on model validation with low subject numbers……….*

An additional limitation of computational models is that model assumptions, tuning of parameters, model validation, and hypothesis testing are challenging to separate.

For example, if the ligaments are assigned hyper-elastic properties, and the model is tuned to these properties, one may be tempted to conclude that the wrist ligaments are hyper-elastic. However, if these limitations can be overcome, computational models may have the potential to better elucidate the carpal mechanism.

Sandow and colleagues have made the most recent progress in this area. The authors created a data-driven computational model of carpal kinematics (Sandow et al., 2014) using ten cadaveric wrists positioned in three positions (neutral, 30° radial deviation, and 30° ulnar deviation). Ligaments were defined by finding origin and insertion sites that minimized the change in length of the ligament across the measured range of motion. In vivo evidence for the validity of isometric ligaments was recently supplied by Rainbow and colleagues, who found that selected capsular ligaments elongate minimally relative to their maximum length as the wrist moved through a large range of motion (Rainbow et al., 2015).

Based on their results, Sandow et al. (2014) proposed that the carpus functions as a stable central column formed by the lunate and the distal row, and argued that the carpus can be conceptualized as a two-gear, four-bar linkage. While an exciting and innovative approach, the concept of a central loadbearing column based on the radiolunate articulation is difficult to fully reconcile with other kinetic studies that demonstrate up to 60% of wrist load during power grip is transmitted through the radioscaphoid articulation (Ulrich et al., 1999). Further, this model will need to be validated through a complete range of wrist motion.

In summary, while the preliminary results of Sandow et al. (2014) may be premature for determining a unifying theory of carpal kinematics, their novel approach to reconstruct ligament courses using an isometric lengthening assumption is important and may lead to tremendous insight into the subtle nuances of carpal mechanics. At this time, a unifying theory of carpal kinematics is still elusive, given the wide variability in wrist ligament laxity, anatomic variability, and bone morphology. Inter-subject differences due to laxity, morphology, and functional activities may be the largest contributing factor to the development of chronic wrist instability. This question will likely remain unanswered until functional carpal and wrist kinematics and kinetics are simultaneously acquired over the full spectrum of wrist motion and functional tasks in a large cohort of patients and controls.” (Rainbow et al 2016)

Based on the improved understanding of carpal mechanics and identification of key elements in the longitudinal stability of the central column, a reconstruction was developed.

The critical stabilising elements were identified as:

1. Scapho-trapezial ligaments
2. Dorsal scapho-lunate ligament and
3. Volar long radiolunate ligament.

This is covered in more details in the introduction, but these structures were key components of the stabilising element as proposed in the initial patents (q.v. Chapter 1).

Using a range of existing reconstructions, a volar and dorsal approach was developed to closely restore the identified critical stabilising elements. This is covered in the ANAFAB (Anatomical Front and Back repair) paper (q.v. Chapter 6).

The work was presented on numerous occasions both nationally and internationally and based on positive feedback, the preliminary results were collated into a paper and submitted to the Journal of Wrist Surgery - and rejected.

Following review of longer-term outcomes, and in response to comment from the reviewers, the paper was submitted to the Journal of Hand Surgery (American), and again rejected.

These are some of the reviewer's comments:

> *" - 1) The Stable Central Column Theory (SCCT), advanced by Sandow et al: (JHSE: 2014) is a relatively new theory of carpal kinematics and has not been widely accepted as true or valid, though it does add to our understanding of the field. Rainbow et al (JHSE: 2016) in their extensive review of various theories of carpal kinematics notes that Sandow's theory "...fails to reconcile with the established work of others (originally Weber and later Kamal). The four-gear linkage model has not been tested in all wrist positions." The technique proposed in this paper is a non-anatomic tenodesis of the scaphoid and lunate that does not recreate the anatomy of the scapholunate or other ligaments any more than the host of other SL reconstructions do. I would delete all references to the SCCT as justifying this reconstruction which is similar to many other reconstructions of the SL. This may in fact turn out to be a more successful method of tenodesis, but from my reading of the paper and the literature of carpal kinematics, it is not backed up by 'science' any more than the others. To state in this paper that all other pre-existing surgical reconstructions are not based upon 'science' is incorrect. While the authors may have faith in the SCCT as the be all and end all of carpal kinematics, that belief is not universal." Reviewer comment, Journal of Hand Surgery (American).*

The ANAFAB repair is based largely on the concept of restoring the stable central column, and so deleting any reference to the Stable Central Column Theory was not tenable, and so withdrawal of the paper was an easy decision.

What was also of significant note is that the reviewers stated that the ANAFAB is similar to many other reconstructions of the scapho-lunate ligament. This supported the suggestion that the ANAFAB was "simply" a compilation of existing reconstruction techniques, but the exact form and combination was re-configured, based on the SCCT.

Longer term review was performed, and the paper re-written to address comments of previous reviewers. The work has now been successfully submitted and published in the Journal of Hand Surgery (European) (Sandow and Fisher 2019, q.v. Chapter 6).

The discussion of the resubmitted, and now in print, paper addresses the issue that the SCCT has not been independently substantiated and that this does not justify dismissing the concept.

> *"There are many alternate reconstructive procedures suggested to address scapholunate dissociation. While the SCCT has not been widely adopted as an accepted explanation of carpal mechanics, this concept was the basis of the ANAFAB reconstruction and the impetus to create a repair construct by combining selected components of existing repairs. An important reason for the SCCT not being widely accepted as true and valid is that it fails to reconcile with the established works of others (Kamal et al., 2016; Rainbow et al., 2015). Given the accepted position that a reliable repair option for scapholunate instability has been elusive (Garcia-Elias, 2013; Sammer and Shin, 2012), an alternative approach such as the one embodied in the SCCT, may have credibility as a potential new solution (Rainbow et al., 2016).*
>
> *The theoretical basis of the ANAFAB repair challenges a number of currently used reconstructive procedures; however, at the very least, this study demonstrated the non-inferiority of the ANAFAB technique compared to alternative approaches." (Sandow and Fisher 2019)*

As an indication of the contemporary interest in the current research, prior to publication of the ANAFAB paper, and on the basis of previous conference presentations and discussion, the ANAFAB and SCCT was the subject of 4 invited presentations at the 2019 American Society of Surgery of the Hand Annual Scientific meeting in Las Vegas, September 2nd-4th 2019.

35th IWIW, International Wrist Investigators Workshop Annual Meeting,

Las Vegas NV, Wednesday September 4th, 2019, 7:50am- 4:50pm

8am: Sandow M, Stable Central Column Theory of Carpal

PRECOURSE 05: Carpal Instability (AM19)

September 05, 2019

From: 1:00 PM To: 5:00 PM

This pre-course will be a whirlwind tour of carpal instability by international surgeon thought-leaders. We will thoroughly discuss the latest ideas and data on biomechanics, classification, treatment and outcomes.

3:10 PM - 3:20 PM: Michael J. Sandow, BMBS, FRACS, FAOrthA

Why I do it this way and how I do it with technique video- ANAFAB Reconstruction

The Linscheid-Dobyns "Excellence in Wrist Research" Award

The 2019 Linscheid-Dobyns Instructional Course Lecture:

The Critical Stabilizers of the Intercalated Segment

Perez:	What Causes DISI? A Cadaveric Study
Sandow:	The stable central column and its ligamentous stabilizers
Wolfe:	A ligament-based classification of dissociative instability
Ross:	Traumatic non-dissociative instability of the proximal row
Van Schoonhoven:	Management of peri-lunate and complex carpal instabilities
Garcia-Elias:	An anatomically based surgical approach to DISI

POSTCOURSE 04: Controversies in Hand Surgery

Saturday September 7th 2019, 1:30-4:30 PM

Sandow M – Management of Scapho-lunate instability – ANAFAB

Recent translational activity:

388 Congrès annuel de la Société fran¸caise de chirurgie de la main / Hand Surgery and Rehabilitation 37 (2018) 382–459

M Burnier, R Jethanandani, A Perez, S Lee… Comparaison biomécanique de 3 méthodes de reconstruction du ligament scapholunaire - Hand surgery and …, 2018 - Elsevier

… L'objectif de cette étude était de comparer les résultats biomécaniques de la technique modifiée Brunelli (MBT), de la reconstruction « Anatomic Front and Back » (ANAFAB) et de la Réduction et association du scaphoïde et du lunatum (RASL) …

(English translation – this study showed that the ANAFAB was beter able to correct the scapho-lunate dissociation, compared to two currently used techniques)

Surgeons who have advised that are using the ANAFAB repair:

- Scott Wolfe, Hospital for Special Surgery, New York – 13 cases
- Andrew Thomas, St Paul MN, USA - 2 cases
- Libby Anderson, Brisbane, Aust – 2 cases
- Steve Moran, Mayo Clinic MN, USA – has informally indicated he has done several, and stated “I love your technique”

Awards and prizes based on the True Life Anatomy software and Wrist Research

Consensus Software Award

Winner 2003

Secrets of Australian IT Innovation - eHealth

Second prize – November 2004 (True Life Anatomy)

American Hand Surgery Society

2003 - 3D Carpal Imaging & Animation Scientific Exhibit:
Best Scientific Content (1st Prize)

American Hand Surgery Society representative to AAOS Feb 2004

3D Carpal Imaging & Animation

Australian Hand Surgery Society:

Best Paper of Annual Meeting, March 1999
Best Paper of Annual Meeting, March 2000
Best Paper of Annual Meeting, March 2017

Australian Health industry Award:

Best technology and honourable mention 2003

Australian Orthopaedic Association ASM,

Evelyn Hamilton Prize, Best Paper of ASM Meeting, September 1993
Evelyn Hamilton Prize, Best Paper of ASM Meeting, September 2008

Australian Hand Surgery Society (SA Branch Annual General Meeting)

2001 - Keith Dodridge Prize for Best Paper: “3D Carpal Animation”.
2008 - Keith Dodridge Prize for Best Paper: “Osteotomy 5th CMC joint””.

Summary of originality and contribution to knowledge

By adopting an outcome driven conceptual based experimental approach, many of the barriers to understanding carpal mechanics and treatment of wrist disorders can be resolved. While longer term outcome research and wider experience is required, this work represents a significant step forward in wrist disorder management.

The concept of the Stable Central Column Theory of carpal mechanics represents a novel approach; it challenges existing explanations of how the wrist works and how to address a dysfunctional wrist. The concept has not been universally accepted by researchers and groups working in the same area of interest, the issue being that it is a radical shift from traditional practice, and thereby considered to not be consistent with current accepted approaches.

Virtually all previous research on the wrist has involved empirical observation, using in-vivo volumetric examination (CT and MRI scans) of normal and abnormal wrists, or ex-vivo imaging or dissection studies on cadavers. The result has been a confusing array of variable data that has defied the characterization of consistent patterns.

The wrist research arena is a competitive environment with significant reputational, commercial and vocational pressures and implications. The investment in various laboratory facilities has been significant, with training courses, fellowship funding, commercial support and academic positions and employment commitments dependent on the acceptance of a particular espoused biomechanical explanation.

Challenging the basic tenets of such pioneers as Drs Linscheid and Dobyns (Linscheid et al 1972) and their research associates such as Mark Garcia -Elias (Garcia-Elias 2013) and more recently Sanj Kakar (Kakar et al 2018) would not be well received. The focus in the wrist research world has therefore been to concentrate on the diastasis between the scaphoid and lunate without specifically regarding this motion segment as only a component of a broader, and more complex wrist mechanism.

Further, the more recent popularity of delivering reconstruction solutions using arthroscopic techniques has spawned a range of techniques promoted by prominent international hand surgeons (Corella et al 2017, Ho et al 2015, Mathoulin 2017). Again, the focus has been on repairing the scapho-lunate diastasis - an example of technology driving technique.

The work presented here may be considered an extension of Taleisnik's original central column concept (Taleisnik 1976). However, Taleisnik's work is based on a purely anatomical descriptive approach, rather than our concept of a functionally stable central column.

Thus, there is a degree of notional consistency between such existing explanations of carpal mechanics and our recent research and findings. Nevertheless, the approach of using a conceptually based reverse engineering analysis as a way to understand the wrist is unique, and challenges the existing ethos.

The significant original contribution to knowledge presented in this thesis is the approach of conceptually based research on the wrist and the development of the concept of Rules Based motion. The idea of Rules Based Motion is new and unique, and such a claim is supported by the successful filing of US patents. This has been extended to help explain the variable findings of existing empirical studies of the wrist and ultimately has led to the proposition of the Stable Central Column Theory of Carpal mechanics.

This work has been enabled by the development of 3D animation software by True Life Anatomy. This software was designed specifically for this project and appears to be the most powerful and intuitive clinician-enabled 3-D imaging platform available. The capability to measure isometric connections between various anatomical structures appears unmatched by any other available programming option, and it is the only one that is able to export a true 3-D mesh object into a DICOM (Digital Imaging and Communication in Medicine) compliant network. This software technology alone constitutes a unique and powerful contribution to the imaging and understanding of musculoskeletal disease. The ability to perform virtual reduction of fractures and disrupted joints allows for pre-surgical planning that facilitates surgical diagnosis, plus reduction and fixation strategy.

The ultimate outcome target of this project when it commenced in 1998 was to find a solution to carpal instability and in particular scapho-lunate dissociation. This remains the holy grail of wrist surgery. The publication of the successful results from ANAFAB surgical reconstruction completes the journey.

This approach (the ANAFAB) can be considered a compilation of a range of existing approaches and viewed as adaptive rather than disruptive to traditional approaches. The reality is that the specific connections created between the trapezium and scaphoid, the dorsal scaphoid and lunate, and the volar lunate to the radius in themselves have never been previously reported or published as specifically described in the ANAFAB, and as a combination, are completely unique. The idea of Rules Based Motion is new and unique, and such a claim is supported by the successful filing of US patents.

Our paper on the ANAFAB reconstruction addresses the shift in approach and scrutinizes various aspects of alternate reconstructive approaches. It was possible to identify specific major issues that suggests that virtually all other approaches are flawed as surgical solutions. The clinical outcomes of the ANAFAB provide essential data for an evidence-base medicine approach to further strengthen the reality of a novel and unique concept, and constitutes both a significant original contribution to knowledge, and a major advance in the management of the injured wrist.

The theory and underlying concepts embodied in this thesis constitute a significant and original contribution to knowledge. The successful reconstruction of scapho-lunate dissociation is a powerful proof of the concepts that are embodied in the rules-based motion and stable central carpal column theories.

Introduction to Wrist Biomechanics

Preamble and project historical background

The wrist has been a challenging structure to analyse. Over many years there have been countless projects, departments and researchers striving to understand and explain the complex mechanics (Garcia- Elias, 2013, Rainbow et al 2016).

Extensive reviews on the observation, explanations and theory of carpal biomechanics have been performed and published. Two recent publications, one each in the American (Kamal et al 2016) and European versions (Rainbow et al 2016) of the Journal of Hand Surgery, provide an excellent overview of the current understanding of wrist biomechanics. The summary of both reviews indicates that a clear understanding of carpal biomechanics has been elusive and this has created issues with reconstructive options. "We use scapholunate ligament tears as an example of the disconnect that exists between our knowledge of carpal instability and limitations in current reconstruction techniques." (Kamal et al 2016.)

At the time of commencement of this project, there were a number of proposed theories or concepts of how the wrist worked (figure 1), and these included the:

1. Row and column (Craigen and Stanley 1995 and 1998, Taleisnik 1976)
2. Ring theory (Lichtman, 1981)
3. DISI/VISI descriptive theory of the Mayo clinic (Berger 1997)
4. Ovoid theory (Moritomo et al, 2004, 2006)
5. Dart throwing motion concept (Garcia-Elias et al 1997, Wolfe et al 2006)

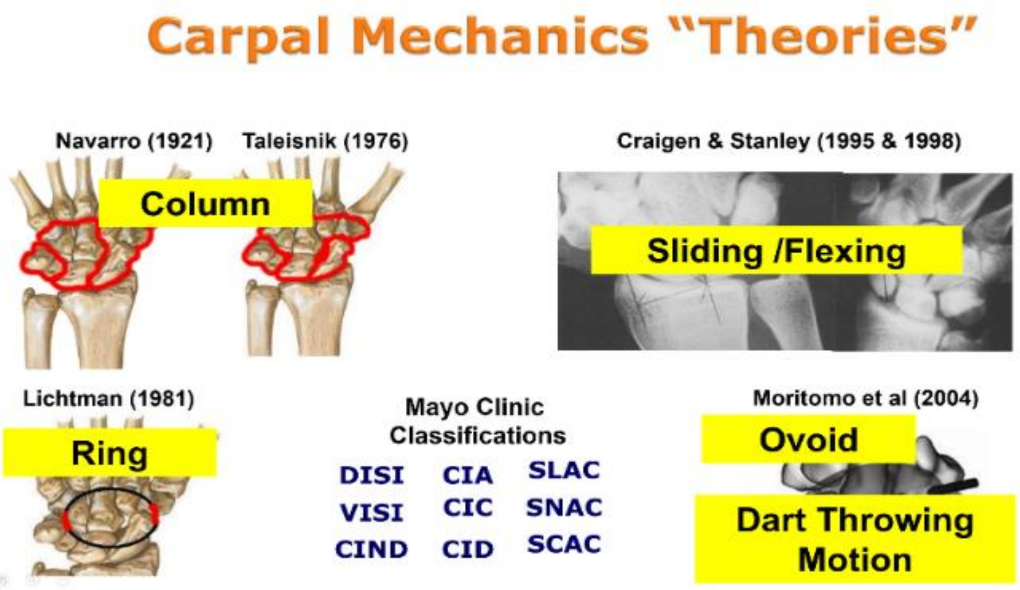

Figure 1. Diagrammatic summary of existing explanations for carpal biomechanics during the 1990s and early 2000s.

The problem with many of the proposed theories at that time, is that they did not explain a number of mechanical challenges of the wrist (figure 2). These issues include the relative motion and connection between the scaphoid and trapezium, the control of the motion of the lunate, and the differential motion between the lunate and scaphoid.

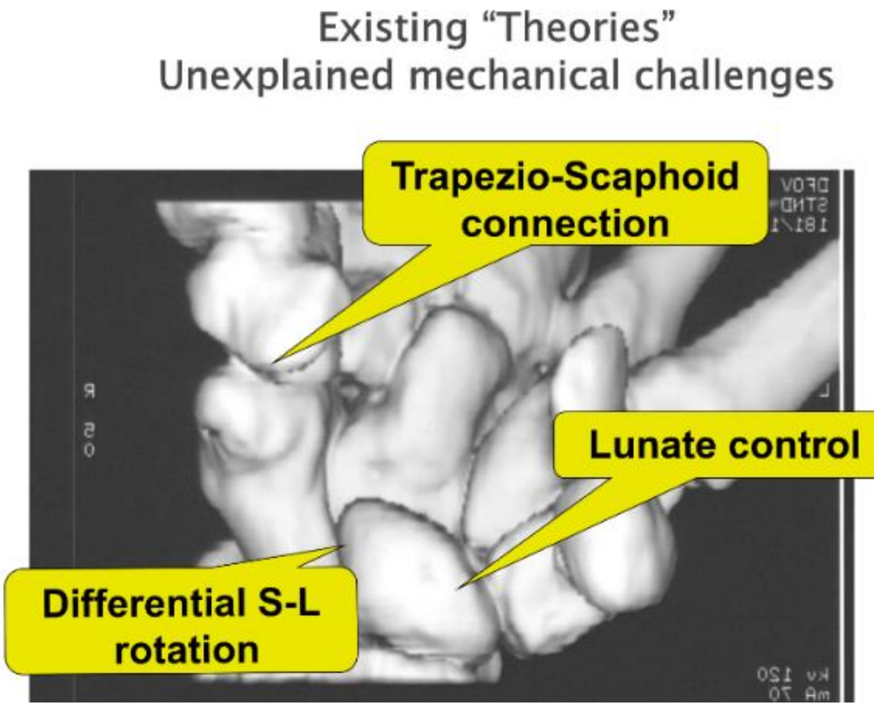

Figure 2. Unexplained mechanical demands on the wrist.

More particularly, many of the proposed theories lack the features of a good theory. In his pivotal publication "Short History of the Universe", Hawkins stated that a theory must provide a description of a mechanical system based on a limited number of observations, must be testable, cannot be proven and most importantly be predictive (Hawkins 1996).

Current theories on carpal mechanics lack some or all of these features and so cannot qualify as theories. They are more in the nature of descriptions of observational data.

The real question is why has the wrist been so difficult to sort out despite all the efforts?

One answer lies in the fact that wrists are all different and much of the work in the past has been based on large amounts of empirical observations with an attempt to find a standard or normal wrist. Such a standard wrist has eluded researchers (Crisco et al 2005).

The work of Linscheid et. al. (1972), and earlier the overview by Fisk (1970), were pivotal in identifying and illustrating the complex relationships between the bones of the carpus. However, they were largely descriptive, and failed to provide a true theory on carpal mechanics.

Multiple procedures have been proposed to address dysfunction of the carpus. Most of these attempts to address an observed and assumed critical defect in the wrist have largely focused on maintaining the coaptation of the scaphoid and lunate bone, without necessarily relating how this particular motion segment may relate to the wider biomechanics of the wrist. However, the clinical results of various surgical procedures have been unpredictable, and subsequent researchers have typically been unable to replicate the outcome of the initial reports of a particular repair or reconstruction.

The situation regarding carpal research in the late 1990's was confusing, and while there have been many claims of an answer to the dilemma, even as recently as 2014, Lee and colleagues stated that *"Current soft tissue reconstruction procedures do not reliably restore normal carpal alignment and kinematics, and limited arthrodeses may alter carpal kinematics in the long term." "No procedure to date reliably fulfils the goals of a SL reconstruction."* (Lee et al, 2014)

While a constant review of ongoing research at other centres of carpal biomechanical investigation has been an important part of this project, to thoroughly detail the current situation would be to reiterate existing publications, and is a major work in its own right. Given that every detailed review to date has failed to confirm a unified explanation for carpal biomechanics, the situation that existed in the mid-1990s when this project commenced has not substantially advanced.

Dr Sandow has been a clinical reviewer for the Journal of Hand Surgery (European version) and has assessed over 80 papers submitted to this journal. A submission subsequently published by Rainbow et al (2016) was reviewed by Dr Sandow and assessed as Reject (request resubmission) as it was quite poorly constructed and incomplete with respect to the coverage of the state of understanding of carpal biomechanics.

The comments to the Editor of the Journal were submitted on 15th June 2015 as detailed below.

> *"I am not aware of the nature of the invite for this paper, but it appears to have missed an opportunity to bring together the evolving research and progress in the understanding of wrist kinematics. This an area of very significant recent advances, and it is opportune to publish a review article to encapsulate the current stage of understanding to give guidance for the needed future studies.*
>
> *Each author will believe that their concept is the key one, and this paper needed to stand back and identify what is acceptable and should be the basis for further work and what is not.*
> *Of more note, the title refers to the importance of the mid-carpal joint, but no mention of the M/C joint made in either the abstract or the summary. In fact, the M/C joint is only mentioned twice in the entire document, and yet features as the key part of the title.*

The main emphasis seems to be on coupled motion, and observing patterns of wrist motion, but does not put either the current understanding of wrist biomechanics, which on the basis of this paper is scant nor provide "clinicians with a framework for functional assessment that would enable tailored and individualized treatment".

While it is a nice summary of the many descriptions, it is incomplete and provide no analysis of the various approaches. While "function" is defined, "theory" is not. The stated purpose of the paper was to review recent work, yet refers heavily on quite old material. While this old material is important, its inclusion and discussion are inconsistent with the stated aims of the paper.

A table that summarises all the credible descriptions of carpal mechanics and classified into the nature of the works, in vivo/invitro, key mechanical concepts (column, ring, linkage from ulnar, linkage from radial etc.) plus some analysis where subsequent work has contradicted (or built on) the previous ideas, would advance our understanding.

While it may indicate the identify of this reviewer, the details in the introduction and discussion of Sandow et al (2014), underpin the previous difficulty of trying to use a purely descriptive overview of observed motion of the wrist, from a range of techniques, and how to predict outcomes of various injuries and interventions. This Sandow paper attempts to put the complex biomechanics of the wrist into context, a feature this current paper has omitted. Most previous "so called" theories cannot be tested and are not predictive, which are critical parts of any true theory.

The authors confuse "model" which describes a set of observation and "theory" where prediction of motion and mechanics is possible, which will also incorporate variations in ligament laxity.

Line 128 to135 is confusing, and talks about % motion and would be clearer citing actual motion.
Line 133 "……note that in extreme extension the distribution of scaphoid and lunate extension to capitate extension is reduced by 25%." Is not very helpful in understanding the variation.

This is a very mixed up overview, and makes little attempt to adjudicate of the various wrist motion descriptions. No mention of the Mayo work and scant mention of Moritomo's contribution, both of which have been pivotal in the advances of carpal understanding.

Questions such as, how mid-carpal instability is explained, why is motion so well preserved with radio-scapho-lunate fusion, and why have such a complicated anatomical arrangement in the first place, are not addressed.

The diagrams are rather unsophisticated and largely unhelpful. A table with a list of various models and some sort of breakdown of the approaches by the many researchers would be more helpful.

This is an interesting observation (line 402 onwards) "Surgery for SLAC arthritis generally includes ablative procedures such as a partial wrist arthrodesis or excision of the proximal carpal row (PRC) (Cohen et al., 2001), and as such, cannot restore carpal kinematics". Normal wrist kinematics has not been adequately defined, so it is difficult to identify what is missing.

There is some very good discussion, but at this point in time, a more incisive and careful, as well as more inclusive overview would be helpful, and at the very least, improve the abstract, summary and introduction to support the title!

In summary, the discussion does not support the title, and the review of the various models of carpal biomechanics and kinematics is superficial at best. There should be more dismissal of various concepts that have been shown to be inconsistent with later work, and there are some significant omissions. There should also be an attempt to put the various different suggestions into context, in terms of the claims of the motion controllers.

The abuse of the term "theory" should be addressed, and the separation of kinematics into analysis and synthesis, to provide some predictive pathway would be helpful. The work by Sandow et al on the stable central column, controlled by two gear four bar composite linkages is one of the first to attempt to provide a true theory of carpal mechanism that is predictive and testable."

The paper was subsequently revised and resubmitted in line with changes, including the title correction, suggested by Dr Sandow. The paper was published as M. J. Rainbow, A. L. Wolff, J. J. Crisco and S. W. Wolfe, Functional kinematics of the wrist, The Journal of Hand Surgery (European Volume) 2016, Vol. 41E (1) 7– 21.

Within that paper, reference was made to published work by Sandow et al (2014): "Sandow and colleagues have made the most recent progress in this area." and "In summary, while the preliminary results of Sandow et al. (2014) may be premature for determining a unifying theory of carpal kinematics, their novel approach to reconstruct ligament courses using an isometric lengthening assumption is important and may lead to tremendous insight into the subtle nuances of carpal mechanics." (Rainbow et al 2016)

The implication is that a clear appreciation of the state of understanding of carpal mechanics underwrote and guided the progress of this project.

The Project initiator

The trigger or genesis of this particular project was the response to a question asked by Dr Sandow in July 1998 to one of the other panel members on a wrist injury symposium looking specifically at ulnar sided wrist pain. Professor John Stanley from Wrightington U.K. was asked by Dr Sandow to explain the peculiar relationship of the lunate to the ulna and to reconcile his claim that ulnar carpal impaction (pathological contact between the ulna and lunate bones) occurred on ulnar deviation of the wrist when the lunate was in fact moving away from the ulnar. Professor Stanley's previous presentation indicated that the impaction of the lunate against the ulna was demonstrated by ulnar deviation of the wrist - the so called "ulnar impaction test". The response from Professor Stanley was that the wrist was a "complicated three-dimensional arrangement that the questioner (i.e. Dr Sandow) clearly didn't understand".

To address the apparent knowledge gap, it was decided to perform multipositional CT scans of Dr Sandow's own left wrist using a standard CT 3D imaging environment. Motion sequences of the wrist were then created in relatively crude form by using screen captures of the 3D images of the various wrist positions, and then playing them in sequence using the no delay transitional slide show feature of Microsoft PowerPoint. This step frame cartoon like demonstration confirmed that the lunate did in fact move away from the ulna on ulnar deviation but it adopted very curious flexion/extension motion despite the fact that there were no particular tendinous connections.

The scaphoid appeared to partly move with the lunate, and the trapezium appeared to pivot over the distal scaphoid, but remained well attached in the region of the scaphoid tuberosity. A screen capture from that original sequence is shown in figure 2.

The motion of the scaphoid and the trapezium similarly were not well described at that stage, although connections to the trapezium through the volar scapho trapezium ligaments had been previously reported (Drewniany et al 1985). A review of the apparent motion of the scaphoid demonstrated on plain x-rays would suggest that the scaphoid is not connected significantly to the trapezium. However, the initial cartoon like step frame animation images suggested a definite connection between the scaphoid and lunate.

To improve the visualisation quality of the crude initial motion sequences, a specialist company in animation and multimedia design, True Life Creations Pty Ltd, was consulted. Their background and expertise were in gaming technology and as a production house for various other three-dimensional imaging environments. They were able to improve the visual quality of the animations and convert them into a true movie format. They were also able to apply crude markers to certain parts of the carpal bone in an attempt to quantify the connections between different carpal components. This initial work was performed in July 1998.

These initial animations were significantly limited as they were only 2D projections of the 3D data set, and thus there were major compromises in measurement accuracy, particularly out-of-plane motion. These limitations are still evident in much of the wrist imaging material and presentations with current clinically available radiological providers, and is detailed by Sandow (Sandow 2014 and q.v. Chapter 4).

An early consideration was to potentially create true 3D objects from the CT scan data set, which would allow true 3D animation and quantification of the carpal bone motion. Existing technology at the time of project commencement was not readily available or capable of performing such an image or model generation. True Life Creations Pty Ltd expressed an interest in pursuing the technology further and the initial project was commenced in an effort to create three dimensional models from the raw CT scan data and then play them in a step sequence relationship to create a more realistic motion sequence. A joint venture and subsequently a company were formed between True Life Creations Pty Ltd principals (Mr Sam Papas and Mr Michael Kerylidis) and Dr Michael Sandow. Funding for the project was to largely be underwritten by Dr Sandow, with True Life Creations Pty Ltd providing fee for service contractor services as well as project management, but with generous in-kind contribution from the principals.

Initial observations and development of Rules Based Motion concept

Even at this early stage, consistent motion patterns were identified and it became clear that there appeared to be quite definite isometric connections between the lunate and the radius, between the trapezium and the scaphoid on the volar side, and between the scaphoid and the lunate dorsally. This linkage system appeared to provide an explanation for the control of the motion of the proximal row of the carpus, hitherto not well explained.

Screen captures of one of the early animations is shown in figure 3. This animation was created from the original CT scan data obtained of Dr Sandow's wrist using 3d Studio Max (Autodesk, Ca, USA) as part of the True Life Creations Pty Ltd production environment. Importation of the scan data and creation of the model was extremely time consuming and not viable as a routine animation creation tool.

Further, the actual image sequences created were limited with respect to quantitative analysis of motion and inter-bone interaction, and in particular the creation of physics based rigid body animation.

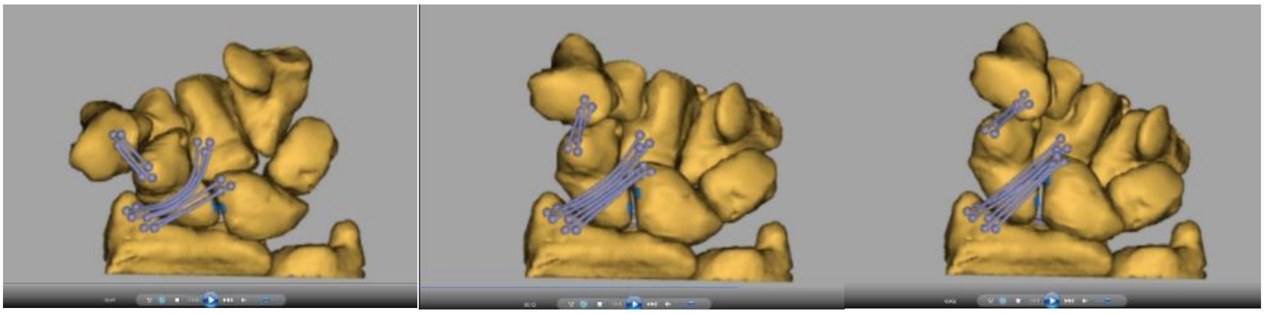

Figure 3. Screen capture of a wrist animation demonstrating sequential motion of a single set of carpal bones moving from radial to ulnar deviation, with isometric regions joined by blue "rope". Also demonstrated in the differential motion of the volar aspect of the scaphoid and lunate. (www.truelifeanatomy.com.au - Screen captured from movie isofront.avi – 15th March 2001).

The process of creating the animation as depicted in Figure 3 was to import the CT Dicom scan data from each of the CT scans performed as Dr Sandow's wrist sequentially moved from radial to ulnar deviation. Mr Sam Papas (as principal production animation specialist at True Life Creations Pty Ltd) has extensive skills and training in 3D animation and he created 7 separate fully segmented 3D models of the sequentially positioned wrist. He then applied markers to a range of regions on the surface of one of the 3D wrist models created. The bones of that single primary model, with its attached surface markers, were then copied and registered (lined up) with the same bone in each of the other positions.

Current diagnostic imaging using computed tomography 3D and 4D scanning creates animations that have the appearance of a single 3D image of the wrist that is moving. In reality the images are simply step frame presentation of a series of separate individual 3D images captured by volumetric (CT) scanning at each wrist position. The number of 3D images obtained and the clarity of each image relates to the scanning capabilities of the imaging equipment and the actual rate of movement of the wrist. The captured 2D image is then presented as a step frame (cartoon) animation to create the apparent motion sequence of the carpal bones. However, each image presented, although of the same wrist, is unrelated to the others.

Further, the images shown are actually volume rendered presentations which are actually a 2D projection of the 3D data set and so no 3D object is created. This means that although the direction of view and certain video presentation details can be modified, such apparent moving images cannot be manipulated in 3D, measured accurately or exported in anything but a 2D screen capture format. The technology conundrum is covered by Sandow (Sandow 2014, and q.v. Chapter 4).

The technique used in this project is quite different. By creating an actual 3D object of a single set of reference bones, and then aligning each of those reference bones with the different wrist positions, an animation of a single set of bones/objects was created. This is in contrast to the usual process which uses a step frame animation of the 7 separate scans of the same wrist taken at sequential positions to create a cartoon like motion sequence where the actual location on each separate image of the same bone is subject to errors due to slight variations in morphology.

By using the single reference set of bones, the changes in the distance between the surface markers could be accurately recorded and areas of isometricty documented, as the same bones with the same markers were assessed as they moved through the captured wrist motion.

Mr Papas, who created the initial animation, had no particular knowledge of the anatomy of the wrist, and the bones were given unrelated names (actually names of pasta styles) to avoid any potential recall of connections in previous discussions.

The result was a quantitative identification of isometric connections between certain areas of the carpus, by the computer program, and essentially independent of any prior anatomical knowledge, and largely independent of the animator input. What was of note is that the connections between the bones as depicted by the blue lines (Figure 3) are actually 3D objects in the form of ropes formed by connected spheres. This allows the connections to be correctly positioned over both convex and concave surfaces.

The animation (as shown as still screen captures in Figure 3) detailed the dorsal scapho-lunate ligament, the connection between the scaphoid and trapezium and the radio-scapho-capitate ligament. It further identified a connection between the volar lunate and the radius in a proximal radial to distal ulnar direction. This structure, which on review of the animation appeared to readily explain the means of controlling lunate motion as indicated in figure 2, had not been identified in previous scientific work or been published in any anatomical papers at that time. Basically, the computer (and Sam) identified a hitherto undescribed anatomical structure by performing a multipositional quantitative isometric analysis.

At that time, the long radio lunate ligament was not recognised as an important structural component of the wrist (based on previous work by Berger (1991and 1997)). Shortly thereafter, Berger (1997) published work on more detailed dissections and histological analysis of the wrist which upgraded an area on the volar region of the lunate from undifferentiated capsule and vascular input to a formal ligament – the long radio-lunate ligament! However, until recently, the long radio lunate ligament was not regarded as an important controller of lunate motion.

Further, while a connection between the trapezium and scaphoid was reported (Drewniany et al 1985, Bettinger et al 1997), the apparent dyssynchronous motion between the scaphoid and trapezium on radial and ulnar deviation was not well explained.

Suitable imaging technology was not available to develop the required imaging capability and given the potential for a quantitative 3D analysis technology, the decision was made to create a new system of software.

Given the observation of certain isometric constraints, it appeared that it may be possible to reverse engineer the mechanics of the wrist to identify a series of rules or mechanical factors that controlled the motion of the wrist. These rules could then be used in a forward kinematic fashion to recreate wrist motion using a mathematical or forward engineering model.

It had been recognised that there was significant variation in the motion of individual components of the wrist, and attempts to find a reliable and consistent pattern of motion had not been identified.

The proposition was made that there appeared to be four specific rules or factors that when combined would potentially create a mathematical (kinetic) model which would explain both the constant overall function of the wrist, but allow for variation of the specific rules or factors. Each rule could vary, but the product of the rules would create the net wrist function.

We were unable to identify any technology that would address this specific requirement. The concept of reverse engineering, and then forward engineering based on specifically identified “rules”, plus the option to modify any or all of the rules in “what if” scenarios appeared a novel concept.

As the initial observations appeared to potentially explain a number of unresolved issues and may identify solutions where there is dysfunction, patents were filed in Australia and subsequently granted to cover the animation technology concept. These involved, as noted above, reverse engineering of the constraints and then forward engineering. US and Australian patents were filed in 2000, and granted in 2002 (Australia) and 2006 (USA) (q.v. Chapter 1). This novel concept remains central to the development of a solution to explain carpal instability and dysfunction. To be considered patentable IP, the proposal needs to have:

1. Novelty – a new idea
2. Inventiveness – non-obvious to the trained observer
3. Utility – must be useful for some purpose

The submitted patents embodied the concept of rules-based motion, which recognised that a motion system can be explained by its four basic rules or factors. These factors are, the morphology of the components of the system, the constraints between those components, the interaction between components and the load applied to the system.

With these four components, which can individually vary, a resultant motion can be created. The wrist would appear to be a good example of such a motion system.

With this system in mind, work was then undertaken to characterise the motion of normal and abnormal wrists using this software developed by True Life Anatomy. This project therefore has been in three main stages. These were:

1. To develop the technology, with which to study the motion of the wrist,
2. To characterise the normal connections and factors that determine the wrist and then to
3. Apply them in an injury situation.

The hypothesis for the overall project was that the understanding of the wrist and characterisation of the normal constraints that are missing in the abnormal wrist could be restored by replacing them based on the understanding of the mechanics that were disrupted.

As discussed previously, the majority of wrist research has been empirical with an extensive examination and measurements of wrist motion in an attempt to explain the patterns. This project has been based on a more conceptual approach where the rules which can vary are defined and then reapplied to simulate motion under its own mathematical or kinetic environment.

Software development (True Life Anatomy)

To allow a quantitative analysis of the carpus and better characterise the motion and relationships between components of the wrist, sophisticated 3D imaging and measurement was required.

When the project commenced in 1998, various existing software systems were reviewed. These included 3D Studio Max (Autodesk, Ca. USA), 3D doctor and various radiology platforms. None were capable of the detailed analysis that was required. Much of the radiology imaging available was only able to create volume rendered images, which in reality are 2D projections of the 3D data set, and thus not suitable. Programs such as Analyse Direct (Analyze Direct, Inc. Overland Park, KS, US) and Mimics (Materialise, Leuven, Belgium) were a possibility, but lacked the analytical and animation capabilities and were very expensive.

There were a number of steps required in the creation of 3D objects from the CT scan data. At that stage, most CT scan data was captured as helical scan volumetric data acquisition and exported into the PACS environment as DICOM compliant overlapping slices of variable thickness. This data needed to be parsed (transferred) into a graphics environment and the model created.

To control and manage this technology development a company, True Life Anatomy Pty Ltd, was set up between Dr Michael Sandow and True Life Creations Pty Ltd. The funding for such a venture was to be initially from Dr Sandow, and in recognition of the investment, he took a majority shareholding. Further funding was obtained from Australian Federal Government Research and Development (AusIndustries) in the form of a (matching) START grant (approximately $400,000), plus other state and industry support such as COMET and R&D Tax offsets. True Life Creations (Adelaide) Pty Ltd as a shareholder was also engaged as a contractor to manage the software development.

True Life Anatomy (TLA) engaged True Life Creations Pty Ltd to develop the required animation technology.

Formal software development commenced in 1999, with a very clear development pathway. In contrast to many development projects, the end points were clearly and rigidly defined. They were to solve the issues related to carpal dysfunction.

These were broken down into various broad steps:

1. Define the mechanics of the wrist
2. Identify deficits that would explain why a wrist injury occurred
3. Identify a means to address the documented dysfunction
4. Develop kinetic mathematical models to allow virtual testing of the proposed solution

Early in the development of the technology it was clear that available technology was unable to delivery such functionality. The True Life Anatomy software, even at an early stage appeared to offer a unique approach to the process of reverse engineering of a mechanical system, in this situation the wrist, and then offer a forward engineering reanimation capability with a “what if” option to add additional mechanical factors. In view of this, patents were applied for in Australia, US and Europe. Such patents were subsequently granted in Australia (q.v. Chapter 1) and USA (q.v. Chapter 1). The application for European patent has been abandoned.

There were therefore various stages to progress the project, with the ultimate aim to:

1. Identify the various Rules (morphology / constraint / interaction / load) in the initial stages of reverse biomechanics

2. Reapply the rules in forward (synthesis) biomechanics to demonstrate and simulate the biomechanics of the wrist
3. Identify the deficits in the wrists that are injured or not functioning correctly
4. Propose a potential strategy to address the deficit in wrist biomechanics
5. Develop reconstructive solutions that are compatible with surgical reality and limitations with respect to surgical approach, repair materials and devices.
6. Carry out the proposed reconstructive strategy on a target group of patients with a specific wrist dysfunction to validate the reverse engineering – forward engineering concept and approach.

However, the initial steps of characterising the rules or characteristics of the wrist motion segment required various stages. These stages in the development of Animation Technology were:

1. Import volumetric data (CT) of 1st position multibody object (e.g. wrist)
2. Threshold volumetric data
3. Create 3D multibody object mesh
4. First level segmentation of 3D Mesh (separate objects)
5. Second order segmentation of 3D Mesh (touching objects)
6. Import 2nd position object into same graphics environment
7. Identify points on pairs of bones that remain isometric through range
8. Reapply isometric constraints on primary segmented object
9. Re-animate multibody object using isometric constraints, collision avoidance and load points with FEA (Finite Element Analysis).
10. Add “What if” additional conditions to re-animated object and using FEA, assess loading pattens and potential pathological correlation.

As detailed earlier, when the project commenced in 1998, technology to analyse the motion of the individual carpal bones, and more importantly to identify isometric regions within the carpus, did not exist in a usable form.

The experimental process was therefore to develop the software to allow the measurement of isometric points on various bones of the carpus to allow reverse engineering of the biomechanics. This is termed reverse biomechanics.

True Life Anatomy Pty Ltd (Australian Company Number (ACN): 098 284 738) was incorporated on 27 September 2001, with Dr Michael Sandow as the (slight) majority shareholder in view of his significant financial commitment. TLA has been managed in accordance with strict Australian

Securities and Investment Commission regulations and continues to manage and control the technology. A web site was created to allow access to the technology (Figure 4).

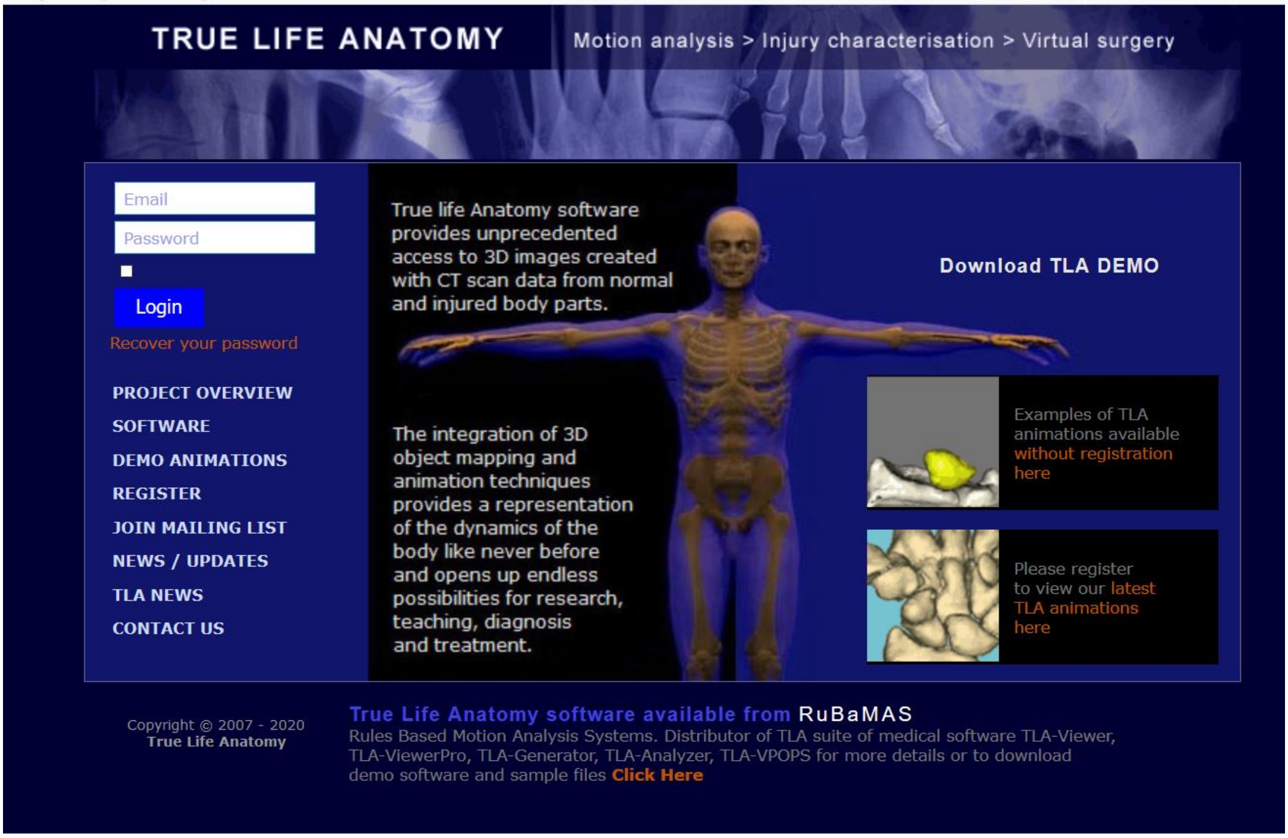

Figure 4. Screen capture of True Life Anatomy web site - http://truelifeanatomy.com.au

A separate entity RuBaMAS Pty Ltd (ACN: 094 742 613 - incorporated on 12 Oct 2000) has been formed as a potential commercialisation platform for the technology – http://www.rubamas.com (Figure 5).

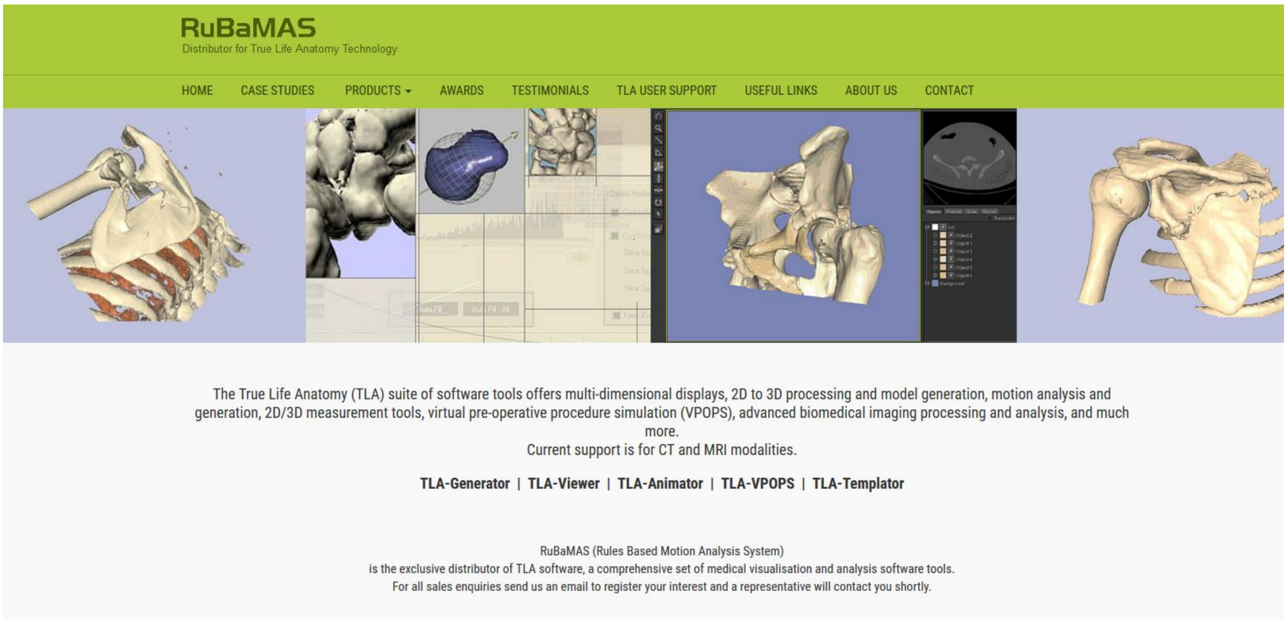

Figure 5. Screen capture of RuBaMAS web site – http://www.rubamas.com

The True Life Anatomy software system was created as three separate programs:

1. TLA Generator (www.rubamas.com/TLA_Generator)
   This allowed the CT scan data to be parsed into the graphic environment, thresholded and a 3D object created. It allowed primary segmentation of distinctly separate components, however, also had the capability to perform secondary segmentation on the created 3D object by using polygonal angle or touching iteration and selection. The created 3D object is saved as a .tla file which contains an STL (Stereolithography) file, plus spatially co-registered 2D (two dimensional) axial slice images and patient demographic data.
   The programs were developed in a Virtual Studio development environment using VTK (Visual Tool Kit). The TLA Generator user manual is in Appendix 1.

2. TLA Animator
   This program allowed the created 3D objects to be imported in a manipulative graphics environment to allow measurement and analysis.

3. TLA Viewer
   This program allows for passive viewing and display of the created TLA files. They can be exported as screen capture images.

An example of the pathway for image creation and analysis is detailed in the following figures 6-9. More details are contained in online site and in the published papers.

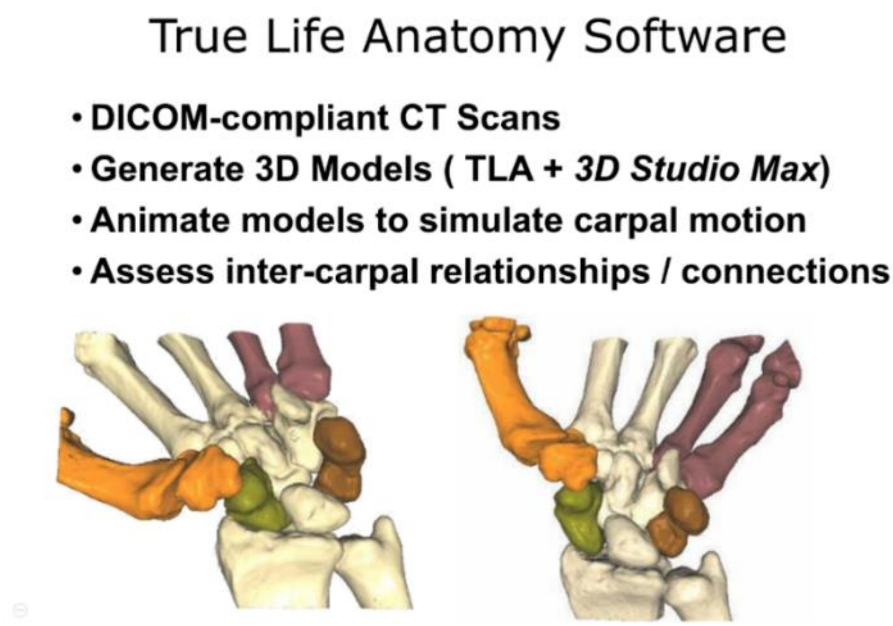

Figure 6. Variable position 3D models, created within True Life Anatomy are imported into the graphics environment.

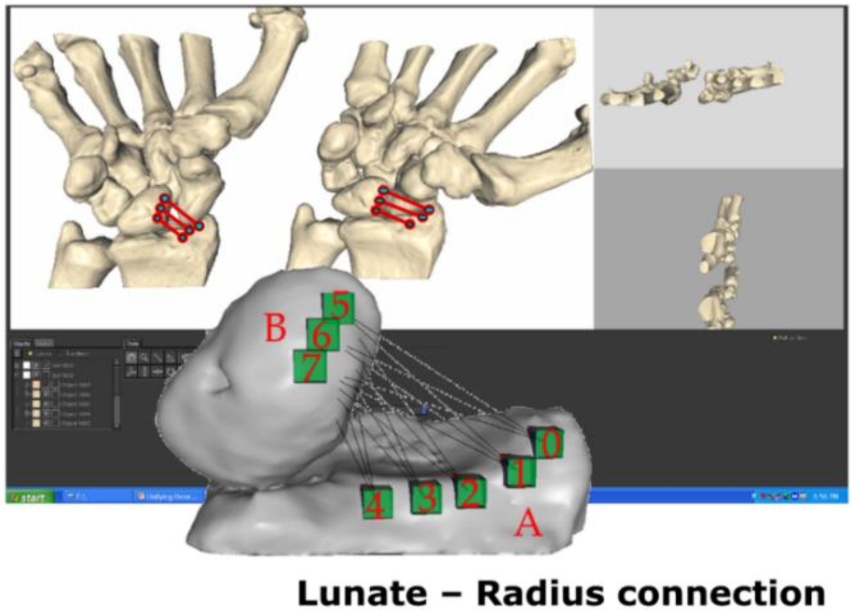

Figure 7. Points are applied to lunate and radius and the degree of isometricity assessed in extremes of radial and ulnar deviation.

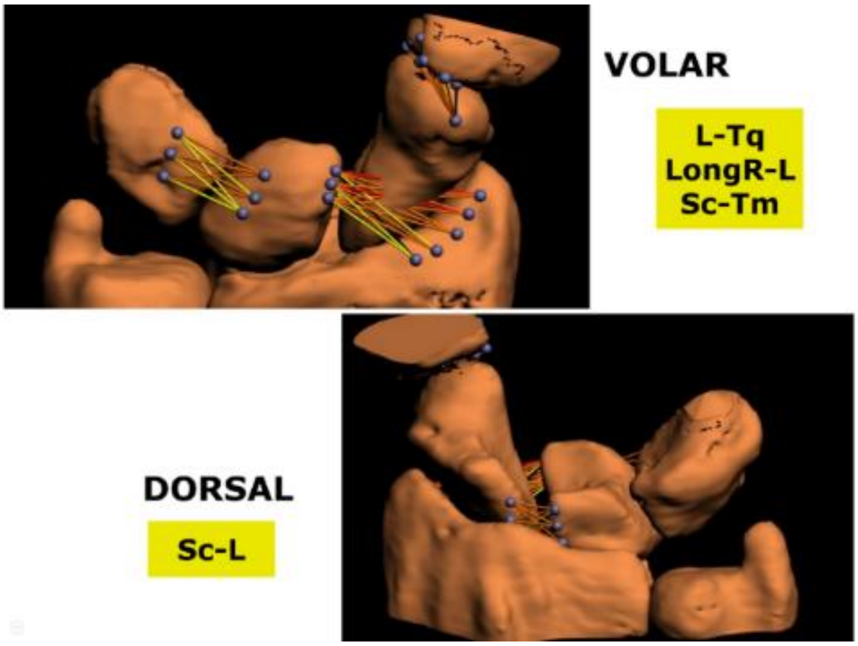

Figure 8. Specific isometric connection was identified in the scapho-trapezial, volar radio-lunate, volar lunato-triquetral and dorsally the scapho-lunate.

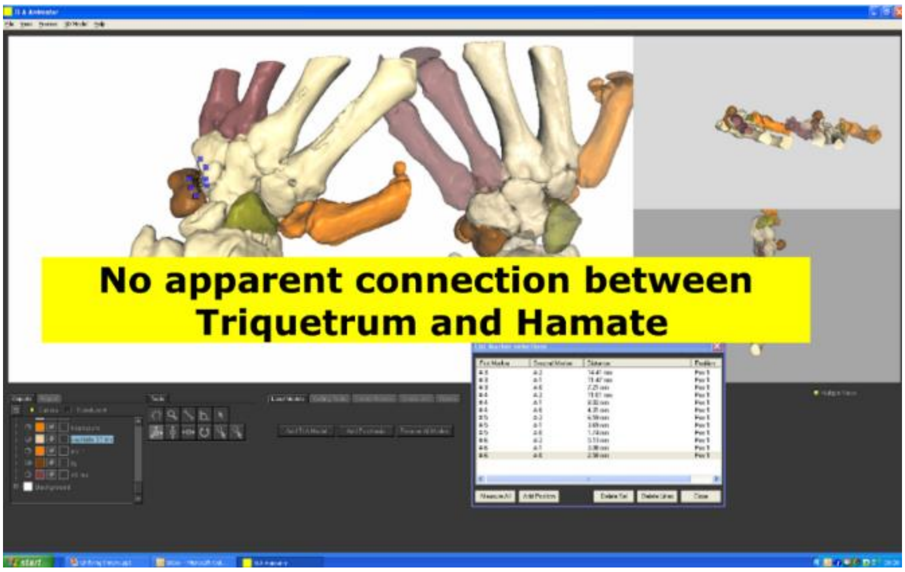

Figure 9. No isometric connection was identified in the region of the triquetrum and hamate.

Further detailed step by step analysis of isometric connection is detailed in Figures 10- 15.

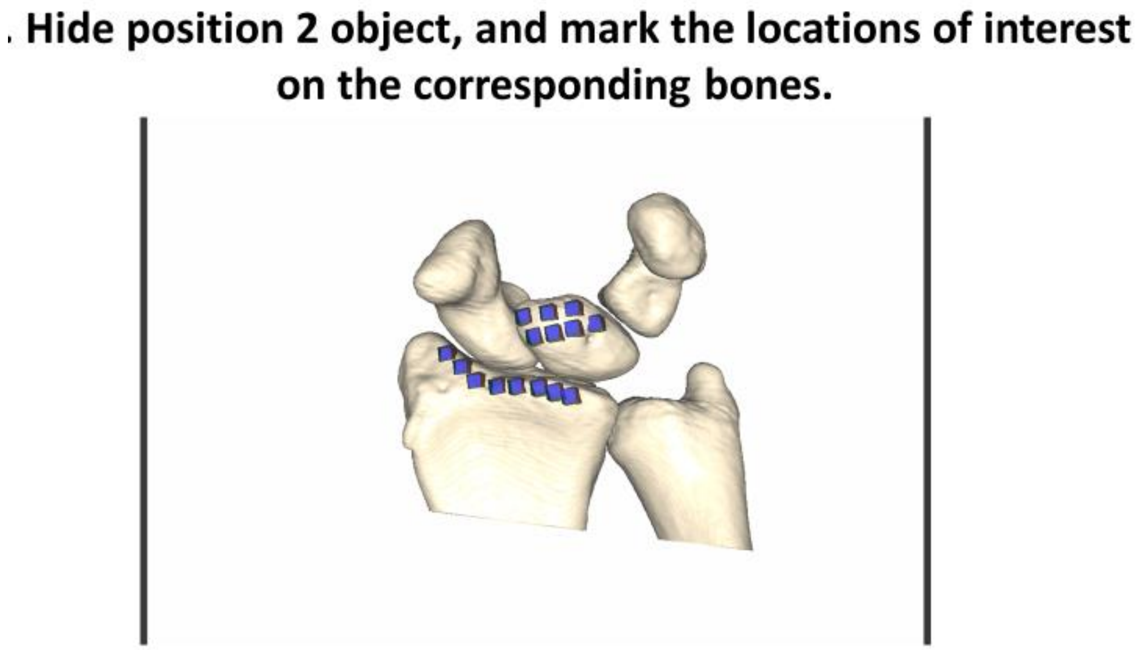

Figure 10. 3D model of wrist is imported and non-target bone are hidden. Markers are applied to regions of interest on the bones of the position 1 model.

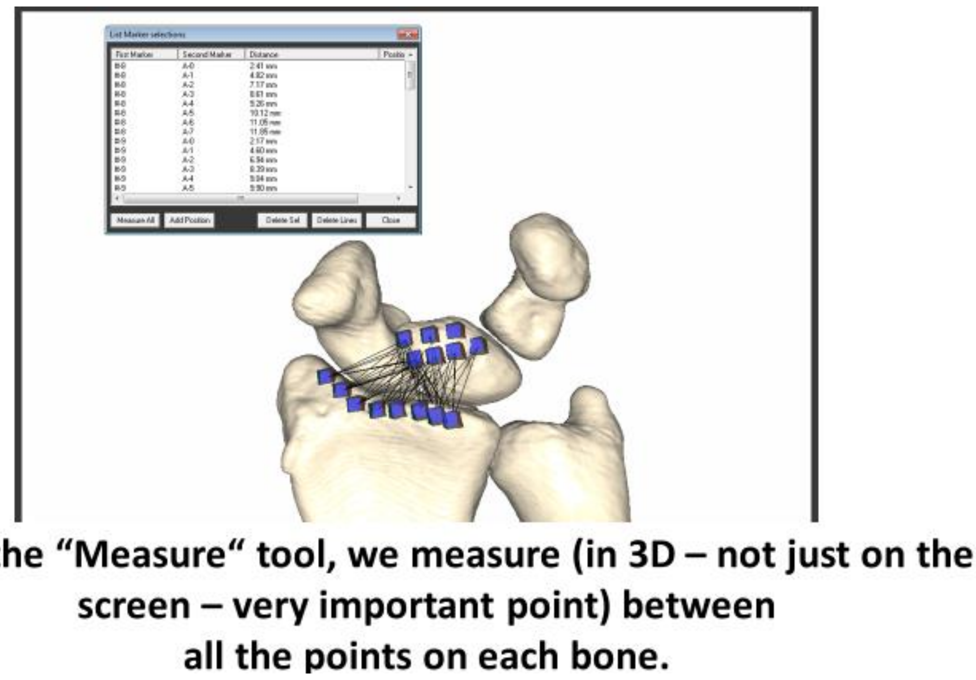

Figure 11. The distances between all the markers on the regions of interest is performed.

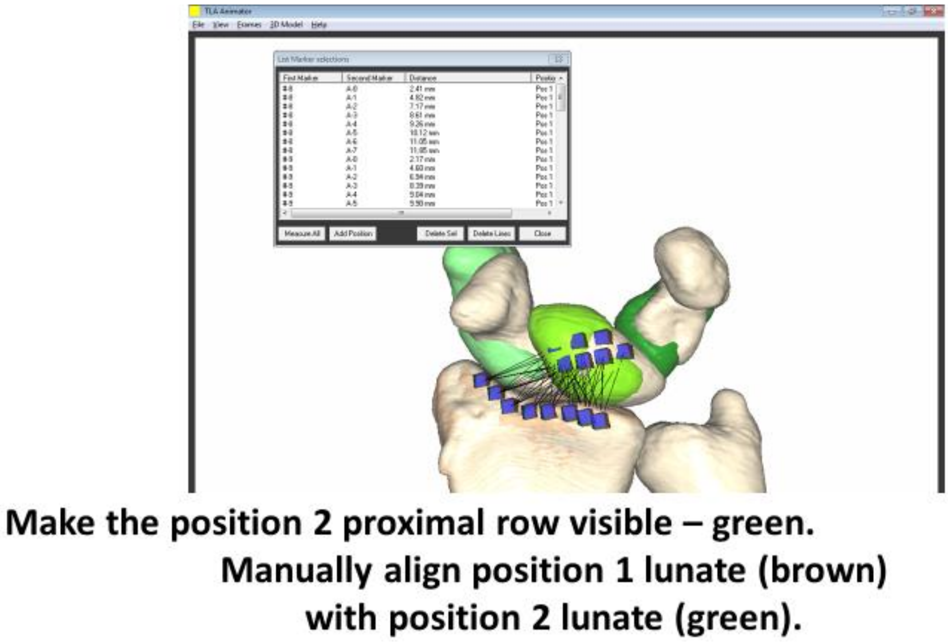

Figure 12. The originally marked and measured bones are then realigned with the position 2 corresponding bones, and remeasured.

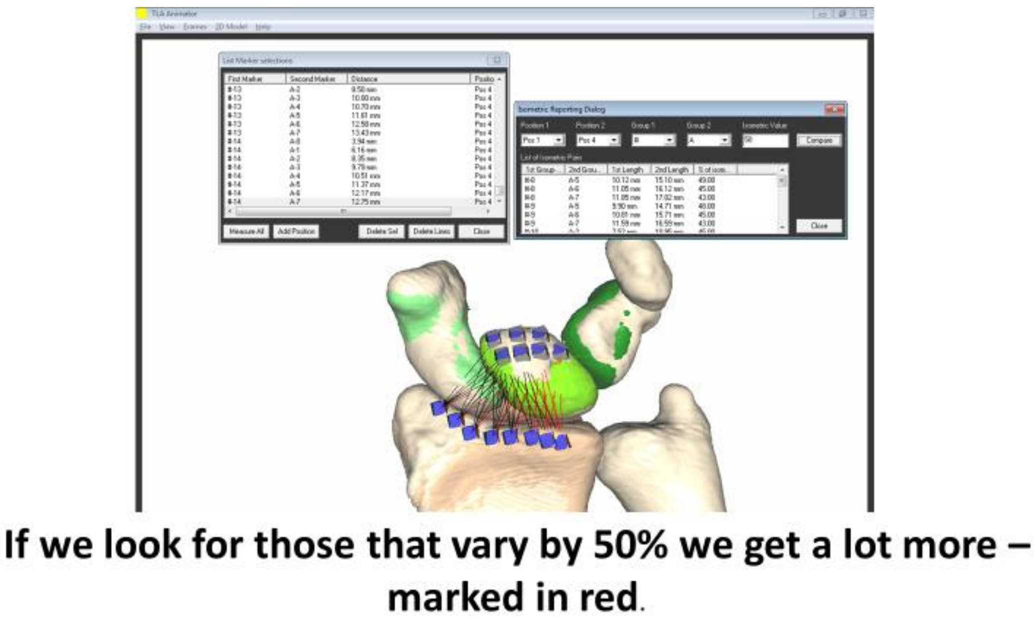

Figure 13. The length of the corresponding regions of interest in position 1 and position 2 are compared, and the degree of isometricity assessed.

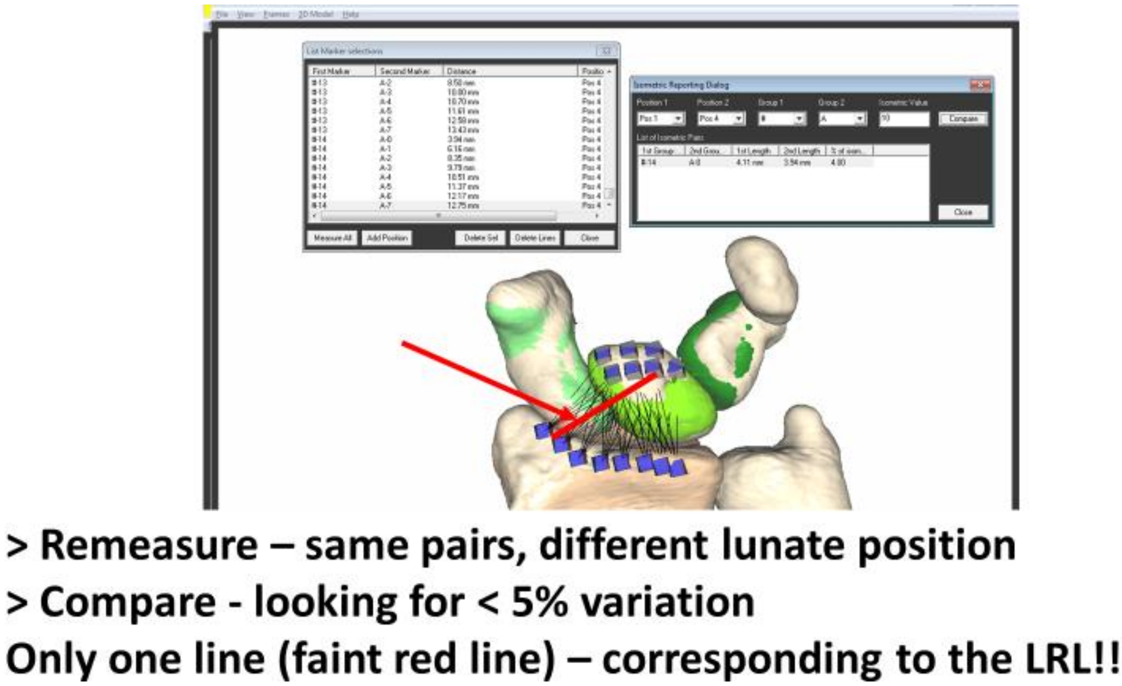

Figure 14. Isometric connection is determined as less than 5% variation between the bone positions.

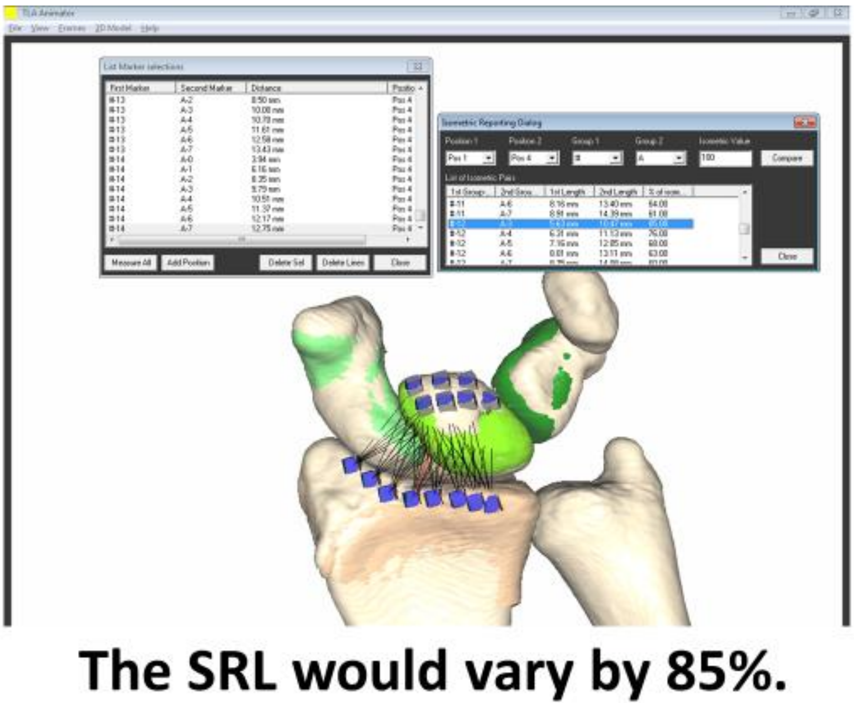

Figure 15. Although reputedly a restraint to lunate extension, the short radio-lunate ligament (SRL) varied by approximately 85% and was therefore clearly not isometric, nor able to effectively control lunate alignment during normal wrist motion.

The 3D analysis software is currently being commercialised, but is yet to achieve significant sales. Dr Michael Sandow remains the majority shareholder, and has a significant potential commercial conflict of interest.

Mechanical challenges of the wrist

The question again arises, "Why has the Wrist been so difficult to sort?"

The empirical approach has been flawed as no standard or average wrist has been characterised, as all wrists are different, with variations in alignment, intercarpal bone motion and shape.

Current "theories" are generally based on attempts to reconcile voluminous empirical observations even though all wrists are different, however all wrists perform basically the same functions and tasks.

This project adopted an alternate approach of utilising a Conceptual or Theoretical approach. In this process, some fairly general observations are made of the motion system and a basic theory is proposed on how they could be explained. This provides a clear hypothesis to test and the theory is thereby validated, enriched or rejected. A theory can only be rejected if it is replaced by an alternate theory.

The primary step is to define the requirements of the wrist. The specific requirements of the wrist are detailed in figure 16.

What are the requirements of the wrist?

1. **To position the fingers and palm in space to allow them to perform the required functions,**
2. **Create a stable central functional axis from the radius to the 2/3rd metacarpals, around which the mobile thenar and hypothenar units act, and**
3. **Provide sufficient gripping and rotational power that is controlled proximally in the forearm to allow for a slim wrist.**

Figure 16. Basic requirement of the hand and wrist.

These basic functions can be further expanded to provide a more specific functional characterisation of what the wrist needs to do.

The 7 basic mechanical capabilities to allow the wrist to perform its functional requirements are:

1. Adequate flexion and extension for holding and pushing
2. Allow side to side motion adjusting to holding different angles
3. Deliver powerful rotational force (resist ROLL)
4. Prevent translation in coronal, sagittal and transverse planes (resist TRANSLATION /COMPRESSION/DISTRACTION)
5. Oblique power grip to improve holding, thrusting and throwing (achieve CO-LINEAR PALM AND FOREARM DURING USE - so called Dart Throwers Motion)
6. Independent finger and wrist motion
7. Low profile distal extremity

However, there are some significant biological constraints and limitations. The carpal bones must be perfused which creates a limitation of bone surface areas to allow articulation. Further, the anatomical connection precludes axles, and so the bone can only be connected by external linkages. There are also considerable anatomical variations between bone shapes and ligament conformation.

With these challenges, a more effective anatomical analytical capability of the carpus was required. With the development of suitable technology (True Life Anatomy 3D animation software), further analysis was now possible to allow us to proceed on the journey of characterising the mechanics of the carpus, with the ultimate aim to find solutions to address the dysfunctional wrist.

Summary

The wrist remains a challenge with respect to the mechanical controls and biomechanics. No standard wrist exists and current attempts to characterise wrist motion or biomechanics have been unsuccessful.

This work is part of a larger project to develop a kinetic model of carpal motion and can be regarded in part as an extension of Taleisnik's concept of carpal columns and rows (Taleisnik 1976).

It does however expand this basic notion to incorporate the concept, or maybe “Law” of Rules Based Motion which states that a motion system, and in particular the wrist can be defined and controlled by its 4 basic rules or factors:

1. Bone morphology
2. Constraints between the bones
3. Interactions between the bones
4. Applied load

The primary philosophy and aims of this project were to adopt a different approach from the way carpal research was typically being conducted, and rather than utilising the standard empirical study design, use a conceptual research strategy. The experimental design was to make a limited number of observations on the mechanics of the wrist, and then propose a theory of how the wrist may work. An important early observation was the apparent isometric connection between various regions in the carpus and thus a concept of Rules Based motion was developed.

This theory, or potentially a Law, stated that the performance of a mechanical system was the net interlay of its various components - each of which could vary, but such variation was offset by the compensatory variation of the other component to create the appropriate net outcome. This concept was called “Rules Based Motion”.

The aim of this work was therefore to define and characterise normal carpal biomechanics, identify the deficit in the dysfunctional wrist and propose and test solutions to address such dysfunction.

Synopsis of Prior Publications and Presentations

The following publications are presented in the order in which they were completed. The contents of the papers largely follow a pathway of initially identifying the potential critical biomechanical elements, expanding and defining the biomechanics based on normal patient 3D scans, identify potential deficits to explain wrist dysfunction, and then proposing and testing a surgical reconstructive solution.

The following papers reflect that journey to:

1. Identify the potential theoretical basis for wrist motion and secure the IP
2. Develop the software to allow quantitative analysis of normal carpal motion
3. Extrapolate the finding in a normal carpus to the injured wrist
4. Identify the deficit
5. Develop a therapeutic solution
6. Perform such a reconstructive solution and follow the clinical outcomes for a minimum 2 years

The paper published by Drs Sandow and Fisher (Anatomical Volar and Dorsal Reconstruction (ANAFAB) for Scapho-lunate dissociation in Journal of Hand Surgery (European) (q.v. Chapter 6 and Sandow and Fisher 2019)) represents the culmination of over 20 years work to create a process of reverse engineering using quantitative 3D analysis to better characterise the normal wrist biomechanics and then extrapolate this to the delivery of a successful reconstructive solution to address wrist dysfunction.

This work contrasts with existing empirical research of wrist biomechanics and represents more of a revolution rather than an evolution, and given the challenges to existing reconstructive option, potentially disruptive rather than adaptive.

A conceptual based research approach used in this project focuses on using limited observational data to develop the concept or theory that attempts to explain or describe the phenomenon of the wrist. The concepts of reverse engineering, rules-based motion and even “what if” reanimation was outlined in the filed patents. Through a process of hypothesis testing, the stable central column theory was defined, enrich and validated.

By proposing and defining a possible explanation for how the wrist works at the start of the project, an orderly and directed investigative pathway could be followed. With this conceptual research approach, it is no surprise that the images included as part of the reconstructive (ANAFAB) solution proposed in the most recent publication (q.v. Chapter 6) bear a remarkable resemblance to the figures in the original 2001 patent.

Summary of Chapter One

Australian patent - 2001237138 Animation technology -

Applicant: Macropace Products Pty Ltd; True Life Creations (SA) Pty Ltd

Inventors: Papas, Sam; Sandow, Michael John

Priority date: AUPQ6001A – 03-3-2000

Patent granted: 05-03-2001

https://patents.google.com/patent/AU3713801A/en (accessed 19th September 2019)

United States Patent 7,236,817-B2;

Granted: 26th June 2007

https://patents.google.com/patent/US7236817 (accessed 19th September 2019)

Animation technology is a process that creates motion of digitally created 3D models within a graphics environment. Once the pathways of the 3D objects are defined, the motion sequence is rendered and exported as a video with the transitions between key frames "smoothed" using tweening or morphing. This is distinct from stop motion techniques such as step frame animation where the apparent motion is created by frame -by-frame animation of 2D illustrations.

While it may be unusual to file patents as a first step in a research journey, to mobilize the investment required to develop the software to spatially analyse the multi-positional 3D objects, protection of the intellectual property was required. More importantly, the characterization of proposed important isometric constraints, including the previously underappreciated long radio-lunate ligament, could be time stamped.

A method for creating an animated image of the bones of a body part is described. The steps involve converting volumetric data (CT of MRI) into 3D objects, and then by comparing the relationship between various regions on pairs of bones in different motion positions, isometric connection can be identified.

The next stage of the technology was to reapply the various components or rules of the system to create motion based on its own biomechanical constraint and interaction, with the potential to perform a "What if" modification. This allows the testing of possible surgical reconstructive solution specifically configured to address the unique biomechanical characteristics of an individual injured wrist. This allows for one of the first examples of quantitative 3D analysis to define the controllers or rules of a motion system (reverse engineering / analysis kinematics), and then to reapply the identified rule (forward engineering / forward or synthesis kinematics) to create rules-based motion of the dynamic system.

Summary of Chapter Two

Sandow MJ, Fisher TJ, Howard CQ, Papas S. Unifying model of carpal mechanics based on computationally derived isometric constraints and rules-based motion - the stable central column theory. J Hand Surg Eur Vol. 2014 May;39(4):353-63

This study was the critical step to transition the theoretical concepts contained in the initial patent to a formalised theory that can be used to explain wrist function in a more tangible form. This was part of a larger project to develop a (kinetic) theory of carpal motion based on computationally derived isometric constraints.

Three-dimensional models were created from computed tomography scans of the wrists of ten normal subjects and carpal spatial relationships at physiological motion extremes were assessed. Specific points on the surface of the various carpal bones and the radius that remained isometric through range of movement were identified. Analysis of the isometric constraints and intercarpal motion suggests that the carpus functions as a stable central column (lunate-capitate-hamate-trapezoid-trapezium) with a supporting lateral column (scaphoid), which behaves as a 'two gear four bar linkage'.

The triquetrum functions as an ulnar translation restraint, as well as controlling lunate flexion. The 'trapezoid'-shaped trapezoid places the trapezium anterior to the transverse plane of the radius and ulna, and thus rotates the principal axis of the central column to correspond to that used in the 'dart thrower's motion'.

This study presents a forward kinematic analysis of the carpus that provides the basis for the development of a unifying kinetic theory of wrist motion based on isometric constraints and rules-based motion.

Summary of Chapter Three

Sandow M. The why, what, how and where of 3D imaging. J Hand Surg Eur Vol. 2014 May;39(4):343-5.

Access to a 3D imaging environment offers considerable advantages in diagnosis, planning and treatment, however is made confusing by misunderstandings of what is 3D imaging, what is true 3D interactivity and what looks like 3D but is really more like a projected shadow. The capture of volumetric 3D data by using computer tomography (CT) and magnetic resonance imaging (MRI) traditionally transforms this data into a 2D planar representation to allow a more familiar appreciation. The reality is that to improve a clinician's 3D comprehension they need an appreciation of the patho-anatomy in 3D and to be able to access and interact with image data within a 3D environment.

There are a number of challenges in the successful utilization of 3D. These can be explained and contextualized as the 'Why, what, how and where' of 3D imaging.

The "WHY" is clear, but the 'WHAT' is a more difficult question, and is at the core of the confusion over 3D imaging. There are essentially two distinct forms of 3D imaging or more specifically 3D data presentation. These are Volume Rendering (VR) and Surface Rendering (SR). This paper presents the advantages of each of these 3D image creation modalities. It also places the strengths and weakness in context, which is supported by comments in the articles in the same journal that 'true 3D analysis can only be done with true polygonal mesh 3D objects." VR can extract animations rapidly to gain an appreciation of motion; however, this is only an approximation that must be validated using specific 3D object tracking.

Summary of Chapter Four

Sandow MJ. 3D Dynamic Analysis of the Wrist. Hand Surg. 2015 Oct;20(3):366-8.

With advances in imaging and computing technology the greater capacity to diagnose, plan and deliver care to patients with hand and wrist disorder is being realised. This paper presents an update on work in our laboratory, which was able to identify certain specific rules that control wrist motion, and identify the factors that control motion.

The ability to extract the isometric constraints of a particular motion system substantially increases the capabilities in the longer term to provide quantitative diagnosis of particularly joint injuries and then when combining this with finite element (FE) analysis again can pre-test various operative solutions and then to assess whether the outcomes match the predictions.

Summary of Chapter Five

Sandow MJ. Computer Modelling of Wrist Biomechanics - Translation into Specific Tasks. Curr Rheumatol Rev. 2019 Jan 18. doi: 10.2174/1573397115666190119095311.

The carpus is a complicated and functionally challenged mechanical system and advancements in the understanding have been compromised by the recognition that there is no standard carpal mechanical system and no typical wrist.

This paper covers the extension of the work identifying the double row concept with each row moving through a single axis, as part of a larger project to develop a kinetic model of wrist mechanics to allow reverse analysis of the specific biomechanical controls or rules of a specific patient's carpus. Those rules, unique to each patient, could be used to create a forward synthesis mathematical model to reproduce the individual's anatomical motion in a virtual environment.

The objective of this paper was to present the background and justification to support the rules-based motion (RBM) concept, which states that the motion of a mechanical system, such as the wrist, is the net interplay of four rules: morphology, constraint, interaction, and load. The stable central column theory (SCCT) of wrist mechanics applies the concept of RBM to the carpus, and by using a reverse engineering computational analysis model, a consistent pattern of isometric constraints was identified, creating a "two-gear four-bar" linkage. This study assessed the motion of the carpus using a 3D (three-dimensional) dynamic visualization model. The hypothesis was that the pattern and direction of motion of the proximal row and the distal row with respect to the immediately cephalad carpal bones or radius would be similar in all directions of wrist motion. To identify the unique motion segments, 3D models were created from five normal wrists that underwent CT scanning in multiple positions of radial and ulnar deviation as well as flexion and extension. Each carpal row (proximal and distal) was animated in a virtual environment with the cephalad carpal bones or radius held immobile. The rotational axis and position of each bone and each row were then compared in sagittal (flexion-extension) and coronal (radial and ulnar deviation) motion.

The carpus appeared to have only two degrees of freedom, and yet was stable in those arcs with the loads applied proximally in the forearm. The proximal row moved in a singular arc, but with a varying extent during sagittal and coronal motion. The isometric constraints were consistent in both directions. The distal row moved on an axis formed by a pivot joint laterally (between the trapezium and scaphoid) and a saddle joint medially (between hamate and triquetrum). The sagittal and coronal alignment of this axis changed as the proximal row moved. This created a distinct pattern of row motion to achieve the various required positions of wrist function. On wrist radial deviation, the scaphoid (with the proximal row) flexed and the distal row extended, whereas in wrist flexion, the scaphoid flexed (with the proximal row) and so did the distal row. The pattern was reversed in the opposite wrist movements. While the general direction of motion of each row was consistent, the extent was quite variable.

This review supports the SCCT of carpal mechanics and the carpus acting as a two-gear four-bar linkage, as well as the concept of RBM as a means to understand the biomechanics of the wrist, and how this is translated into specific functional tasks. More sophisticated 3D modelling will be required to further understand the specifics of carpal motion; however, reverse engineering of the specific rules that define each individual wrist can also be applied to a mathematical model to provide a “what if” test of particular surgical interventions for a variety of wrist injuries. The use of quantitative 3D Computed Tomography Scan (CT) analysis, surgical planning and virtual surgical intervention allows potential surgical solutions to be applied to a computer model of an injured wrist to test the possible outcomes and prognosis of a proposed treatment.

Summary of Chapter Six

Sandow MJ, Fisher TJ. Anatomical Volar and Dorsal Reconstruction (ANAFAB) For Scapho-lunate dissociation. Journal of Hand Surgery (European) – in press October 2019, published November 2019.

The reconstructive option detailed in this publication represents the culmination of the main part of the project. The explanation of how the wrist works, and what to do about it when it does not was not well defined in 1998. Based on a better understanding of the mechanics of the wrist and largely based around the stable central column theory, a reconstruction to address scapho-lunate dissociation using an anterior and posterior approach with a hybrid synthetic tape/tendon weave between the trapezium, scaphoid, lunate and radius: an anatomical front and back (ANAFAB) repair. This study reviews the efficacy of the ANAFAB repair, which can be seen as a compilation of the components of a number of previously reported repair techniques, and based on published kinematic evidence. It aims to restore the anatomical mechanical constraints on both anterior and posterior aspects of the carpus. Patients were immobilized in a cast for 6 weeks, but no stabilizing wires were used. Ten patients have undergone the reconstruction and were assessed at a minimum 24-month follow-up. They achieved excellent realignment of the carpus, post-operative median scapholunate gap of 3 mm, and a recovery of more than 75% of grip strength and range of motion. No patient required secondary surgery or treatment related to the carpal stabilization.

The ANAFAB procedure appears to have the ability to reverse the scapholunate diastasis and proximal scaphoid subluxation, but still retain functional motion. Significant load on the carpus and radius is generated during a push-up (Scordino et al., 2016; Smith et al., 2018). The ability of the ANAFAB reconstruction to allow patients to perform push-ups provides compelling evidence of its ability to restore longitudinal stability of the carpus without a significant loss of motion, indicating the successful restoration of functional carpal biomechanics.

Summary of Chapter Seven (Invited Presentations)

This chapter contains various invited and submitted presentations at international hand and biomechanics meetings that expands the discussion on the stable central column theory of carpal mechanics, as well as detailing surgical technique of the ANAFAB. The opportunity to present such work at these specialised forums allowed theory testing and feedback.

The critical contribution of these presentations was to allow other researcher and surgeons with an interest in wrist surgery to be exposed to our work to allow appraisal and critique.

Only the most recent presentations have been included in this chapter, but such presentations at local, national and international forums were regularly given from the very initiation of the work in the late 1990s.

Sandow MJ, Fisher TJ. Proximal Carpal Row Controls Midcarpal Alignment and Motion – The Offset Unitary Motion of the Rows Creates a Stable Carpus. Journal of Wrist Surgery. 2015; 04 - A021 DOI: 10.1055/s-0035-1545659
https://www.thieme-connect.com/products/ejournals/abstract/10.1055/s-0035-1545659
(Accessed 27 January 2019)

Sandow MJ, Fisher T. Proximal carpal row controls midcarpal alignment and motion. XXVI Congress of the International Society of Biomechanics 23 -27 July 2017 Brisbane, Australia
https://isbweb.org/images/conferences/isb-congresses/2017/ISB2017-Full-Abstract-Book.pdf (Accessed 27 January 2019)

Sandow MJ. Anatomical volar and dorsal reconstruction (ANAFAB) for scapho-lunate dissociation. XXVI Congress of the International Society of Biomechanics 23 -27 July 2017 Brisbane, Australia
https://isbweb.org/images/conferences/isb-congresses/2017/ISB2017-Full-Abstract-Book.pdf (Accessed 27 January 2019)

Sandow MJ. Stable Central Column Theory of Carpal Mechanics. Presented at International Wrist Investigators Workshop, ASSH ASM Las Vegas September 2019.
https://www.asshannualmeeting.org/servlet/servlet.FileDownload?file=00P0a00000mMZOAEA4 (Accessed 11th March 2019)

Sandow MJ. Why I do it this way and how I do it with technique video - ANAFAB Reconstruction. American Society for Surgery of the Hand, PRE-COURSE 05: Carpal Instability, ASSH ASM Las Vegas September 2019. http://assh.force.com/annualmeeting/servlet/servlet.FileDownload?file=00P0a00000mN3O9EAK (Accessed 11th March 2019

Sandow MJ. Does the Stable Central Column Theory offer anything useful? It explains how the wrist works!! Instructional Course: IC11: The 2019 Linscheid-Dobyns Instructional Course Lecture: The Critical Stabilizers of the Intercalated Segment. The stable central column and the critical ligamentous stabilizers. ASSH ASM Las Vegas September 2019. http://assh.force.com/annualmeeting/servlet/servlet.FileDownload?file=00P0a00000mMoDLEA0 (Accessed 11th March 2019)

Chapter One – Patents: Animation Technology

Australian patent - 2001237138 Animation technology -

Applicant: Macropace Products Pty Ltd; True Life Creations (SA) Pty Ltd

Inventors: Papas, Sam; Sandow, Michael John

Priority date: AUPQ6001A – 03-3-2000

Patent granted: 05-03-2001

https://patents.google.com/patent/AU3713801A/en (accessed 19th September 2019)

See Abstract below.

United States Patent 7,236,817-B2

Granted: 26th June 2007

https://patents.google.com/patent/US7236817 (accessed 19th September 2019)

Animation technology

Abstract

A method for creating an animated image of the bones of a body part is described. The steps include converting Computed Axial Tomography (CAT or CT) scan and Magnetic Resonance Imaging (MRI) 2-dimensional cross-sectional images (slices) into 3-dimensional images of individual bones (FIG. 1). A first ordered series of slices of a body part in a first position is converted into a 3-dimensional representation of the skeleton of the body part and then a second ordered series of slices of the same body part in a different position is converted. The converted images are then used to create a step frame animation of the movement of the skeleton of the body part. Additional ordered series of slices of the body part in other intermediate positions could be used in the step frame animation. The steps of the method may also include the process of separating the bones if they are depicted as co-joined in a slice (FIGS. 6 and 7). The method can also include the identification of isometric points (FIGS. 8 to 11) on the separated bones to aid a clinician in the diagnosis of a problem or abnormality as well as assist in the application of "what if" surgical procedures on the digital representation of the skeleton of the scanned body part. The method can also include steps that create movement of the bones of the body part by applying rules of motion for one or more points on the separated bones of the scanned body part.

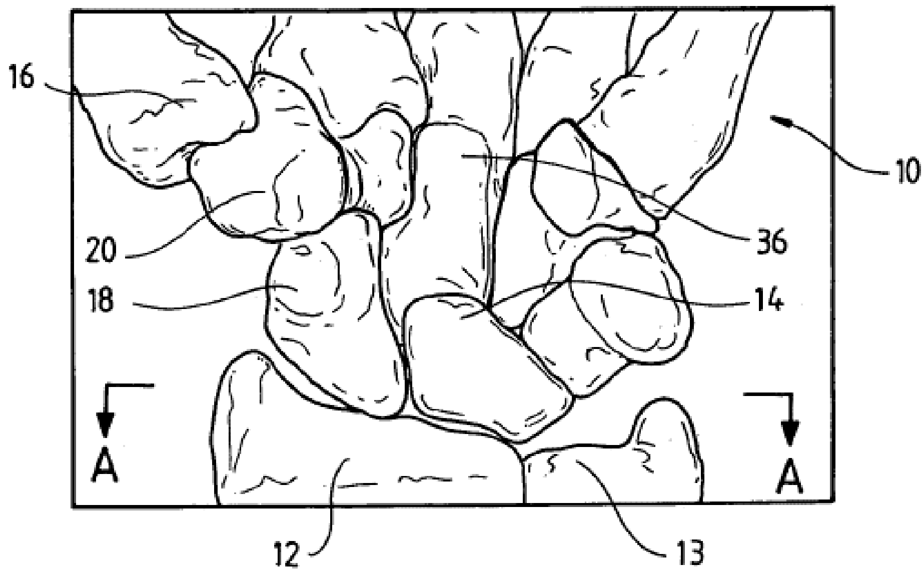

Fig 1

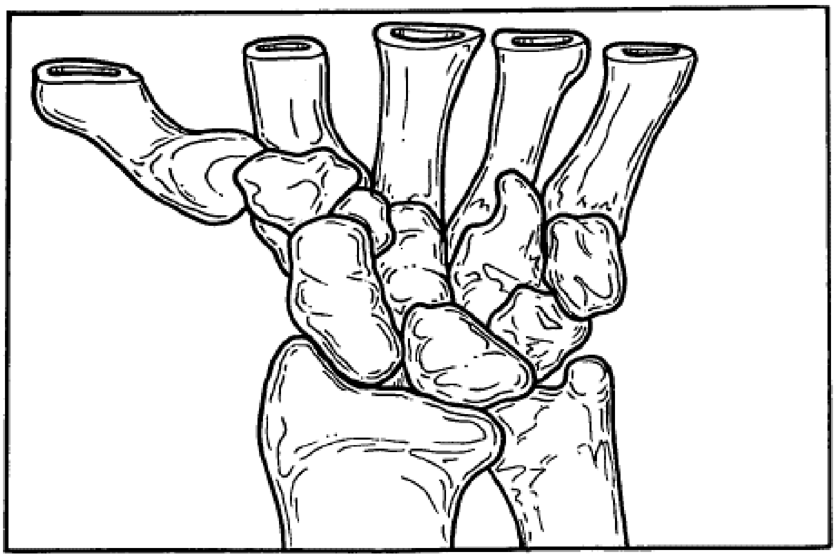

Fig 2

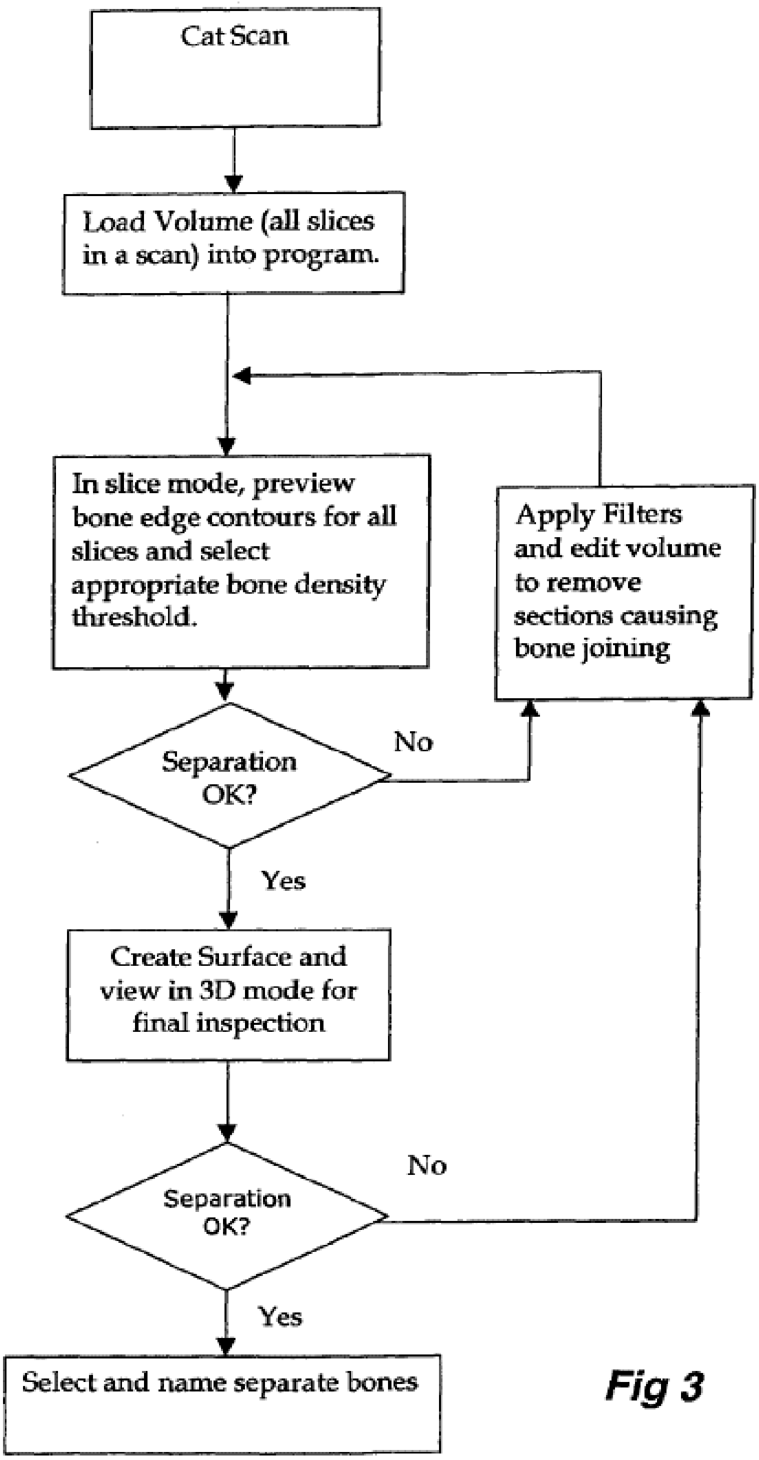
Cat Scan
Load Volume (all slices in a scan) into program.
In slice mode, preview bone edge contours for all slices and select appropriate bone density threshold.
Apply Filters and edit volume to remove sections causing bone joining
Separation OK?
No
Yes
Create Surface and view in 3D mode for final inspection
Separation OK?
No
Yes
Select and name separate bones

Fig 3

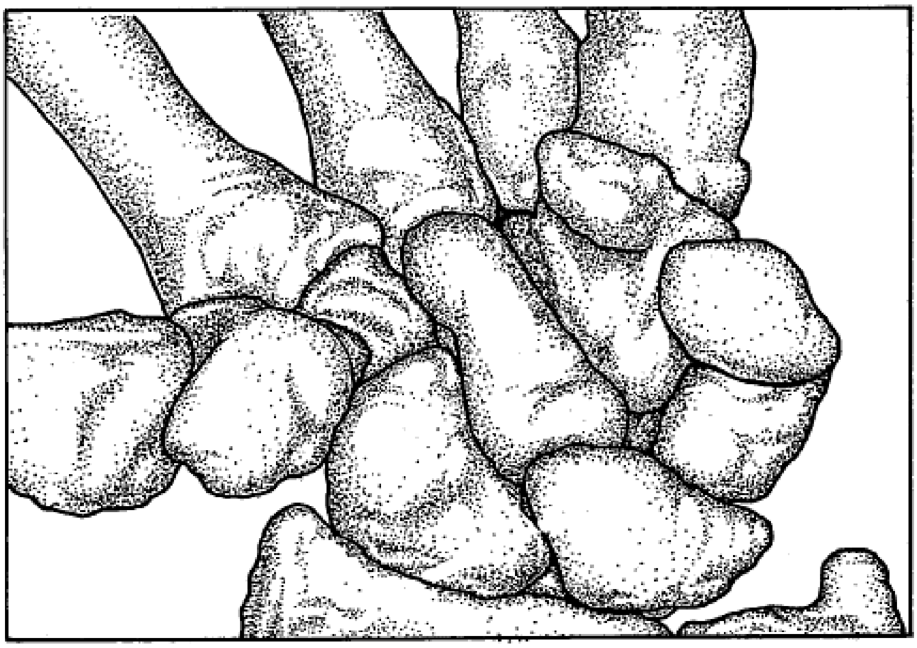

Fig 4

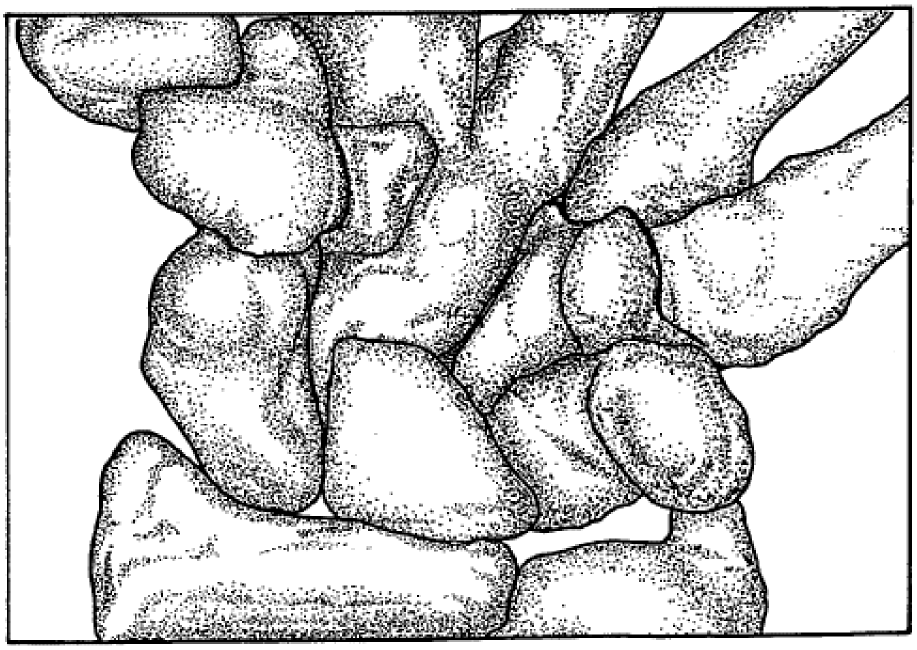

Fig 5

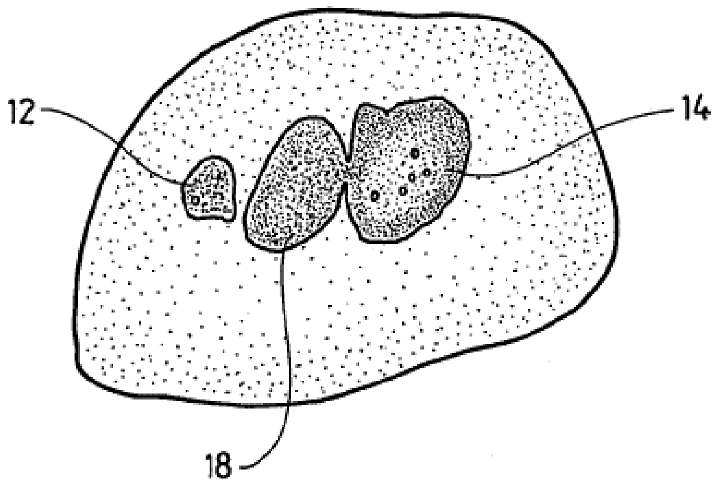

Fig 6

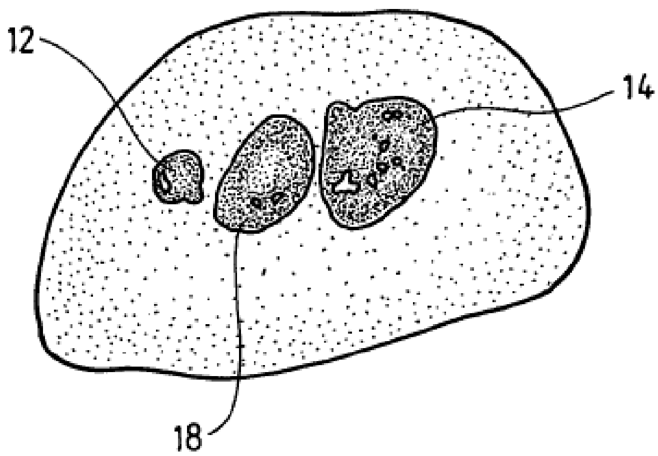

Fig 7

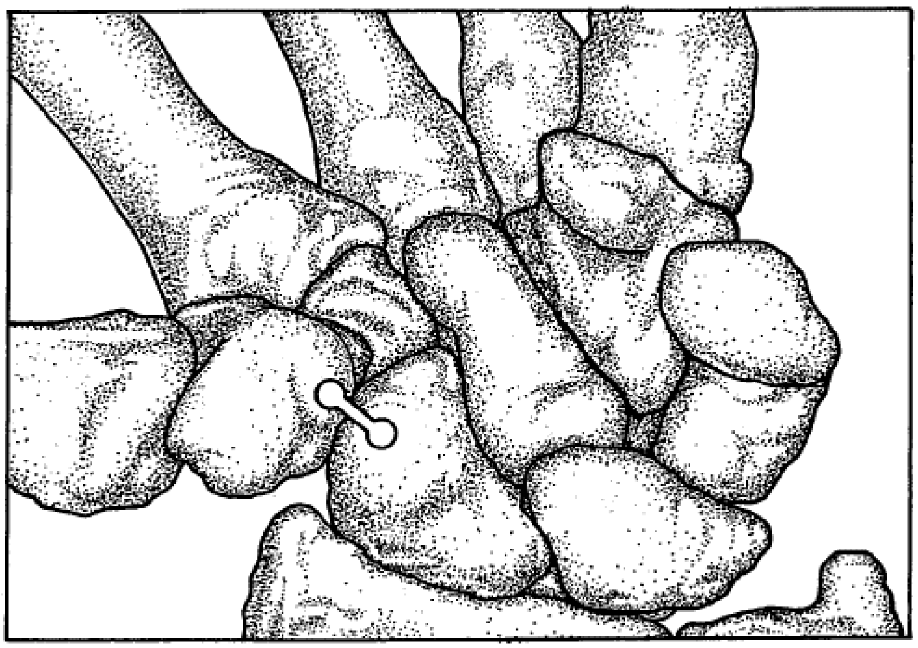

Fig 8

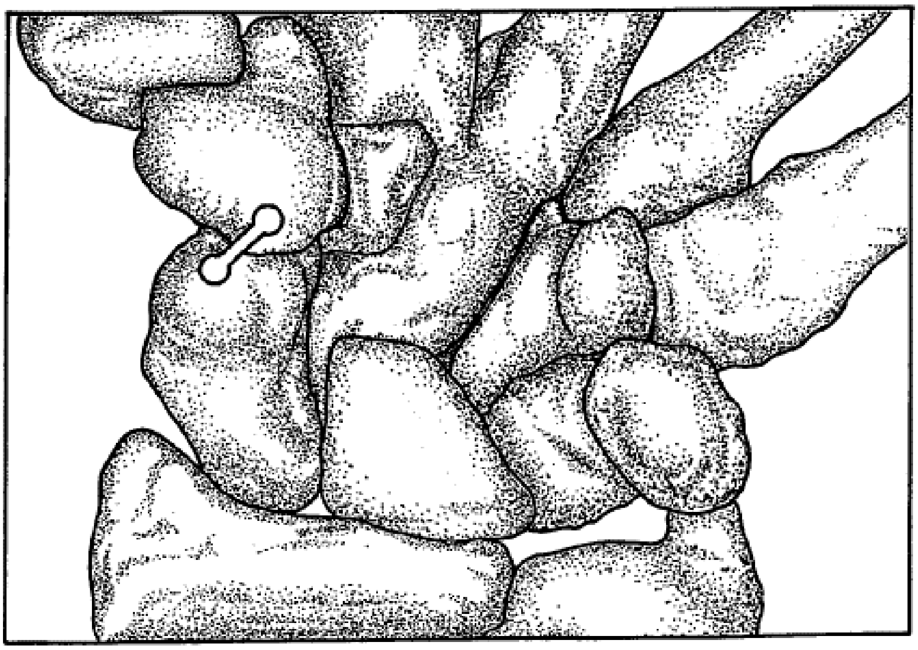

Fig 9

U.S. Patent Jun. 26, 2007 Sheet 6 of 6 US 7,236,817 B2

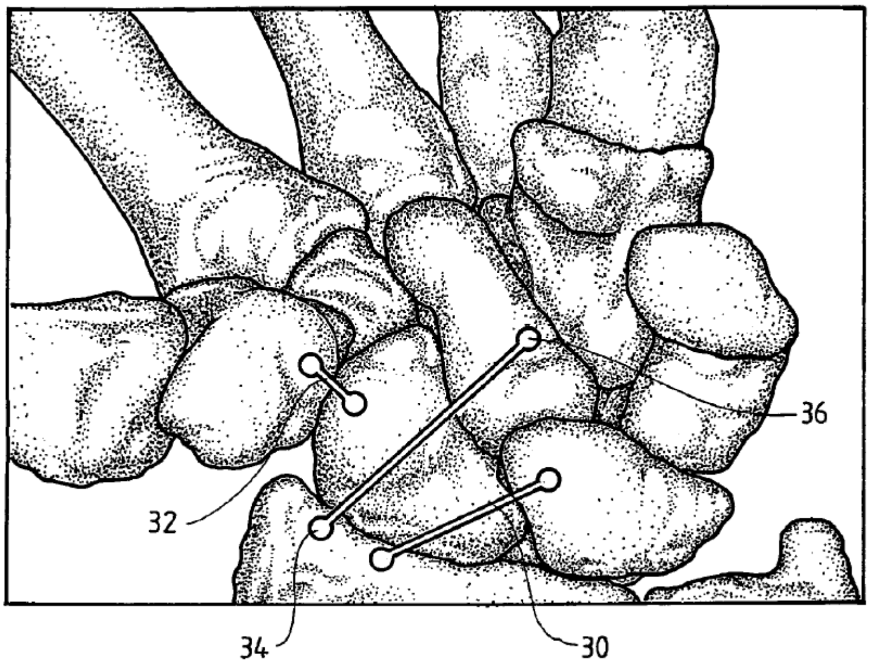

Fig 10

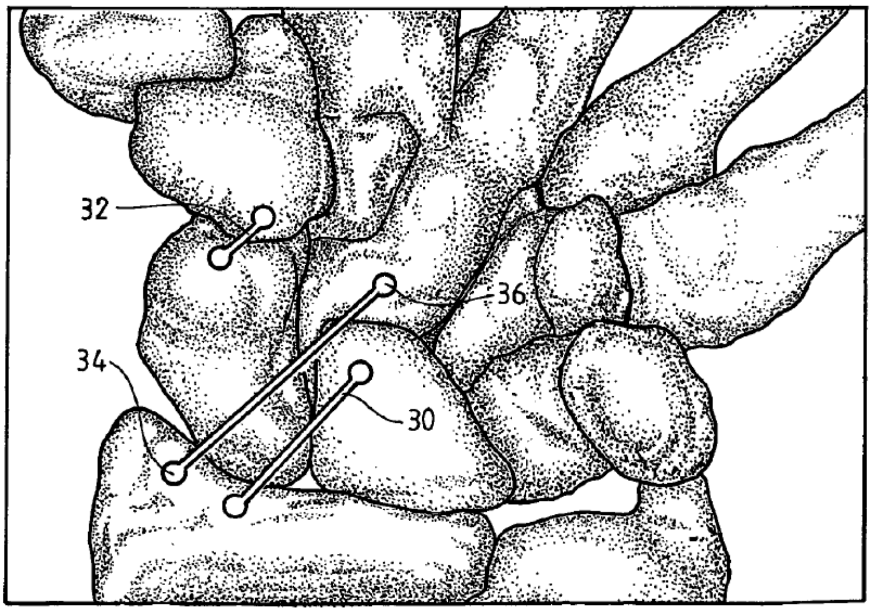

Fig 11

Further details on the patent are contained in Appendix 2.

Chapter Two – Stable Central Column Theory of Carpal Mechanics

Subsequently published as:

Sandow MJ, Fisher TJ, Howard CQ, Papas S. Unifying model of carpal mechanics based on computationally derived isometric constraints and rules-based motion - the stable central column theory. J Hand Surg Eur Vol. 2014 May;39(4):353-63.

Abstract

This study was part of a larger project to develop a (kinetic) theory of carpal motion based on computationally derived isometric constraints. Three-dimensional models were created from computed tomography scans of the wrists of ten normal subjects and carpal spatial relationships at physiological motion extremes were assessed. Specific points on the surface of the various carpal bones and the radius that remained isometric through range of movement were identified. Analysis of the isometric constraints and intercarpal motion suggests that the carpus functions as a stable central column (lunate-capitate-hamate-trapezoid-trapezium) with a supporting lateral column (scaphoid), which behaves as a 'two gear four bar linkage'. The triquetrum functions as an ulnar translation restraint, as well as controlling lunate flexion. The 'trapezoid'-shaped trapezoid places the trapezium anterior to the transverse plane of the radius and ulna, and thus rotates the principal axis of the central column to correspond to that used in the 'dart thrower's motion'. This study presents a forward kinematic analysis of the carpus that provides the basis for the development of a unifying kinetic theory of wrist motion based on isometric constraints and rules-based motion.

Level of Evidence - Non-clinical study

Introduction

In an attempt to explain carpal mechanics, there have been multiple studies based on detailed empirical observation. These include ex-vivo cadaver studies (Werner et al., 2005; Short et al., 2007) and motion capture techniques from in vivo wrist data derived from Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) scanning (Moojen et al., 2002; Moojen et al., 2003; Crisco et al., 2005).

However, these purely kinematic descriptions (Gardner et al., 2006) may not constitute usable and useful theories of carpal motion. A good theory must satisfy two requirements: “It must accurately describe a large class of observations on the basis of a model which contains only a few arbitrary elements, and it must make definite predictions about the results of future observations” (Hawking, 1996).

Because of the variation in carpal bone motion between wrists, a consistent and simple motion pattern has not yet been identified. It is therefore not possible to predict changes in normal and abnormal motion if such motion has not previously been studied or observed, which is in contrast to a good theory (Hawking, 1996).

Current carpal motion theories fail to achieve a consensus among researchers, are largely observational and thus poorly predictive, and are generally unable to test the effect of a particular intervention in one part of the carpus on overall wrist biomechanics. Consistent with this is the observation by Moojen et al. (2003) that “… a single functional model of carpal kinematics could not be determined.” as well as work by Galley et al., (2007) and others (Craigen and Stanley, 1995; Garcia-Elias et al., 1995; Moojen et al., 2002) who showed that there is a “spectrum of normal carpal kinematic motion”.

Kinematics describes the motion of bodies (objects) and systems (groups of objects) without consideration of the forces that cause the motion (Beggs, 1983; Bottema and Roth, 1979). Carpal Kinematics can be seen to comprise two components:

1. **Analysis (Inverse) Kinematics**, which aims to identify the parameters and characteristics of the wrist motion to create a record of the mechanics of the wrist (Tolani et al., 2000), and
2. **Synthesis (Forward) Kinematics**, which creates a model to allow predictions of spatial motion of the system components relative to each other but not the response of the mechanical system under a load or force (Bottema and Roth, 1979; Tolani et al., 2000).

Kinetics is concerned with what causes a body to move the way it does. It relates to the effect of forces and torques on the motion of bodies having mass (Bottema and Roth, 1979; Garcia-Elias, 1997).

Previous studies have been largely observational (Inverse) kinematic analyses. In contrast, Rules Based Motion (RBM) kinetic modelling states that the resulting motion of a solid body articulation is the net result of an applied load acting on the components of the motion system that have a defined mass, surface interaction and connections (Papas and Sandow, 2001). This mechanical concept implies the presence of four “rules” viz: 1. Bone morphology; 2. Inter-bone constraints; 3. Inter-bone surface interaction; and 4. Applied load (Papas and Sandow, 2001).

A kinetic (rules based) analysis identifies specific controls and constraints between the motion segments that are unique to each individual wrist. Thus, if these “rules” can be applied to an individual wrist, where these rules have been defined, there is a greater chance that some hitherto “unvisited” motion sequence can be predicted.

This study is as part of a bigger project to develop a unifying kinetic model of carpal motion based on computational analysis of the three-dimensional isometric constraints within the wrist, as both kinematic analysis and synthesis are required stepping stones on the way to creating the kinetic model (Bottema and Roth, 1979; Tolani et al., 2000).

While this approach may challenge some of the existing concepts, by examining the causes and controls of the carpal bones during motion, it is anticipated that a more unified theory of carpal mechanics could be developed. In reality this is likely to embrace and bring together many of the other wrist motion “theories”.

Further, once the “Rules” are identified, the kinetic model can determine the behaviour of the system when a force is applied to the constrained objects. This model would potentially explain variances that occur in normal and injured wrists, as well as test the effect of certain reconstructive interventions.

The specific aim of this part of the project was therefore to develop a forward kinematic analysis of the carpus which provides the basis for the development of a unifying kinetic theory of wrist motion based on isometric constraints and rules-based motion.

Methods

The project comprised a number of discrete stages:

1. Creation of three dimensional (3D) models of normal wrists taken from CT scans at extremes of radial and ulnar deviation using computer surface rendering software.
2. Identification of the spatial relationships between the bones of the wrist, and in particular the identification of computer-derived isometric points between specific surfaces on individual carpal bones and between specific carpal bones and the radius.
3. Identification of the patterns of isometric relationships on the volar and dorsal aspects of the carpus.
4. Based on isometric relationships and motion patterns, development of a forward kinematic model of the wrist that could be used to help create a unifying kinetic theory of carpal motion.

1. Creation of 3D models

Following institutional review board authorisation, CT scans (GE light speed RT8 helical scanner, GE Healthcare, UK) were performed of the right wrists of ten normal adults (8 men and 2 women). Their wrists were placed manually in each of the three positions at 30° of ulnar deviation, neutral and at 30° of radial deviation and saved to compact discs in a DICOM compliant format (Kabachinski, 2005). The wrist position during the CT image capture was established using a manual goniometer aligned with the long axis of the radius and the middle finger metacarpal.

The CT scans were taken at the lowest possible radiation dose (25mAs at 120 kV) consistent with adequate image resolution and clarity. To achieve adequate image generation, approximately 105 slices (0.625mm thick) were created for each wrist position. Three-dimensional models were generated using True Life Anatomy software (True Life Anatomy Pty Ltd, Adelaide, Australia,) which creates mesh models that could be animated and manipulated within a graphics environment in an OpenGL platform. The various bones of the carpus were then separated (segmented) into the radius, ulna, scaphoid, lunate, triquetrum and trapezium. The hamate, capitate and trapezoid were not routinely individually segmented, as these bones typically function as a rigid distal row (Taleisnik, 1976).

2. Identification of the isometric connections between individual carpal bones and between carpal bones and the radius

The spatial relationship between various bones of the carpus and the radius were analysed. We assessed the relationships between several pairs of bones looking for isometric points between the relevant bones throughout the ranges of movement. The bone pairs were: radius and lunate; radius and triquetrum; scaphoid and lunate; lunate and triquetrum; and scaphoid and trapezium.

To emulate carpal movement and allow assessments of distance between pairs of bones in various positions of wrist motion, the bones were tracked and animated using 3D software from True Life Anatomy (True Life Anatomy Pty Ltd, Adelaide, Australia,) and 3dsMax (Autodesk, Inc., California, USA).

To identify the location of isometric connections, both the dorsal and volar aspects of the respective bones were analysed using a standardised template pattern of points and numbering system. To reduce computational work, the selection of points for study was based on the likely approximate ligament attachment as described in previous cadaveric work (Berger, 2001), but without being localised to exact attachment descriptions. Between four and six points were selected on each of the bone regions, depending on the actual target area of the bone.

To validate the concept of specific locations of isometric constraints, the same template pattern of measurement points was applied to the opposite side of the bones and tested for isometricity. The extent of isometricity on the dorsal or volar aspect of certain bones pairs was then subjected to statistical analysis to establish a likelihood of isometricity occurring in specific region on specific pairs of bones.

The distances between the selected measurement points on each of the respective paired bone surfaces was measured using the “distance measure” and “compare” tools in the TLA software of the three wrist positions – at 30° of ulnar deviation, in neutral and at 30° of radial deviation (figure 1). All the measurements obtained were straight line distances, and not the distance around curved surfaces. While this may create potential measurement errors, almost all distances measured in this study were “line of sight”. This contrasts with an assessment of the paired points that may correspond to the radio-scapho-capitate ligament, which was not part of this study. There was a complete set of all measurements for all ten wrists.

A percentage change between the maximum and minimum lengths of each such connecting line was recorded. The measurements and percentage change in length was repeated three times and for each pair of points and an average recorded. Percentage differences of < 5% were designated as isometric connections (IC) points. The ICs that joined isometric points (IP) on various pairs of bones were regarded as representing the net effect of ligaments that constrain motion between those bones. This generally corresponds to a specific anatomical structure, but may actually be the net result of a number of ligaments. It is important to appreciate that the actual location and position of the isometric constraints where identified not on the basis of previously described anatomical patterns but by the computer software.

Data was analysed with log binomial generalised estimating equations (GEE) regression models (Liang and Zeger 1986). This was to determine whether the difference in the frequency of isometric lines between the ventral and dorsal bone regions was statistically significant. For the purpose of this analysis, IPs were defined as those connecting lines that varied by 10% or less. The GEE regression models were chosen, as the primary outcome is a binary variable. The analysis of these findings was based on the percent change in length of the connection lines between the paired bone surfaces each region, and identified that respective bony regions remained either isometric or non-isometric through the studied range of motion.

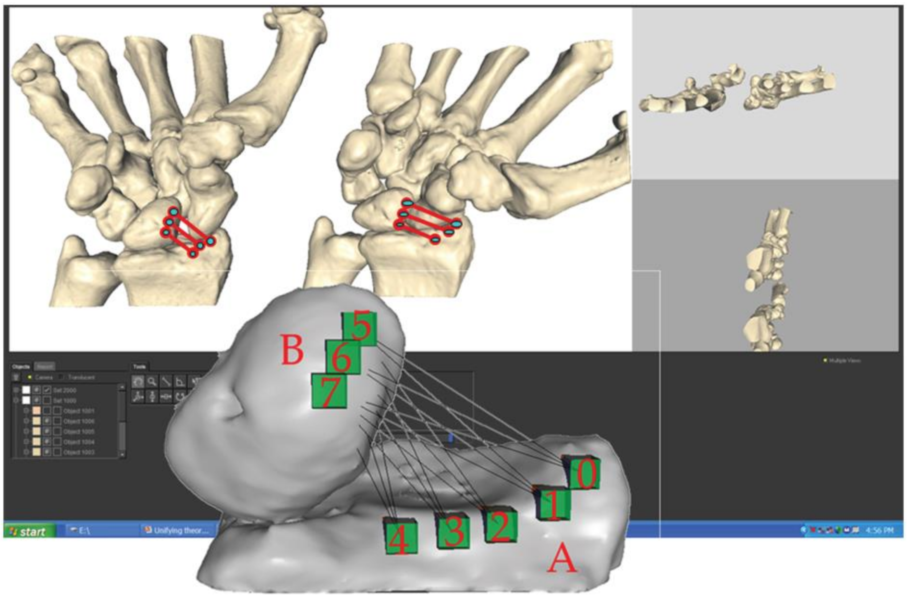

Figure 1. Example screen image generated by True Life Anatomy (True Life Anatomy Pty Ltd, Adelaide, Australia, www.truelifeanatomy.com) of a 3D wrist model, with the carpal bone segmented and measurement lines drawn between points on adjacent carpal bones in extremes of wrist motion. This example is of the assessment of isometricity on the volar aspect of the radius and lunate. (Published with permission JHS-Eu, Sandow et al. 2014)

3. Identification of the patterns of isometric relationships of bones of the carpus

Using the 3D animation software True Life Anatomy (TLA Animator, True Life Anatomy, Adelaide, Australia) and 3ds Max, (Autodesk, Inc., California, USA), the patterns of isometricity between each pairs of bone regions studies were determined by identifying:

isometric connections only on the volar aspect,
- isometric connections only on the dorsal aspect,
- isometric connections on both the volar and dorsal surfaces of the bones.

An isometric connection on both sides implied the bones move together throughout the range of motion of the wrists for these experiments.

4. Based on isometric constraints and motion patterns, development of a (forward) kinematic predictive model of carpal motion

To assess the respective spatial motion of the various components of the wrist, the geometric centre of mass (Centroid) of the bones (or groups of bones that moved together) of the wrist were identified by using the volumetric analysis algorithms in 3ds Max (Autodesk, Inc., California, USA), and TLA Animator (TLA Animator, True Life Anatomy, Adelaide, Australia) programs (Belsole et al., 1988). The centroid (the geometric centre of mass) is not the same as the centre of rotation, which is a point around which the object moves. For a body that moves with linear and angular motion, it is often not possible to have an instantaneous axis or point of rotation. This means that no single point in space, either within or outside the carpal bone remains stationary through the testing range. Therefore, the most convenient method of kinematic analysis of rigid bodies in 3D space is by using the principles of relative motion of the centroids (Belsole et al., 1988). By using modelling software, 3ds Max and Adams (MSC Software Corporation, California, USA) the dynamic relationships between components of the segmented carpus were reviewed to identify movement patterns. This looked specifically at the relative motion of the centroids of the individual segments of the carpus that appeared to move differently from other segments.

Results

Isometric connections between individual carpal bones and specific carpal bones and the radius

We identified patterns of isometric constraints between carpal bones corresponding to previously described ligaments. The occurrence of isometric lines was concentrated in specific areas and other areas demonstrated little or no isometricity (Table 1). There was a clear difference ($p<0.05$) between those areas (typically either volar or dorsal depending on the bones) that remained isometric and those that did not (Table 1). The IPs corresponded to previously documented ligament attachments (Berger, 2001).

Isometric connections were identified on the volar side of the wrist between the following joints:

- Trapezioscaphoid
- Radiolunate
- Triquetrolunate

Isometric connections were identified on the dorsal aspect of the wrist between the following joints:

- Scapholunate
- Radio-triquetral

It was not possible to measure the dorsal aspect of the trapezium and scaphoid because of overlap of the bones. In all subjects the overall shape of the distal row (trapezoid, capitate and hamate) did not change in the various carpal positions, indicating that they move together, and can therefore be regarded has having isometricity on the volarly and dorsally. Similarly, there was isometricity between the volar and dorsal surfaces of the trapezium and trapezoid, indicating that the trapezium moves with the distal carpal bones.

There was no isometricity on either volarly or dorsally between the triquetrum and the hamate, and there was no isometricity between the volar or dorsal surfaces of the lunate and the capitate.

The relative motion and spatial relationship between the carpal bones

An analysis of the spatial relationships between the carpal bones identified a number of distinct motion segments. Consistent with previous work by Taleisnik (1976), the capitate, hamate, trapezoid and trapezium moved as a single entity. These bones moved out of sequence with the other carpal bones (i.e. scaphoid, lunate, triquetrum and radius) which also moved relative to each other. The scaphoid, while attached to the trapezium and lunate, also moved out of sequence with other parts of the carpus, as did the triquetrum, despite its isometric attachments to the radius and lunate.

Study Subject	volar Radius Lunate	dorsal Radius Lunate	volar Scaphoid Lunate	dorsal Scaphoid Lunate	dorsal Radius Triquetrum	dorsal lunate Triquetrum	volar Lunate Triquetrum	volar Scaphoid Trapezium
1	1.48	10.44	7.95	1.80		6.50	0.97	2.09
2	4.38	5.83	14.45	1.82		6.96	9.71	2.81
3	0.15	18.66	8.28	4.01		4.72	5.12	1.15
4	2.93	6.08	9.23	5.54	5.52	13.79	6.61	4.92
5	1.22	10.04	6.88	1.45		3.63	3.09	2.32
6	3.92	3.55	1.48	5.45		8.24	3.53	5.17
7	2.10	8.27	2.82	0.57		11.71	1.21	0.03
8	1.39	14.70	1.83	2.99	11.10	14.29	1.07	4.61
9	0.87	11.25	9.94	1.25		28.36	5.36	2.84
10	2.26	7.64	5.75	0.15	8.49	6.73	3.01	2.61

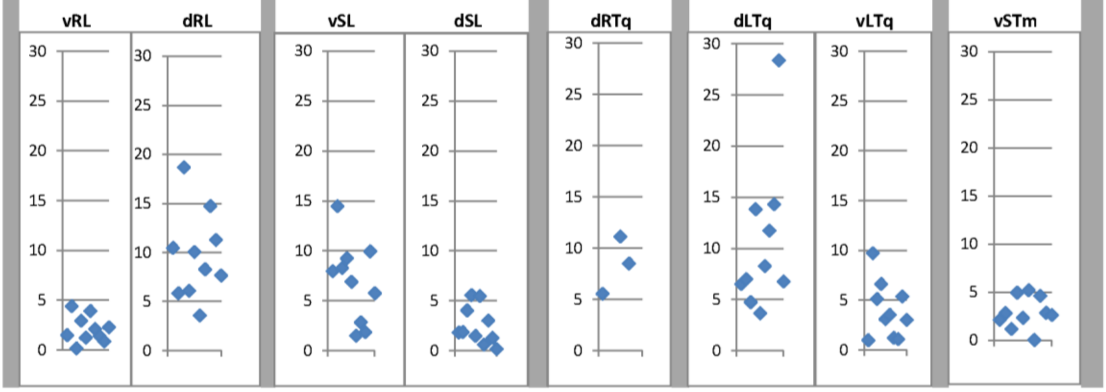

Figure 2. Average percentage change of the most isometric line joining points on the surfaces of respective bone pairs during extremes of wrist motion (at 30° of ulnar deviation, in the neutral position, and at 30° of radial deviation) in each region, in each of the 10 wrists studied. The statistical likelihood of a pair of bone surface regions being isometric is expressed as a p value where volar and dorsal regions could be compared. The statistical comparison related to the frequency of a pair of regions being isometric, not the occurrence of the most isometric line between each region. (Published with permission JHS-Eu, Sandow et al. 2014).

The triquetrum is connected to the radius, dorsally by the radio-carpal ligament and volarly via the lunate through the triquetrolunate and radiolunate ligaments. This would appear to give the triquetrum a role as preventing ulnar translation of the carpus as it is constrained in an oblique direction to the radius both dorsally and volarly (figure 3).

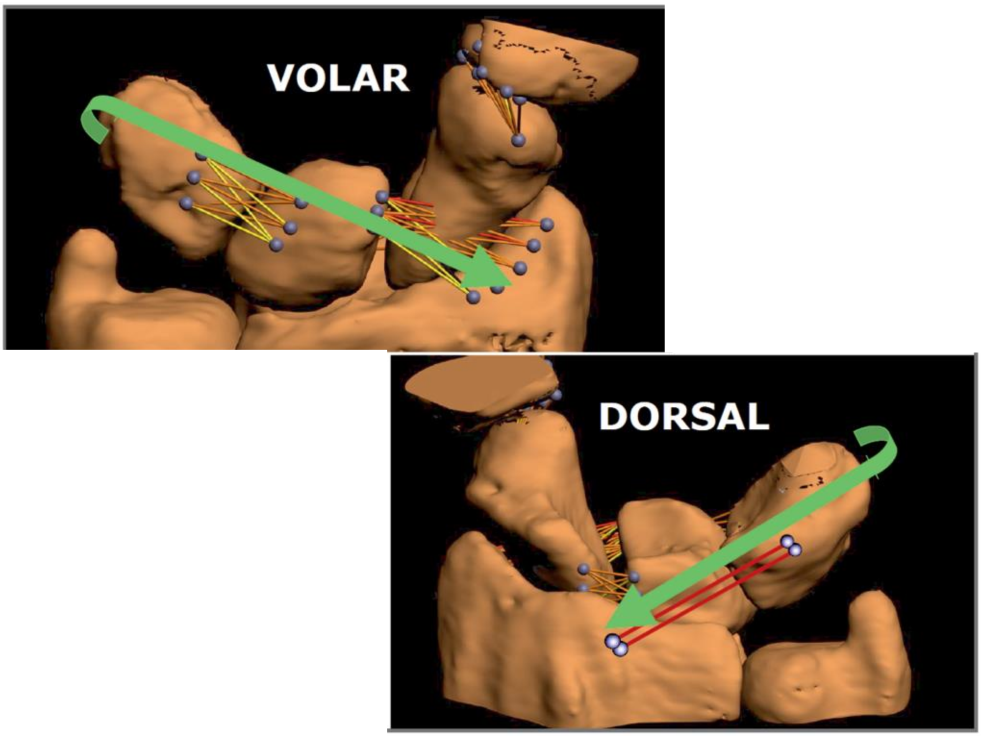

Figure 3. The triquetrum acts as an ulnar translation restraint of the proximal row of the carpus. The connection to the radius is directly via the radio–triquetral connection, and on the volar side via the interosseous ligaments attached to the lunate. The other areas of the carpus that demonstrated isometric connections are shown.

On the basis of the identified motion segments and previous work by others (Taleisnik 1976, Moritomo et. al. 2003), the proximal row therefore comprised the lunate alone and the distal row comprised the capitate, hamate, trapezoid and trapezium.

It was therefore considered that the wrist could be analysed as corresponding to four distinct motion segments:

- The distal segment (capitate-hamate-trapezoid-trapezium)
- Lateral column (Scaphoid)
- Proximal segment (lunate)
- Medial segment (Triquetrum)

Centroids were identified in each of the motion segments. The proximal row centroid (located in the lunate) translated radially with ulnar deviation and ulnarly with radial deviation. The centroid of the distal row of carpal bones (located in the central portion of the trapezoid) moved in a radial direction with radial deviation, and ulnarly with ulnar deviation (Figure 4). Therefore, the centroid of the distal and proximal rows moved in opposite directions during radial and ulnar deviation.

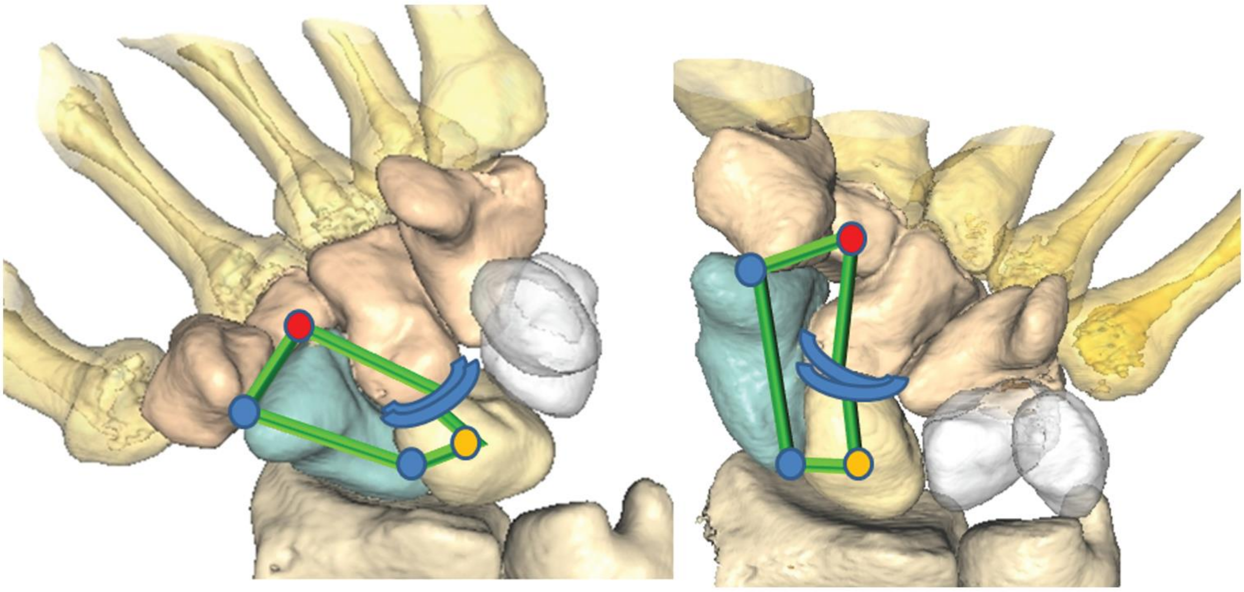

Figure 4. AP View – Diagrammatic representation of the motion pattern of the carpus with overlaid linkages (as green lines) of the proximal and distal carpal row. The blue dots represent the connection points of the scaphoid to the proximal and distal rows, the red dot is the centroid of the distal row, and the yellow dot is the centroid of the proximal row. The curved blue lines represent the cam motion between the two rows. The carpus appears to function as a Two-gear Four-bar linkage (Published with permission JHS-Eu, Sandow et al. 2014).

The translation plus rotation which occurred between the proximal and distal rows is constrained by the documented isometric connections. There are two linkages between the proximal and distal rows, one being the scaphoid's connection to the lunate and trapezium and the other through the capitolunate articulation, the latter acting as a ball and socket joint. These actual connections or articulations, plus their virtual linkages to the centroids, create four distinct arms (or bars) that form the carpus. This is more consistent with a two geared 4-bar linkage (Figure 4) rather than a slider crank mechanism. Five and four bar linkages are a well-recognised mechanical system and can incorporate an articulating joint or meshing gear as one or more of the linkages, thus creating an additional linkage which provides greater power transmission with more design flexibility (Muller, 1996, Zhenying, 2011).

Motion modelling software was used to identify that the principle axis of rotation of the distal carpal row was in a plane approximately 45 degrees pronated from the coronal plane of the radius and ulna, placing the trapezium anterior to the transverse plane of the radio-carpal joint. This appears to be in large part due to the trapezoid shaped trapezoid (Figure 4), which rotates the principal axis of the distal row of the central column to correspond to the “Dart Thrower Motion” (Brigstocke et.al. 2013, Crisco et al., 2005, Garcia-Elias et.al 2013, Wolfe et al., 2006).

On the basis of the apparent isometric constraints, motion patterns and axes of rotation, the carpus appears to consist of a stable central column which could provide a platform for the relatively immobile (with respect to the distal carpal row) index and middle finger metacarpals. The thenar and hypothenar rays are mobile and could act against the central metacarpals. Due to its connections to the trapezium and lunate, the scaphoid acts a stabiliser of the proximal and distal rows and the triquetrum acts as an ulnar translation restraint of the proximal row, and as a controller and restraint of lunate flexion (Figure 3 and 5).

Discussion

The analysis methods used in this study have been shown to be a powerful tool for quantitative kinematic in vivo analysis of carpal motion, and serve to provide insights into the complexity of wrist mechanics. By a combination of oblique isometric (ligamentous) constraints and obligate translation and rotation of the carpal bones, the carpus can achieve sufficient spatial excursion with essentially two functional degrees of freedom. These ligamentous structures resist indirect rotation force delivered by the forearm muscles, creating a wrist that is stable in rotation but allows motion in other directions. Only pitch (flexion-extension) and yaw (radial and ulnar deviation) are under active control by muscular loading delivered direct to the carpus. Although some rotation through the actual carpus has been suggested, giving the wrist an extra degree of freedom as rotation (Palmer et al., 1985; Garcia-Elias, 2008), the forearm muscles are not aligned optimally to control this motion vector.

The function of the wrist can therefore be seen to allow adequate excursion in space of the relatively immobile central metacarpals (second and third) with two degrees of freedom. These metacarpals provide a post on to which the more mobile lateral (first metacarpal) and medial (fourth and fifth metacarpals) rays can work – allowing thenar and hypo-thenar opposition. The connecting lines joining these isometric points (IP) largely corresponded to the previously described inter-osseous and extra-osseous carpal ligaments (Berger, 2001; Berger, 1997). However, it is important to appreciate that these connecting lines were computationally derived from the serially positioned 3D carpal geometric primitives and not by using existing anatomical descriptions or knowledge.

The lunate exhibits rotational and translational excursion during wrist motion yet has no tendon attachments. Lunate stability and motion are achieved through the obliquely orientated volar isometric constraint to the radius (corresponding to the long radiolunate ligament) which limits extension, and on the volar aspect to the triquetrum which acts as a flexion restraint. The lunate is attached on its dorsal aspect to the scaphoid which causes it to largely, but not completely follow the motion of that bone. The obliquity of the various constraints (in particular the long radiolunate ligament) allows stable lunate motion through a synchronous combination of rotation and obligate translation during radial and ulnar deviation.

The “ring theory” of Lichtman et al. (1981), suggests that the triquetrum plays an important role in stabilising the carpus on its medial side. However, this would imply some specific connection or fixed relationship with the hamate. Our study failed to identify any isometricity between the triquetrum and hamate, and this is consistent with the recent work of Moritomo et al. (2004, 2006) suggesting the motion between these two bones does not have a fixed link, but moves in an ovoid pattern.

There was however, a very clear isometric connection between the triquetrum and the radius on the dorsal aspect, corresponding to the dorsal radio-carpal ligament (Viegas, 2001), and indirectly via the lunate on the volar aspect. This suggests the triquetral connections are ideally suited to act as an ulnar translation restraint of the proximal row of the carpus, rather than having any direct role in vertical carpal stability (Figure 3). The connection to the triquetrum on the volar aspect to the lunate is also ideally suited to control lunate flexion. Triquetral flexion is in turn controlled by the dorsal radio-carpal ligament. The triquetrum thus contributes to vertical carpal stability, but only by its connection to the volar aspect of the lunate, and not with any specific linkage to the medial carpus or, more specifically, the hamate.

The difference may be the inaccuracy due to their manual selection of measurement points based on anatomical descriptions of ligament attachment. As distinct from Xu and Tang (2009), clear evidence of isometricity (< 5% variation) was identified, and this generally corresponded to the described ligament structures. It was evident that even minor variation in the position of the selected points on the surfaces of the bones to be assessed created quite large variation in connecting line length in the different wrist positions. As such, the existing description of ligamentous attachment may not exactly reflect the isometric points between various bones of the carpus in different individuals.

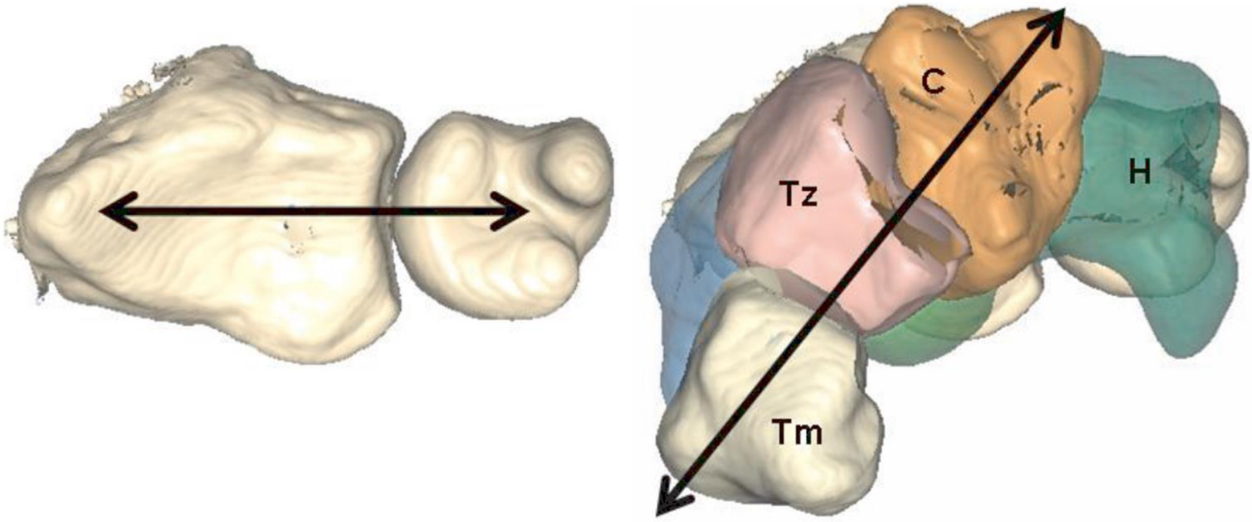

Figure 5. Axis of motion of the mid-carpal joint from the distal aspect corresponds to an angle of 45° to the transverse axis of the radius. Note the wider non-articular portion of the dorsal aspect of the trapezoid. This tends to push the trapezium anteriorly, thus rotating the prime mid-carpal motion axis in line with the dart thrower's motion.
Tm, trapezium; Tz, trapezoid; C, capitate; H, hamate. (Published with permission JHS-Eu, Sandow et al. 2014).

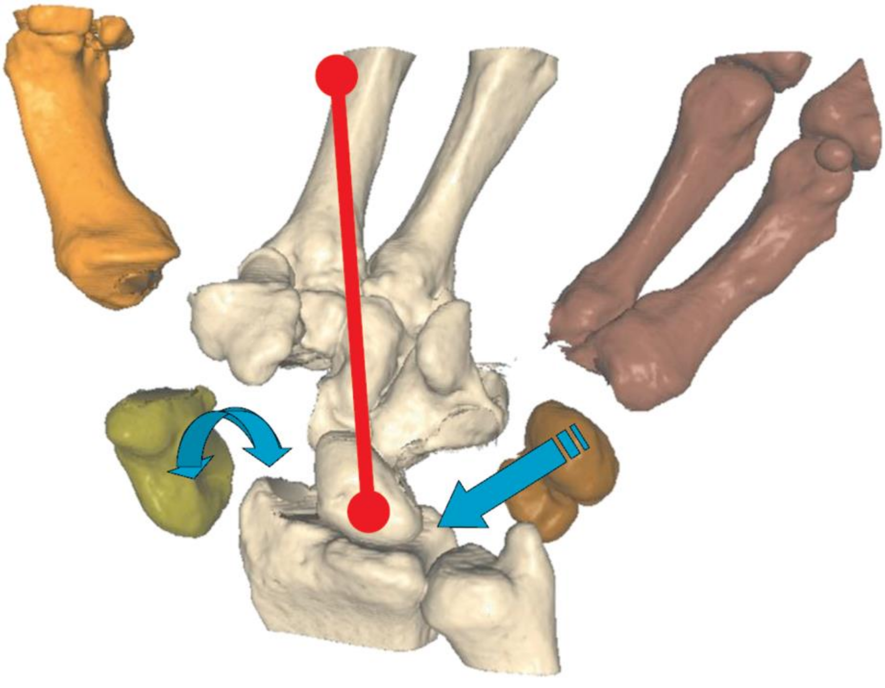

Figure 6. Stable central column theory of carpal kinetics. This consists of a stable central column that provides a platform for the relatively immobile second and third metacarpals. The thenar and hypothenar rays are mobile and act against the central metacarpals. The scaphoid acts as a stabilizer of the proximal and distal rows, and the triquetrum acts primarily as an ulnar translation restraint and as a controller and restraint of lunate flexion. (Published with permission JHS-Eu, Sandow et al. 2014).

It should be noted however, that the simplicity of straight isometric lines measured between bone surfaces may not entirely represent the actual interactions occurring within the carpus. Many ligaments do not run in straight lines, as they may at times pass over convex bone surfaces. Such interactions involving multiple other ligaments and the carpal bones should be considered in future work. The regions assessed in this study were largely connected by lines that did not have an intervening convex bony surface, and further, measuring around curves was outside the scope and software capabilities of this study.

On the basis of the computationally derived isometric constraints and inter-row motion identified in this study, the carpus appears to function as a stable central column (lunate-capitate-hamate-trapezoid-trapezium) with a supporting lateral column (scaphoid). The carpus can be seen as a closed linkage joining the radius to the bases of the metacarpals, achieving the required motion and stability. The carpus itself functions much more like a "Two–gear Four-bar linkage" (figure 4) than the traditionally described "slider crank". On the medial side of the central column, the triquetrum acts principally as an ulnar translation restraint, counteracting the tendency of the carpus to slide down the obliquity of the distal radius (Figure 5). This is very similar to Taleisnik (1976) and earlier Navarro (1921) but with a more defined supporting lateral column (Scaphoid) creating a four-bar linkage (incorporating two gears) – upon which tendons would act to achieve motion.

The "trapezoid" shaped trapezoid places the trapezium anterior to the transverse plane of the radius and ulna, and thus rotates the principal axis of the central column, and more specifically the mid-carpal joint, to correspond to that used in the dart thrower motion. This arc of motion change allows for obliquity of the palm for gripping objects parallel to the forearm, thus co-linearly extending the upper limb which has major implications with respect to tool use. A variation in the shape of the trapezoid alters the prime axis of the rotation of the distal row, and may thus explain cross-species variations in wrist function, particularly the ability to throw darts (Crisco et al., 2005; Wolfe et al., 2006). The anterior positioning of the trapezium and the attached thumb metacarpal may also facilitate tool use by allowing thumb pad to index finger pad holding, a function that is possible in humans but not in the chimpanzee (Young, 2003; Marzke, 2009).

The concept of the stable central column of carpal motion provides the basis for the development of a truly kinetic motion theory using the rule-based motion system, extending the central column concept described by Taleisnik (1976). This is consistent with the ideals of a good theory in that it provides a simplified description of a mechanical system based on isolated observations, it is predictive and it can be tested (Hawking, 1996). It unifies the mechanical observations derived from a range of previous researchers, in particular the intercalated segment motion of the lunate (Berger, 1997), the ovoid motion of the midcarpal joint (Moritomo et al., 2004) and, more recently, the dart thrower motion concept (Crisco et al., 2005; Moritomo et al., 2007).

By identifying the derived and implied rules of a particular wrist, proposed reconstructive procedures could potentially be applied to the mathematical model to predict actual outcomes in a particular patient or injury pattern. In the future, this may be able to identify the most appropriate reconstructive or repair procedure for the individual wrist with a particular injury pattern. Further work will be needed to develop and apply the kinetic theory to a range of injuries and validate the use of this quantitative analysis technology to plan more mechanically based treatments.

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Chapter Three – The Why, What, How and Where of 3D Imaging

Subsequently published as:

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The Why, What, How and Where of 3D Imaging

The collection of articles in this issue provides an indication of the increasing use and value of three-dimensional (3D) imaging in hand surgery. Increased access to 3D visualization techniques enables accurate diagnosis, improved comprehension of anatomical and pathological complexities, and potentially more reliable treatments, particularly of the wrist.

3D imaging is a natural evolution of computer tomography (CT) and magnetic resonance imaging (MRI) that capture 3D data, but traditionally transform this data into a 2D planar representation to allow a more familiar appreciation. The reality is, clinicians need an appreciation of patho-anatomy in 3D. Access to, and interaction with, image data within a 3D environment is likely to improve a clinician's 3D comprehension.

There are a number of challenges in the successful utilization of 3D. These can be explained and contextualized as the 'Why, what, how and where' of 3D imaging.

The **'WHY'** has been highlighted above, in that ultimately it is the surgeon's 3D interpretation of the pathology that is key to improving patient care. Diagnostic imaging investigations are performed in large part to assist this 3D appreciation.

In this issue, Garcia-Elias et al. (2014) demonstrate clearly the value of achieving a 3D perception of wrist motion and the implications for post-repair rehabilitation. In an earlier publication, Kunz et al. (2013) highlighted the value of planning the surgery prior to performing a multiplanar osteotomy. This is much more difficult and unpredictable if relying on the 3D perception of the surgeon, based on reviewing of 2D images, as done previously. These articles highlight the critical technical reality in that what is called 3D imaging is not a single entity. What type of 3D data is captured, and how it is displayed, will depend on the need, as well as the advantages and limitations of each type of data display technology – The **'WHAT'**.

The **'WHAT'** is a more difficult problem, and is at the core of the confusion over 3D imaging. There are essentially two distinct forms of 3D imaging or more specifically 3D data presentation. These are Volume Rendering (VR) and Surface Rendering (SR). The image data of the anatomical part studied is captured, particularly in CT scanning, as a series of points in space (called voxels – '3D pixels'), that have a specific spatial (x,y,z) location, and radiological (Hounsfield) density values.

In VR, these 3D data points are given a visual attribute such as colour or variable transparency, and the resulting image is projected as a type of shadow against the incident or viewing surface. This is thus a 2D projection of the 3D data set. This can be seen as a sort of coloured shadow of, for example, a tree projected onto a window. What is available is not a 3D model or object, just the projected 3D data on to a screen as a 2D image. This is called ray casting, which is a way to achieve a 2D projection of the 3D data, but not a true 3D object or model. As no actual 3D object is created, although the viewing aspects and proximity can be changed and areas can be masked out or hidden, it is not possible to manipulate or interact with the apparent 3D image, which in reality is a projected 2D image. Consequently, measuring distances, for example, is difficult as the measurement tools are applied to the projected imaging, not the actual 3D data points. Out-of-plane measurements are particularly unreliable. The images created can be shared as a series of screen captures (snap shots of a particular view), or alternatively, the entire data set can be shared, plus the various data manipulation values to reproduce the previously demonstrated views. This latter option requires significant computer capacity and is usually confined to the work stations attached to the CT scanner.

The majority of radiology imaging utilized today is based on VR. This has many advantages, including speed of image creation and the ability to fade and vary the transparency to provide appealing visual representations. As VR can provide a rapid simulation of the 3D anatomy, it is particularly useful in displaying moving anatomy, such as the motion of the heart, or to provide an impression of 3D motion of joints, as displayed in the article by Garcia-Elias et al. (2014).

However, it is in reality an optical illusion. As a 3D object or model is not created, what are seen are different 2D projections of the data set, not a moving 3D model. As a record, selected images can be saved as screen captures, or even as movies, but to select different or additional viewpoints of the imaged region, the 3D data needs to be reloaded and viewed in real time. This requires the loading of the entire data set. This is typically only available on the CT work station, or on selected high-capacity computers. There is widespread misunderstanding about the shortcomings of this form of 3D data imaging. It is not possible to utilize any 3D manipulative tools or separate and pull apart any of the component parts (such as the carpal bones). The various anatomical components cannot be moved independently or measured accurately.

While the radiologists' requirement to achieve a usable 2D image on their computer screen is well satisfied by the various VR programs, they are unable to provide the sort of measurement and manipulative needs of a surgeon who may want to perform virtual surgery or templating. A classic misnomer, used frequently in the imaging industry, is suggesting that VR can perform '3D segmentation'. This implies that the VR imaging technology is able to separate a 3D object into its component parts. As no 3D object exists, all the system is doing is modifying the 2D images by preventing the projection of certain parts of the imaged region. True 3D segmentation is not possible using VR, however challenging such claims can be problematic!

SR is quite different as an actual 3D model is created from the volumetric data; from CT scan data (as in the articles by Chen et al., Tan et al., and Sandow et al., 2014), by tracking devices attached to the skin (as in the article by Brigstocke et al., 2014) or by scanning the tissue surface (as in articles by Lee et al.2014 and Quigley et al., 2014).

When applying SR to CT data, boundaries (also called thresholding) between different tissue densities are identified and a series of points in space are created to mark out a layer between these different tissues in the 3D space. The computer program assesses the values of the voxels that define the anatomical information and identifies boundaries, such as between bone and muscle, or skin and air, and makes a virtual 3D model, based on those surfaces. This model, not the original data set, is used for the subsequent image display and manipulations. The points in space that define the boundaries are called nodes. They are joined by lines (called vertices) to create a mesh appearance and the area between the vertices is filled in (creating polygonal shapes) to create a surface layer. This is called a geometric primitive, which is made up of a polygonal mesh. This is the basis of virtually all design and manufacturing processes that use 3D modelling. SR creates a true 3D object that can be manipulated and modified by a range of interactive tools. Once the model has been created, the original scan data are removed and all further manipulations are on the 3D model derived from the original scan data, not the scan data itself.

Surface shading (as distinct from surface rendering) is a form of VR in which the closest voxels are made opaque, and a shadowing effect created to simulate surface contouring. This gives the appearance of an interactive surface, but as this does not actually create a true 3D object, has the limitation of VR as detailed above.

The **'HOW'** of 3D imaging is that current diagnostic imaging almost exclusively creates VR images, whereas almost everywhere outside radiology creates true 3D mesh models utilizing SR. There are numerous imaging processes that can utilize a 3D surface rendering system, as is well shown in the articles in this issue. In the medical world however, these are largely research tools, and virtually none of these are used currently in clinical medical diagnostic imaging. This is primarily because the perceived needs of those requesting a '3D image' as part of patient care will be delivered by the 2D snap shots created by VR.

Each way of presenting the 3D data set has advantages and disadvantages (as explained above), and in medicine they are very much complimentary. 3D animation movies and video games all use surface meshes, not VR. To suggest the '3D' images that a radiologist creates have any of the capabilities of other (entertainment or manufacturing) industries indicates a significant lack of technological comprehension.

The **'WHERE'** of 3D imaging depends on the need. If a simple (essentially non-manipulable) 3D image is required, or the data set is best projected as a volume rendered image due to the size of the data set, such as in cardiac imaging, then VR works well. If accurate measurement, tracking through space or more complex segmentation is required, then VR will not deliver. SR technology is not generally available through existing radiology imaging pathways, but development in DICOM integration and PACS data management will allow this transition in the future.

This issue of the journal demonstrates quite clearly the advantages of each of these 3D image creation modalities. It also places the strengths and weakness in context, which is supported by comments in the article by Garcia-Elias et al. in this issue that: 'true 3D analysis can only be done with true polygonal mesh 3D objects. VR can extract animations rapidly to gain an appreciation of motion; however, this is only an approximation that must be validated using specific 3D object tracking.

The series of articles in this issue of the journal are an indication of the potential for advanced imaging in hand surgery, and in particular the power of 3D image analysis. With an appreciation of the how, why, when, and where of 3D imaging, the value and limitation of the approach used in each of the various articles can be appreciated and seen in context – to increase our understanding of the mechanics of the hand and wrist.

Conflict of interests

Editor-in-Chief's note: Associate Professor Sandow has a commercial interest in the development and utilization of 3D imaging technology, and in particular surface rendering. He is the senior author of an article included in this issue. This was an invited commentary in view of the author's significant experience and understanding of the imaging technology, however, any comments on the advantages or otherwise of the imaging technology in which he has been involved are his own, and not necessarily the view of the journal.

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Chapter Four – 3D Dynamic Analysis of the Wrist

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3D Dynamic Analysis of the Wrist

Abstract

With advances in imaging and computing technology the greater capacity to diagnose, plan and deliver care to patients with hand and wrist disorder is being realised. Work in our laboratory, has been able to identify certain specific rules that control wrist motion, and is a step on the pathway to creating a unified theory of carpal mechanics which will incorporate a kinetic biomechanical model. This will allow more precise anatomically based as well as quantitative diagnoses, but also an ability to test a proposed intervention in a "what if" scenario.

Introduction

As surgeons we work in 3 dimensional environments as part of our analysis and treatment of hand and wrist disorders. We need to think 3 dimensionally to effectively make the correct diagnosis and deliver the appropriate treatment. However, many medical technologies such as plain radiographs and ultrasound impose two dimensional restrictions which limit the ability to diagnose and treat patients effectively.

The wrist in particular has very complex mechanics. Despite considerable work and attempts to explain this with various observational investigations utilising both cadaveric and in human measurements and many so-called theories have been proposed a unifying understanding of carpal mechanics has been elusive. However, a theory as defined by Hawking[1] should be a description of a mechanical system based on a relatively limited number of observations, should be predictive and testable but as with all theories cannot be proven. Most of the existing descriptions and explanations of carpal mechanics have not successfully achieved these components of a theory.

3D motion analyses of carpal bones

In our laboratory, we have been working on dynamic 3-dimensional imaging since the mid 90's to develop an appreciation of 3D spatial carpal relationships to better understand the wrist motion. This work first started following confusion, in fact a direct challenge, regarding the relationship of the lunate and the distal ulna in radial and ulnar deviation. Our initial work, on my own wrist, showed that the lunate move well away from the ulna on ulnar deviation and the ulnar lunate impaction occurs in radial deviation, not as often assumed.

More curious were the movement of the lunate on coronal wrist motion, and the dilemma of how it is constrained and controlled. By using a reverse engineering software analysis, it was evident that there was a region on both the lunate and volar radius that remained isometric through range. Although not described at the time, this anatomical region now corresponds to the long radio-lunate ligament.

As an extension of the work by Taleisnik,[2] we have developed his concept to describe the "Stable Central Column of Carpal Mechanics" (figure1). This work expanded to review the relationships between the proximal and distal row of the carpal as well as the radius, allowing us to propose a complex linkage controller of the carpal mechanics. – Two gear four bar linkage (figure 2). This opens the way for quantitative 3D analysis of motion in the wrist, both normal and pathological, with an option to build a mathematical model to both explain the injury, but also allow a "what if" capability to test potential surgical solutions.

This work has now been published in the European volume of the Journal of Hand Surgery (Sandow et al. [(3)]) and complete details can be seen there. In summary however, the study design was to create a 3D mesh model of the wrist in several positions (radial and ulnar deviation) and then analyse the relationship between the various bones. By identifying those regions on the bones that remain isometric the position of the stabilising ligaments can be imputed. This is a crucial step in the development of a mathematical model to explain carpal motion. This anticipated kinetic model incorporates the bone shape and size, the isometric constraints and then adding a measure of the interaction between the bones such as friction as well as the loading patterns delivered by the tendons.

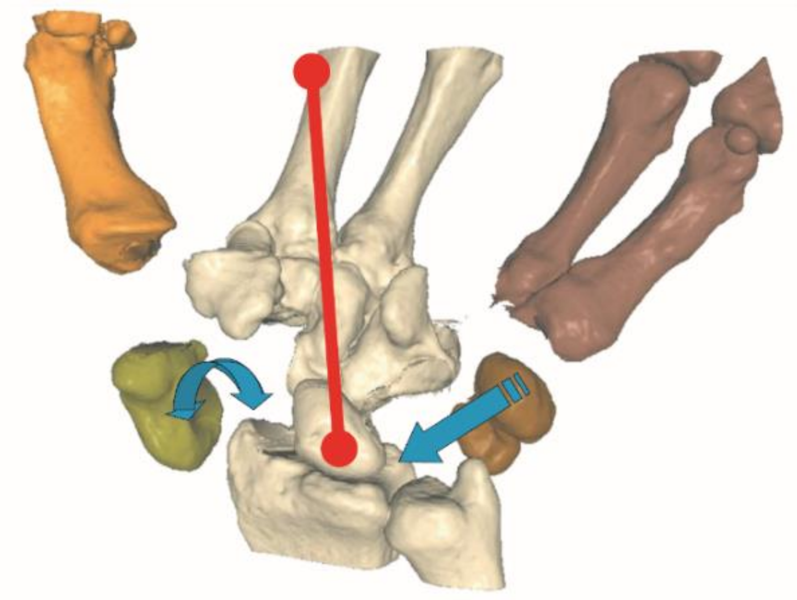

Figure 1. Stable central column theory of carpal kinetics. This consists of a stable central column which provides a platform for the relatively immobile 2nd and 3rd metacarpals. The thenar and hypothenar rays are mobile and act against the central metacarpals. The scaphoid acts a stabiliser of the proximal and distal rows, and the triquetrum acts primarily as an ulnar translation restraint and as a controller and restraint of lunate flexion.[3]

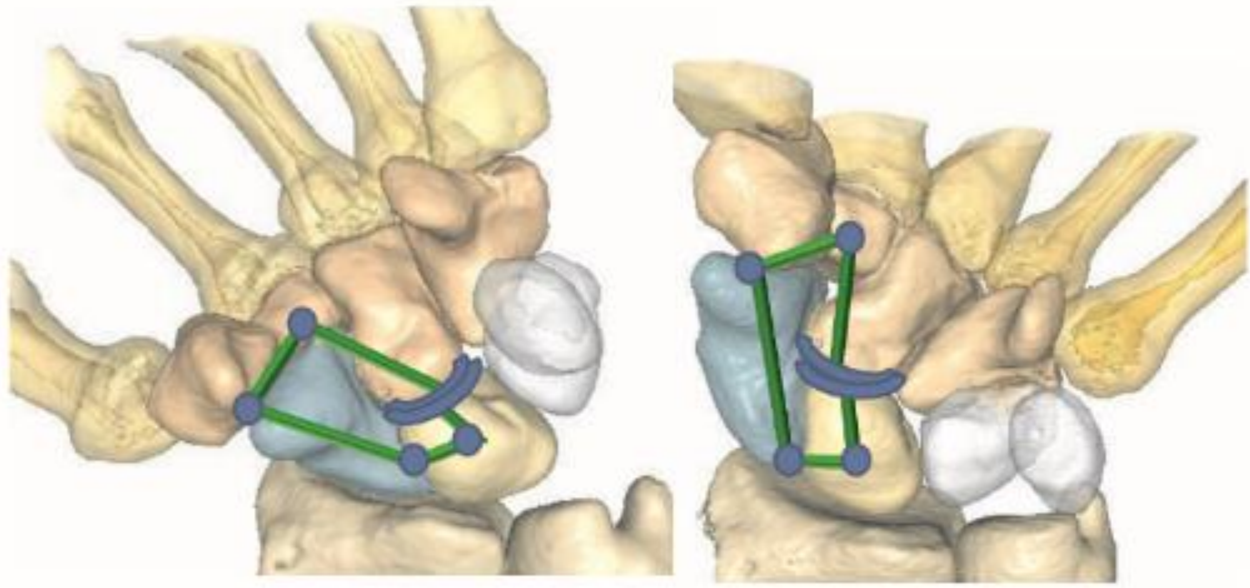

Figure 2. AP View: Diagrammatic representation of the motion pattern of the carpus with overlaid linkages (as green lines) of the proximal and distal carpal row. The blue dots represent the connection points of the scaphoid to the proximal and distal rows, the red dot is the centroid of the distal row, and the yellow dot is the centroid of the proximal row. The curved blue lines represent the cam motion between the two rows. The carpus appears to function as a Two-gear Four-bar linkage.[3]

This has been developed as rules-based motion analysis. “Rules Based Motion (RBM) kinetic modelling states that the resulting motion of a solid body articulation is the net result of applied load acting on the components of the motion system that have a defined mass, surface interaction and connections.[4] This mechanical concept implies the presence of four “rules” viz:

1. Bone morphology;
2. Inter-bone constraints;
3. Inter-bone surface interaction; and
4. Applied load”.[3]

This is currently being developed into a kinetic model of carpal mechanics to provide both diagnostic capabilities but also pre-test surgical solutions based on the patient’s own anatomical and motion characteristics.

One of the major efforts in our work to date is to bring together the various observational kinematic analyses into a unified theory of kinetic motion for carpal mechanics, and this is reflected in the title of our recent publication.

3D visualization of the wrist for pre testing

The work in this area being expanded to extend this into clinically usable and relevant kinetic modelling and what if analysis for the pre testing of potential reconstructive solutions.

As well as the potential to explain and pre-test carpal motion in a dynamic way, there are many advantages with an improved 3D static visualization of the carpal, and none more evident than in the management of scaphoid injuries. These include the ability to:

1. Identify an injury and its particular characteristics, particularly where the fracture pattern is complex
2. Characterize secondary effects of a specific injury, including associated carpal instability
3. Plan the surgical approach and deformity correction
4. Perform virtual surgery to pre-operatively assess an anticipated or planned reconstructive option.

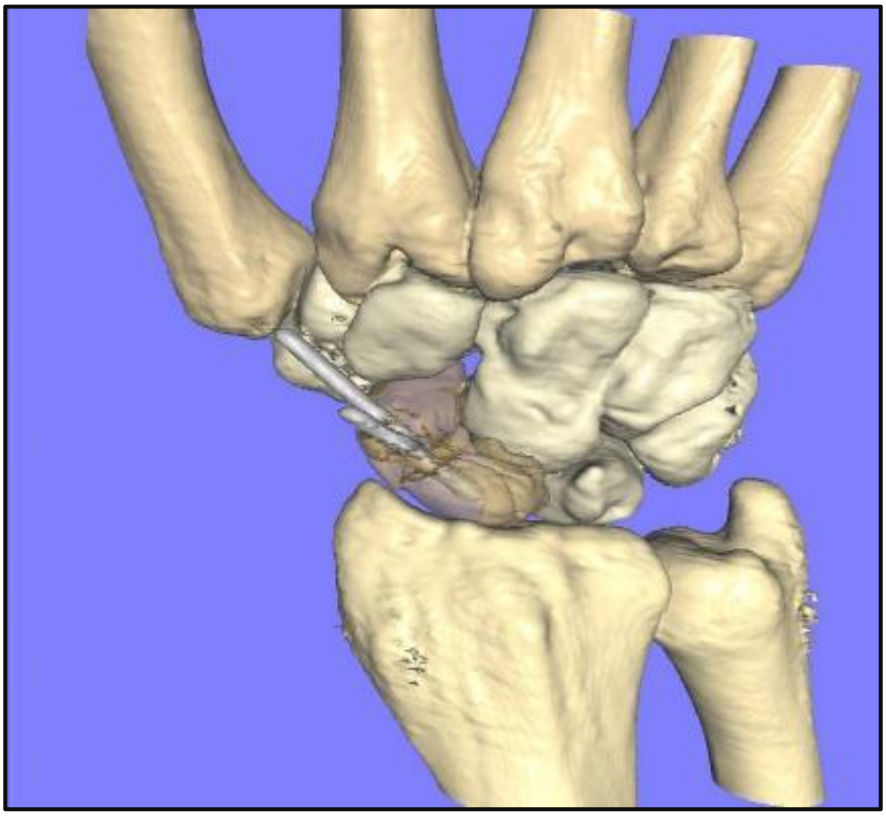

Figure 3. Showing previously inserted k-wires within the scaphoid.

Visualization of complex carpal injury allows for a faster, more confident appreciation of the injury and treatment decisions, and allows a quantitative analysis for accurate planning, staging and assessment. Improvement in patient care and explanation provides clinical confidence, reduces surgical time, cost and invasiveness.

This 3D capability has also allowed us to better analyses problems such as those that may occur following distal radial fractures and particularly radial mal unions. By creating a true 3D model, virtual surgery can be performed on the created 3D mesh model to pre plan the surgery and in particular the appropriate plates that may require and the direction and extent of the osteotomy. This has provided significant increased capabilities in terms of planning and understanding the surgical requirements. The big advantage of this sort of approach is that by being entirely computer based, the requirements for models and actual physical devices is reduced and thereby reducing the cost but still allowing the capabilities to understand and plan the surgery.

The further work that is currently under way is to analyse the ideal plates that may be required for a particular distal radial fracture. Most radial plates are designed based on an intact radius. With this 3D manipulative capability and by the analysis of a range of distal radial fractures, the fracture reduction can be performed virtually and the appropriate implant trialled.

With more complex surgery, the capabilities to analyse and pre-test in 3D will become increasingly valuable and with advanced computer power now becoming a convenient reality. At the moment the work that we are doing is based on some research-based software which is not commercially available but there are a number of other systems from various other companies that are offering similar capabilities.

The ability however to extract the isometric constraints of a particular motion system I think has substantially increased capabilities in the longer term to provide quantitative diagnosis of particularly joint injuries and then when combining this with finite element (FE) analysis again can pre-test various operative solutions and then to assess whether the outcomes match the predictions.

Conclusions

We are entering a brave new world in terms of IT facilitation of our surgical capabilities however the tools need to be simple, intuitive and configured to suit the surgical requirements without requiring a large degree of back end technical support. Further work in our laboratory involves extending the diagnostic capabilities to other joints such as the shoulder and even the hip where problems such as femoro-acetabular impingement can be very effectively demonstrated. The important part of the work recently published of unified diagnosis is to try and identify a true theory which as detailed in that publication has hitherto been relatively absent from the discussions on carpal mechanics.

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Chapter Five – Computer Modelling of Wrist Biomechanics - Translation to Specific Tasks

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Computer Modelling of Wrist Biomechanics: Translation into Specific Tasks and Injuries

Abstract

Background: The carpus is a complicated and functionally challenged mechanical system, advancements in the understanding of which have been compromised by the recognition that there is no standard carpal mechanical system and no typical wrist. This paper covers components of a larger project that seeks to develop a kinetic model of wrist mechanics to allow reverse analysis of the specific biomechanical controls or rules of a specific patient's carpus. Those rules, unique to each patient, could be used to create a forward synthesis mathematical model to reproduce the individual's anatomical motion in a virtual environment.

Objective and methods: Based on previous observations, the carpus essentially moves with only two degrees of freedom—pitch (flexion/extension) and yaw (radial deviation/ulnar deviation)—while largely preventing roll (pronation/supination). The objective of this paper is, therefore, to present the background and justification to support the rules-based motion (RBM) concept, which states that the motion of a mechanical system, such as the wrist, is the net interplay of four rules: morphology, constraint, interaction, and load. The stable central column theory (SCCT) of wrist mechanics applies the concept of RBM to the carpus, and by using a reverse engineering computational analysis model, a consistent pattern of isometric constraints was identified, creating a "two-gear four-bar" linkage. This study assessed the motion of the carpus using a 3D (three-dimensional) dynamic visualization model. The hypothesis was that the pattern and direction of motion of the proximal row and the distal row with respect to the immediately cephalad carpal bones or radius would be similar in all directions of wrist motion. To identify the unique motion segments, 3D models were created from five normal wrists that underwent CT scanning in multiple positions of radial and ulnar deviation as well as flexion and extension. Each carpal row (proximal and distal) was animated in a virtual environment with the cephalad carpal bones or radius held immobile. The rotational axis and position of each bone and each row were then compared in sagittal (flexion-extension) and coronal (radial and ulnar deviation) motion.

Results: The carpus appeared to have only two degrees of freedom, and yet was stable in those arcs with the loads applied proximally in the forearm. The proximal row moved in a singular arc, but with a varying extent during sagittal and coronal motion. The isometric constraints were consistent in both directions. The distal row moved on an axis formed by a pivot joint laterally (between the trapezium and scaphoid) and a saddle joint medially (between hamate and triquetrum). The sagittal and coronal alignment of this axis changed as the proximal row moved. This created a distinct pattern of row motion to achieve the various required positions of wrist function. On wrist radial deviation, the scaphoid (with the proximal row) flexed and the distal row extended, whereas in wrist flexion, the scaphoid flexed (with the proximal row) and so did the distal row. The pattern was reversed in the opposite wrist movements. While the general direction of motion of each row was consistent, the extent was quite variable.

Conclusion: This review supports the SCCT of carpal mechanics and the carpus acting as a two-gear four-bar linkage, as well as the concept of RBM as a means to understand the biomechanics of the wrist, and how this is translated into specific functional tasks. More sophisticated 3D modelling will be required to further understand the specifics of carpal motion; however, reverse engineering of the specific rules that define each individual wrist can also be applied to a mathematical model to provide a “what if” test of particular surgical interventions for a variety of wrist injuries. The use of quantitative 3D Computed Tomography Scan (CT) analysis, surgical planning and virtual surgical intervention allows potential surgical solutions to be applied to a computer model of an injured wrist to test the possible outcomes and prognosis of a proposed treatment.

Introduction

For hand surgeons, an appreciation of the anatomy of the wrist is critical. The work of Dr Lou Gilula has been pivotal in furthering the understanding of the relationships of the proximal and distal carpal row on plain x-rays. The “Gilula’s lines” [1] are an embedded part of the initial training of any hand surgeon and have saved many a wrist from misdiagnosis by simply ensuring that the arcs lined up and any break needed to be explained and addressed.

This paper, which is written in recognition of the efforts of Dr Gilula, aims to provide an increased appreciation of 3D imaging, which has improved the understanding of wrist biomechanics as required for various specific tasks. Inherent in the understanding of the mechanics of the wrist is the development of a specific theory to explain the biomechanical construct. The underlying premise is that the specific biomechanical constraints and rules for the wrist can be identified and are based on the theory of wrist mechanics that has been previously presented and published.[2]

In the past, many of the so-called theories used to explain wrist mechanics by observational accounts of motion recorded in various ways, either clinically, using step frame animations of three-dimensional (3D) models, or using various tracking techniques both in vitro and in vivo. [3–6]

However, a true theory describes a biomechanical system using a relatively limited number of observational records, can be tested, cannot be proven and more importantly needs to be predictive.[7] The majority of historical carpal motion theories have failed to meet one or more of these basic criteria. In contrast, underlying the stable central column theory (SCCT) of wrist mechanics is the concept or law of rules-based motion (RBM).[8] This law states that the resultant motion of a dynamic system is defined by:

- The morphological components of the motion system and, in this situation, the bones
- The constraints between the bones and, in this situation, the isometric ligaments that have been identified in 3D motion testing
- The interaction between the bones; this can be an applied variable based on friction and motion between the bones, which is a feature of the surface interaction and friction
- The applied load.

This provides a mathematical and, potentially, a kinetic explanation that fulfils the criteria of a true theory and that is a prerequisite to the ability to perform computer modelling of wrist mechanics with translation into specific tasks.

Dr Gilula's contributions formed the basis for defining the two-dimensional (2D) relationships of the carpus and identifying a gross disruption. However, the components of wrist have a complex 3D relationship, and surgeons operate within a 3D environment. Therefore, a surgeon must have a 3D appreciation of the anatomy and the injury to effectively make the correct diagnosis and deliver the appropriate treatment. The term 3D imaging or display is a widely used term; however, the current discussion refers to the display format that aims to convey an appreciation of the anatomy or injury in 3D to the treating clinician. The brain must interpret the images that are being presented to achieve an actual 3D concept of the anatomy or injury. This is a complex process which can be achieved in a variety of ways.

It is important to understand what 3D imaging means, and the limitations, constraints, shortcomings and advantages of its various technologies. The majority of currently available radiological imaging is based on a volume rendering (VR) process. VR provides a real-time projection of the 3D data (typically Computed tomography (CT) volumetric data) set as a 2D planar image, but does not actually create a 3D object. The projected image can be saved as a series of screen captures, but there is no capacity to perform any form of 3D object manipulation or virtual surgery, as there is no 3D object – just a 2D projection of the 3D data set [9,10]

VR offers significant advantages in terms of the viewing of multiple tissues, the demonstration of subcortical defects and the identification of minimally displaced fractures. The technique handles artefact and complex surfaces more easily than surface rendering (SR).[11]

Using VR, the interactive image can be transmitted to a remote computer with the appropriate viewing software via a network, but the image in that station will remain only while it is “live” on the primary workstation. Once the application is closed or the computer is turned off, the interactive 3D image is lost. The pathway to create the 3D image can be saved; however, to review it at a later time, the relevant dataset must be reloaded into the computer workspace and, using the predetermined values, the image recreated. A geometric 3D model is not created and so there is nothing to save. The concept is akin to trying to save an image of a hologram.

In surface rendering (SR), the object within the volumetric dataset is specified by identifying the object’s boundary or edges. Although it is not the only way, these boundaries are usually identified on the 2D CT slice images using thresholding, a technique in which a density value of the interface between two materials (e.g., bone and soft tissues) in the dataset is selected so that the object surface can be identified for rendering. Once this boundary has been identified, the surface reconstruction can be rendered using conventional computer graphics techniques. Only a single object or boundary surface can be extracted at each rendering which is represented as a series of meshes or polygons, visualizing the outer (and inner) surface., SR treats objects as having a surface of virtually no thickness and of a uniform colour; however, adding shadows by varying the source of light can demonstrate contours.

Clinician access to a true interactive three-dimensional object derived from the CT data substantially improves the ability to plan, demonstrate proposed procedures to patients, and even perform some form of virtual surgery or arthroplasty templating. With the increasing use of radiology networks and technology, volume rendered 3D images are now more readily available in clinical settings. However, because of the nature of VR techniques, this image data has limitations as an interactive tool for surgeons.

The ability to perform computer modelling relies on access to SR and 3D mesh animation technology with an intuitive graphics interface to optimize the clinical usefulness of the CT scan image data.

Normal Wrist Mechanics

A key element in the study of wrist mechanics is to understand why the wrist is such a complex mechanical construct and, further, why the identification of a “typical” and predictable wrist motion model has eluded researchers.

Moojen et al. [3] claim that there is no standard wrist and, therefore, an attempt to identify a specific pattern of wrist motion that defines the behavior of individual bones and the total construct under load has been elusive. The premise underpinning the work of Sandow et al. [10] is that the wrist is best analyzed using the RBM concept. Each of the factors—1) component morphology, 2) isometric constraint/connection, 3) interaction between the components, and 4) applied load—can be varied to produce the resultant biomechanical outcome. Changes to one factor, for example the shape of the bones, will typically require a change in one or more of the other factors or rules to achieve the same final outcome.

The other important concept for consideration when addressing the complexities of the wrist is that according to the law of parsimony,[12] the wrist is unlikely to be any more complex than is necessary to achieve the required mechanical tasks, but must still be able to achieve the demands placed upon it. Einstein has stated that "everything should be as simple as possible but no simpler." [13] The wrist, therefore, is as complex as it needs to be to achieve its functional outcome. By inference, if a more basic construct would have achieved the required mechanical outcome, then the apparent frailties of the wrist in terms of fractures, ligament disruptions and other weaknesses would have disappeared due to evolutionary pressure.

These concepts can be applied to the wrist as part of the process of computer modelling for both normal and pathological motion. To achieve an adequate range of flexion and extension within the constraints of maintaining vascular supply to the various components, some form of double articulation is required. However, this would create an inherently unstable linkage.

Further, the requirement of the wrist to function in confined spaces necessitates that the muscles that drive the various functions of flexion, extension, radial and ulnar deviation, and forearm rotation are proximal to the wrist itself to maintain the narrow profile. This differs from the other joints such as the hip or the shoulder, in which the muscles powering those activities surround the actual joint, creating a bulky profile. The functional requirements of the wrist create significant difficulty in terms of providing circumduction by a combination of flexion and extension as well as radial and ulnar deviation, while preventing any longitudinal rotation through the carpus itself.

This is achieved through a series of oblique ligaments, including the scapho-capitate and the dorsal radiocarpal ligaments, which largely prevent rotation through the radiocarpal joint. Forcible supination and pronation of the radius around the ulnar powered by proximal forearm muscles—such as the pronator teres, pronator quadratus and supinator, and as well as biceps—is transmitted through the carpus, by its rigid connection to the forearm that resists rotation through the radio-carpal joint While some authors, such as Garcia Elias, [14] have suggested that there is a dynamically controlled supination and pronation of the wrist, the muscles that would provide active control of such rotational forces are clearly not in the optimum alignment. While there is a certain degree of laxity within the carpus itself, the majority of the pronation and supination power and control is generated well proximal to the wrist and delivered to a rotationally stable radiocarpal articulation. This ensures that the wrist can work in confining spaces while delivering power in all vectors.

A further feature of the human carpus is the so called “dart thrower’s motion.”[15] This implies that the predominant functional arc of motion in many human activities is in the oblique arc of the wrist—in particular from radial extension to ulnar flexion. Recent work has demonstrated that the majority of this activity occurs through the midcarpal joint, with minimal motion through the radiocarpal joint in this dart throwing motion arc.[15] However, flexion and extension occurs predominantly through the radiocarpal joint whereas the oblique dart throwing motion occurs from the midcarpal joint. This suggests, therefore, that the two joints are rotated with respect to each other.

In previous work on the SCCT, Sandow et al. [10] identify that this twist in the midcarpal joint most likely occurs through the unique shape of the trapezoid, which translates the trapezium anteriorly with respect to the coronal axis of the proximal carpal row. This volar position, when combined with the specific connections of the trapezium scaphoid joint, creates a motion segment through the midcarpal joint, which is at an angle of approximately 45˚ to the radiocarpal joint. The unique socket-type articulation that the capitate and hamate form within the sulcus created by the triquetrum and the lunate, combined with an array of socket-deepening ligaments, ensures that the distal carpus articulates in an almost cylindrical fashion between the constraint formed by the triquetrohamate joint and the controlling fixed pivot point through the scaphoid trapezium articulation. This provides an elegant transmission of forces through the midcarpal joint and the radiocarpal joint, which are approximately 45˚ offset, and, therefore, specific to different functional activities.

The oblique nature of the midcarpal joint is particularly important for human activities in that it allows for an oblique power grip. This is critical in facilitating activities such as holding a spear or shaft as well as throwing, as the throw can occur in an oblique fashion in line with a sight aiming capability, a function which is denied for primates. In a primate wrist, the trapezoid is triangular and does not translate the trapezium in a volar direction to the same extent as the human wrist. The biomechanical consequence of this anatomical arrangement is that primates’ midcarpal axis is less pronated than humans’ and, therefore, the maximum obliquity within their midcarpal joint is less than that in humans. This precludes an efficient oblique power grip, translating to a reduction in the ability of the primate wrist to efficiently throw objects (such as darts) or to hold or use a heavy object such as a spear in a functional or defensive fashion. To achieve the degree of complex functionality, the wrist requires a degree of necessary complexity. This is offset by Occam’s razor [12] and rings true to Einstein’s concept that “everything should be as simple as possible but no simpler.”[13] The wrist, therefore, becomes an exciting puzzle to unravel rather than a confusing apparently overly complex collection of linkages that surely could be simpler.

Basic biomechanical concepts have been proposed in attempt to explain carpal mechanics, namely:

- Link
- Multiple column
- Central concept [16]
- Row [17]
- Ring concept [18]

As indicated previously, none of these biomechanical descriptions qualifies as utilitarian theories and, in particular, fail to explain many of the carpal relationships. The motion and functional relationship between the trapezium and scaphoid, and the apparent distinct difference in the axis of rotation of the scaphoid and lunate, are not adequately explained.

More curious is the movement of the lunate on coronal wrist motion and the dilemma of how it is constrained and controlled. By using a reverse engineering software analysis, it became evident that there was a region on both the lunate and volar radius that remained isometric through range. Although not described at the time of identification using computational analysis, this anatomical region now corresponds to the long radiolunate ligament.

As an extension of the work of Taleisnik,[16] a more complete theory has been developed—stable central column of carpal mechanics (see Figure 1). This work was further expanded to review the relationships between the proximal and distal row of the carpal and the radius, allowing the characterization of a complex mechanical controller of the carpal motion—a two-gear four-bar linkage (see Figure 2). This opens the way for quantitative 3D analysis of motion in the wrist, both normal and pathological, with an option to build a mathematical model to both explain the injury and allow a “what if” capability to test potential surgical solutions.[8] This provides the basis for computer modelling of each individual’s wrist, based on its own unique “rules”.

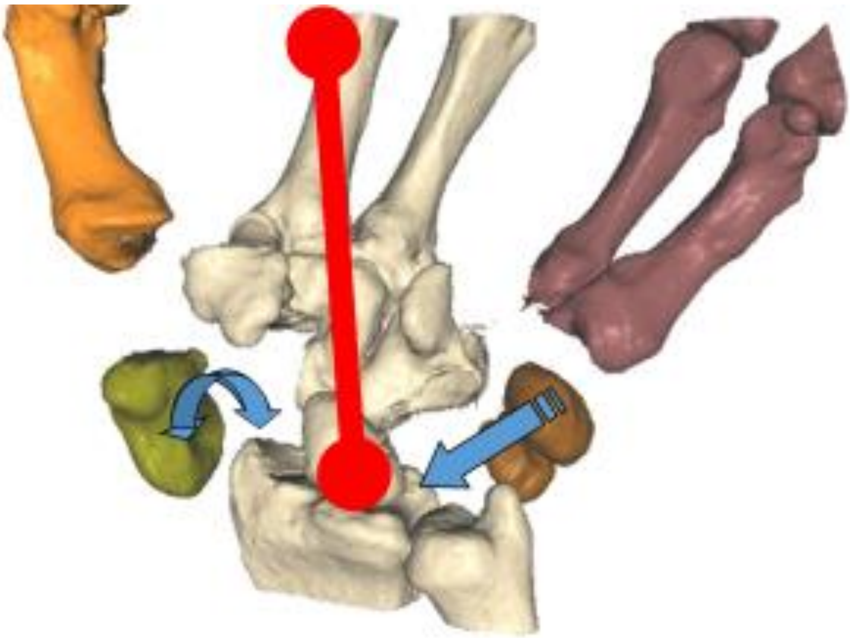

Figure 1. SCCT of carpal kinetics. This consists of a stable central column that provides a platform for the relatively immobile second and third metacarpals. The thenar and hypothenar rays are mobile and act against the central metacarpals. The scaphoid acts as a stabilizer of the proximal and distal rows, and the triquetrum acts primarily as an ulnar translation restraint and as a controller and restraint of lunate flexion. (Published with permission JHS-Eu, Sandow et al. 2014)

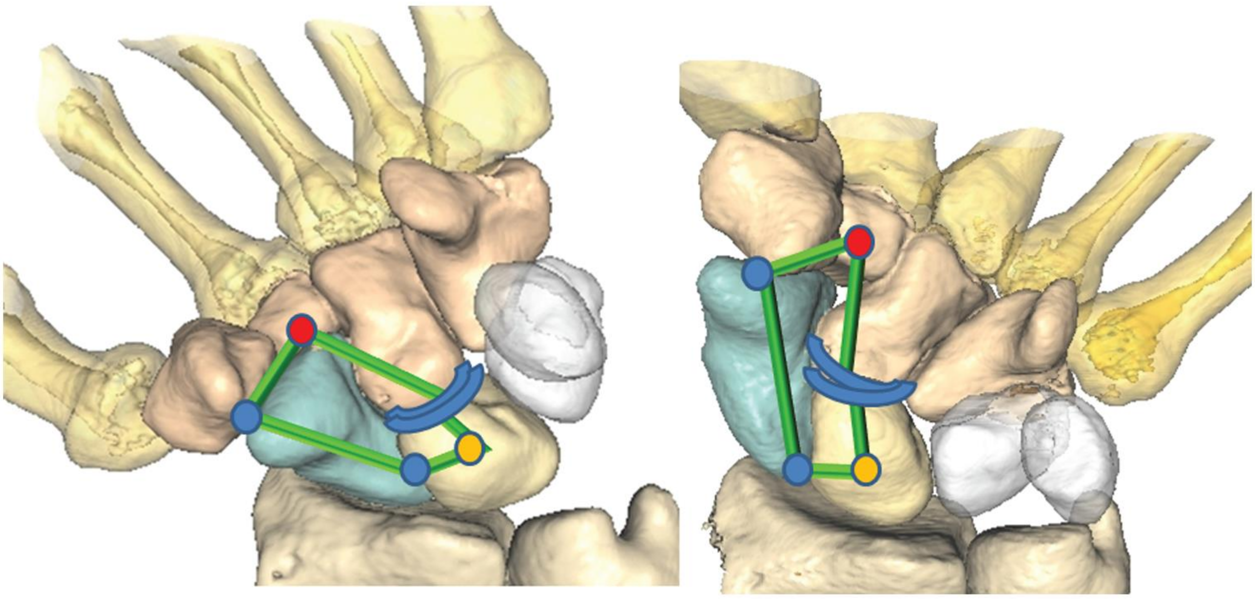

Figure 2. AP view: Diagrammatic representation of the motion pattern of the carpus with overlaid linkages of the proximal and distal carpal row. The dots represent the connection points of the scaphoid to the proximal and distal rows, or the centroids of each row. The curved lines represent the cam motion between the two rows. The carpus appears to function as a two-gear four-bar linkage. (Published with permission JHS-Eu, Sandow et al. 2014[])

Injuries / Disrupted Carpal Mechanics

Therefore, an important function of the theory is that it must be predictive and have the ability to identify the deficit within the mechanical system when a functional impairment is identified. The classic model for this would be a disruption between the scaphoid and the lunate.

Scapholunate Dissociation

As part of the scapholunate dissociation injury, there are specific patterns of intercarpal bone disruptions. These are the separation between the scaphoid and lunate, the excessive flexion of the scaphoid, extension and ulnar translation of the lunate, and dorsal subluxation of the proximal scaphoid. This apparent loss of the stability of the central column occurs as a result of the flexion of the scaphoid due to a disruption of the scaphotrapezial joint, a loss of connection between the dorsal scapholunate joint, and an extension of the lunate, which most likely occurs as a result of a disruption of the volar long radiolunate ligament.

All these constraints were well defined by previous published papers [2,8-10] and indicate a cascade of mechanical disruptions that may occur either completely or partially depending on the extent of injury.

There are secondary constraints in terms of both dynamic and static that will provide some support for the failing mechanical linkage. However, ultimately these may fail, producing the standard carpal collapse that is identified with the classic long standing scapholunate instability of a SLAC (Scapho-Lunate Advanced Collapse) wrist deformity. When a solution is proposed, the specific loss of the mechanical constraint must be identified and a solution developed based on an attempt to restore the normal mechanics if this is possible. Based on this theory, work is now underway to create a tether to initially address the scaphotrapezial joint on its volar aspect, the dorsal scapholunate disruption, and the volar lunate restraint by the volar radiolunate ligament. This is currently under trial as the “anatomical repair: front and back” (ANAFAB) procedure, which is an anatomical reconstruction on both the volar and dorsum of the carpus (see Figure 3).

Results to date are only short-term but appear to provide at least an initial attempt to restore the identified disruption within the carpus using computer modelling based on the theory of carpal mechanics.

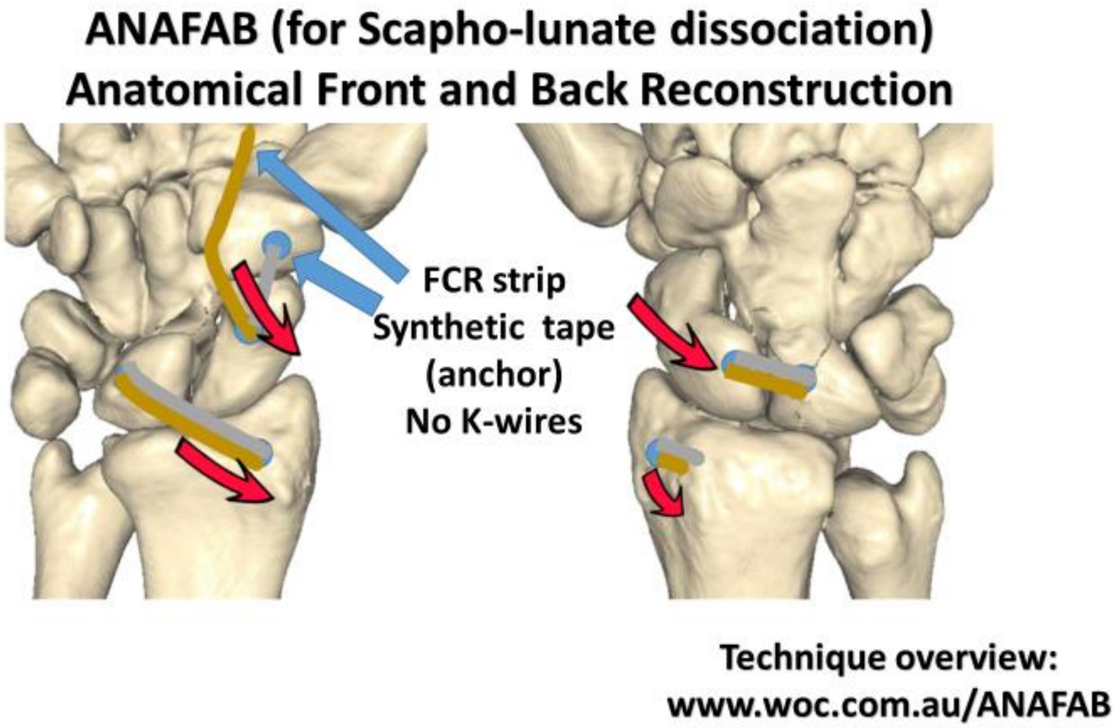

Figure 3. ANAFAB reconstruction: Diagrammatic representation of the ANAFAB reconstruction using a distally based strip of FCR tendon, supplemented by a synthetic tape passed from the trapezium transosseously to the scaphoid dorsum, transosseously through the lunate and then volarly to the radial styloid where it is secured with an interference screw. (Published with permission JHS-Eu, Sandow and Fisher 2019)

Midcarpal Instability

Computer modelling and computer simulation are technologies that are designed to simulate what did or what might happen in a particular situation. They have a valuable predictive or explanatory purpose. Such technology is also of value to test hypotheses that may be proposed to explain a particular phenomenon. Midcarpal instability is one such ill-defined phenomenon, as it has failed to achieve a consensus on the description of the deficit, or reliable options for management.[19]

Midcarpal instability is generally regarded as increased laxity on the medial side of the wrist, and characteristically associated with the so-called “midcarpal clunk”. This clunk appears to be caused by the desynchronized motion of the proximal and distal rows. Various anatomical studies have proposed a range of ligament failures; however, “it is often difficult to diagnose and classify. Treatment protocols are still controversial.”[19]

The SCCT contends that the longitudinal stability of the central column is largely (but not entirely) controlled by the lateral column, more specifically with the connections of the scaphoid to the lunate and trapezium. When combined with various other constraints, this constitutes the two-gear four-bar linkage that is the key to the longitudinal stability of the carpus. Each column cannot be viewed entirely in isolation, but a loss of stability within the central column—in particular, the capitate and lunate—is likely to be related to some loss of the stabilizing effect of the lateral column.

While the motion pattern in midcarpal instability can vary, if the wrist motions of patients are studied using dynamic 3D imaging, the scaphoid, lunate and triquetrum will generally move as one. This indicates that although on plain radiographs the lunate can be observed to be abnormally flexed, there is no disruption within the proximal row. This loss of linkage occurs specifically between the scaphoid and the trapezium, allowing excessive flexion of the entire proximal row on radial deviation and delayed extension on ulnar deviation. As the wrist moves into ulnar deviation, the failure of the connection between the trapezium and scaphoid delays the usual synchronous extension of the proximal row. The proximal row remains flexed until the triquetrum can no longer continue impacting against the hamate, which then causes a rapid translation of the triquetrum up the volar cortex of the hamate. This results in the obligate but delayed catch-up clunk as the proximal row goes suddenly from excessive flexion to the required extension for that degree of ulnar deviation.

This computer modelled explanation can be tested and validated clinically by demonstrating that the normal synchronous extension of the proximal row during radial to ulnar deviation can be restored by applying finger pressure on the scaphoid tuberosity as the wrist moves into ulnar deviation, thereby preventing the reduction clunk. This supports the contention that the cause of the midcarpal clunk often relates to a loss of integrity between the trapezium and the scaphoid, which thereby delays the obligate extension of the proximal row as the wrist moves from radial to ulnar deviation. The theory therefore identifies that the defect is present and also what strategic surgical reconstruction may be possible.

The outcome for such an intervention may well be compromised by the stretching of secondary constraints, in particular the dorsal radiocarpal ligament and ulnar sided stabilizers, However, the proposed theory (SCCT)provides a possible explanation of the likely underlying biomechanical failure mechanism and presents possible physiologically based remedial surgical strategies.

Conclusions

The carpus is a complicated and functionally challenged mechanical system, advancements in the understanding of which have been compromised by the failed search for a simple mechanical explanation of a standard carpal mechanical system based on empirical observation and analytical biomechanics. By using a reverse engineering analytical pathway and accepting the Law of RBM , wrist biomechanics can be considered a culmination of the interplay between the concepts of necessary complexity constrained by an assumption of parsimony.[12] Therefore, a mechanical description can be proposed based on the RBM concept, which can incorporate the variability within the wrist but still allow for the definition of a true theory that explains carpal mechanics and carpal stability.

More sophisticated 3D modelling will be required to better understand the specifics of carpal motion; however, the reverse engineering of the specific rules that define each individual wrist can be applied to a mathematical model to provide a “what if” [8] test of particular surgical interventions for a proposed injury.

The ability to extract the isometric constraints of a particular motion system has substantially increased capabilities in the longer term to provide quantitative diagnoses of various joint injuries. When combined with finite element analysis, this can allow for the pre-testing of various operative solutions and the assessment of whether the outcomes match the predictions.

This provides one of the first examples of quantitative 3D CT analysis and true computer modelling of the wrist, allowing surgical planning and virtual surgical intervention. It further allows for provided surgical solutions to be applied to the unique characteristics of an individual wrist and an outcome analysis, expectation and prognosis to be defined. However, if this new information technology environment is to facilitate surgical capabilities, the interactive tools need to be simple, intuitive and configured to suit the surgical environment and workflow requirements without requiring a large degree of back-end technical support.

The basis for the analysis of the normal relationships within the carpus that were defined by Dr. Gilula with his lines have been expanded upon using advanced computer modelling. However much remains the same, even in this advanced imaging environment – if Gilula’s lines are broken, something needs to be addressed.

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Chapter Six – ANAFAB Scapho-Lunate Reconstruction

Subsequently published as:
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Anatomical Anterior and Posterior Reconstruction (ANAFAB) for Scapholunate Dissociation: Preliminary Outcome in Ten Patients

Abstract

This study reviews the efficacy of a reconstruction to address scapholunate dissociation using an anterior and posterior approach with a hybrid synthetic tape/tendon weave between the trapezium, scaphoid, lunate and radius: an anatomical front and back (ANAFAB) repair. This repair is a compilation of the components of a number of previously reported repair techniques, and based on published kinematic evidence. It aims to restore the anatomical mechanical constraints on both anterior and posterior aspects of the carpus. Patients were immobilized in a cast for 6 weeks, but no stabilizing wires were used. Ten patients have undergone the reconstruction and were assessed at a minimum 24-month follow-up. They achieved excellent realignment of the carpus, post-operative median scapholunate gap of 3 mm, and a recovery of more than 75% of grip strength and range of motion. No patient required secondary surgery or treatment related to the carpal stabilization.

Level of Evidence: IV

Introduction

The restoration of wrist function after injury has been an enduring challenge and reliable reconstructive solutions have been elusive (Garcia-Elias, 2013; Sammer and Shin, 2012). A contributor to this challenge is that carpal research has been largely empirical (Garcia-Elias, 2013) and not based on the development of a conceptual theory using forward kinematics to reconcile the variability of wrist biomechanics (Sandow et al., 2014).

The process of finding suitable surgical repairs to address carpal instability has involved extensive trials on potential solutions (Garcia-Elias, 2013). They are generally based on the use of locally available tendons or synthetic materials to replace observed ligament deficits, which have been presumed to be important. This approach is guided by the interpretation of empirically derived biomechanical data, which is problematic given the variations in relationships and the complex interactions between the various wrist structures in different individuals (Abe et al., 2018; Kamal et al., 2016; Moritomo et al., 2006). In the case of scapholunate diastasis, this has generally created a narrow focus on maintaining the coaptation of the scaphoid and lunate, without appreciating the more complex relationship of this particular motion segment with the other critical biomechanical factors that maintain carpal stability (Sandow et al., 2014). A more logical approach would be to define a general theory of carpal mechanics and use that concept to apply solutions that are based on theory and logic to the variety of carpal dysfunctions that may occur.

The stable central column theory (SCCT) of carpal mechanics (Sandow et al., 2014) provides a basis on which observed wrist dysfunction can be explained and logic-based solutions defined and applied. Although disputed by some (Rainbow et al., 2015; Tan et al., 2018; Xu and Tang, 2009), the existence of isometricity between multiple paired regions in the carpus is central to the rules-based motion concept of carpal mechanics (Papas and Sandow, 2001; Sandow et al., 2014).

Although often part of a spectrum of injury, in the typical case of scapholunate dissociation there are variable degrees of diastasis between the scaphoid and lunate, flexion, pronation and proximal posterior subluxation of the scaphoid, and extension and possibly ulnar translation of the lunate (Omori et al., 2013). By applying the SCCT, the absence of certain specific ligamentous constraints could reasonably explain such biomechanical failure. These ligaments are the posterior scapholunate interosseous, scaphotrapezial and long radiolunate ligaments. On this premise, a reconstructive solution should focus on correcting these deficits and seek the optimal means to do so, rather than adopting the usual approach of adapting locally convenient tissues (Papas and Sandow, 2001).

The current reconstruction was developed to address the specific defined mechanical deficits and restore the precise geometric pattern of isometric restraint, as defined by the SCCT. Components of previously reported individual reconstructive procedures, including those of Almquist et al. (1991), Brunelli and Brunelli (1995), Garcia-Elias et al. (2006) and Henry (2013), have been adapted and combined to create an anatomically based restorative solution that addresses both the posterior and anterior structures: an anatomical front and back (ANAFAB) repair. The current study reviews the preliminary outcomes of this reconstruction with a hybrid synthetic tape/tendon weave, in a consecutive group of patients with scapholunate dissociation. It was hypothesized it would achieve a more predictable outcome in terms of restoring carpal stability without excessive loss of motion.

Methods

Surgical technique

This repair technique used a hybrid of a synthetic tape (Labral Tape, Arthrex, Naples USA) and tendon strip, without temporary Kirschner (K)-wire stabilization. The reconstruction was done through an anterior and posterior approach. Through the anterior incision, a double strand of the synthetic tape was attached to the anterolateral facet of the trapezium using a 3.5 mm bone anchor (Swivel-Lock, Arthrex, Naples Fl. USA). This tape, supplemented with an approximately 3 mm diameter distally based strip of flexor carpi radialis (FCR) tendon, was passed from the trapezium to the scaphoid tuberosity, transosseously to the dorsum of the scaphoid, transosseously from posterior to anterior through the lunate and then anteriorly to the radial styloid. Tension was applied to the tape and tendon construct to reduce the intercarpal joints, and it was then secured with an interference screw inserted from the posterior radius (Figure 1).

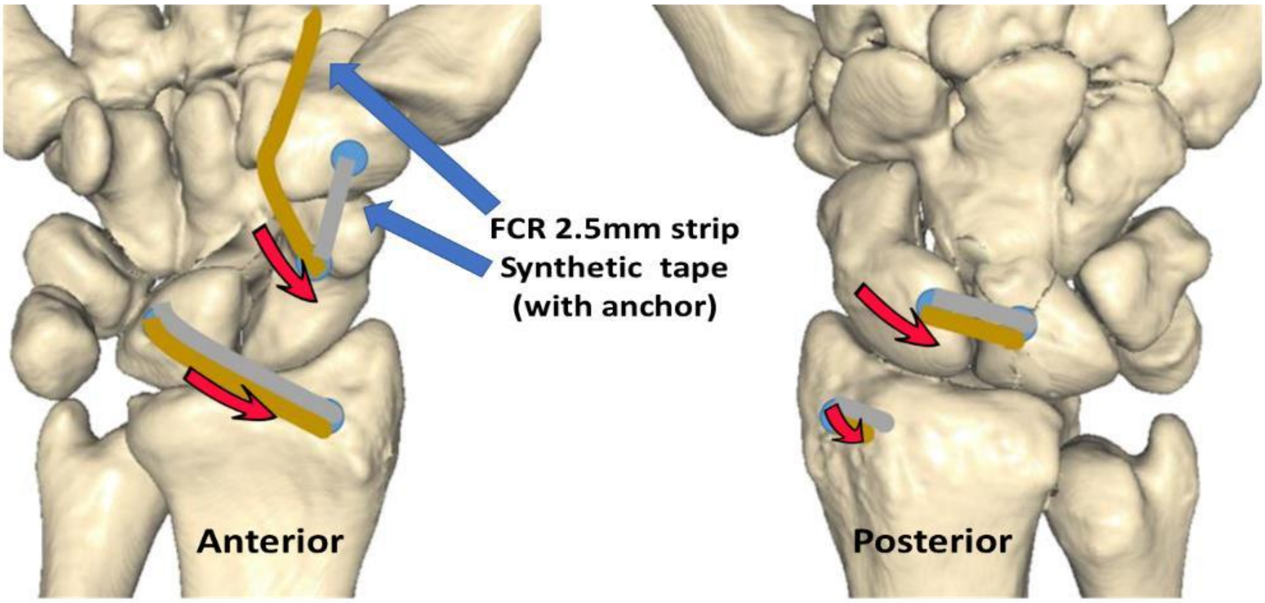

Figure 1. Anatomical anterior and posterior reconstruction (ANAFAB).

All transosseous drill holes were 3 mm in diameter. Posterior neurectomy was not specifically done, but may have occurred in some patients as part of the posterior capsular mobilization. Patients were immobilised in a cast for 6 weeks. Patients were then mobilised in a supportive, but removable, soft brace for a further 6 weeks. Moderate loading was avoided for 3 months and heavy loading delayed until 6 months after the procedure.

Details of the technique details are available in the supplementary documents (available online) and at www.woc.com.au/ANAFAB.

Research methodology

After ethics approval (Royal Adelaide Hospital HREC approval R20171203), a retrospective review of prospectively gathered clinical outcome data was assessed in a consecutive series of ten patients (eight men and two women) with scapholunate dissociation who were treated with the ANAFAB procedure. The median age was 28 years (range 23–58).

All patients attended a review clinic at a minimum follow-up of 24 months to obtain outcome information, which was then combined with their prospectively gathered data.

Inclusion criteria were patients over the age of 18 who were well informed of the current reconstructive options and prepared to undergo a non-standard procedure. Patients were advised that the actual procedure was a compilation of components of previous reconstructive techniques, but adapted to address the mechanical deficit identified in their wrist. They all had a positive scaphoid shift sign (Lane, 1993; Tomas, 2018) and subjective loss of function due to pain and/or weakness. All patients had a scapholunate diastasis of 3 mm or greater (median 3 mm, range 3 mm–6 mm), assessed as the minimum separation between scaphoid and lunate in a neutral wrist position measured on plain anterior-posterior radiographs. On quantitative analysis of three dimensional computed tomographic (3D CT) images, the displacement of the attachments of the posterior scapho-lunate ligament were generally greater than that reflected on the plain radiograph owing to the associated posterior subluxation and pronation of the scaphoid (Figure 2 and supplementary material, available online). All patients also had an abnormal scapholunate angle (>60˚) when measured between the long axis of the scaphoid and lunate on the lateral image of the wrist. None had undergone previous surgery, apart from diagnostic arthroscopy in three patients. Two patients with early degenerative changes in the radioscaphoid joint were included, but any patient with significant mid-carpal degeneration was not considered for the procedure.

All patients also underwent 3D quantitative spatial analysis (True Life Anatomy, Adelaide, Australia) of their wrist, with many undergoing two-position analysis to quantify the presence or absence of isometry between various carpal bones, as previously described by Sandow et al. (2014) to define the specific ligamentous disruption. Using the same imaging technology, most patients underwent computer-based virtual reduction and analysis to assist with localizing the attachment points of ligaments, which guided the location of drill holes and attachments for the subsequent repair (Figure 2 and supplementary material, available online).

Patients were assessed pre- and postoperatively, with formal documentation of motion and strength, as well as subjective pain and loss of function at 3, 6, 12 and 24 months after operation. Subjective functional loss, range of motion, grip strength and the presence of a positive scaphoid shift sign were recorded preoperatively, but no objective pain score or patient reported outcome measure. Strength was assessed using a Jamar dynamometer (JLW Instruments, Chicago, Il, USA) in the second grip setting with the elbow flexed at 90°, and compared to the opposite uninjured wrist. The values were not adjusted for dominance. Wrist motion was assessed with a manual goniometer to the nearest 5° and recorded for preoperative and postoperative comparison.

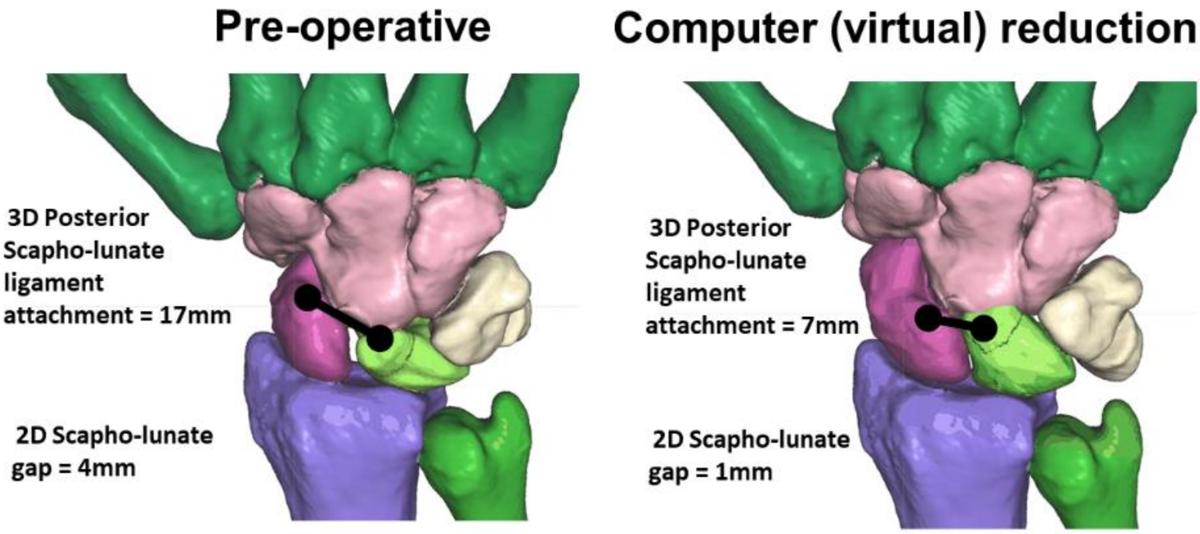

Figure 2. Quantitative three-dimensional computed tomographic (3D CT) image analysis of the injured and computer (virtual) reduced scapholunate dissociation. This demonstrates that the separation of the attachments of the posterior scapholunate ligament are generally greater than reflected on the plain radiograph owing to the associated posterior subluxation and pronation of the scaphoid. In this example the distance between the posterior scapholunate ligament attachments is 17 mm, with a "radiological" scapholunate separation of 4 mm. After manual virtual reduction of the carpus, the posterior scapholunate ligament attachments is reduced to 7 mm, with a "radiological" scapholunate separation of 1 mm. The pathological separation of the attachments of the posterior scapho-lunate ligament is therefore 10 mm, not 3 mm as would be suggested by the two-dimensional views. (Video reduction; supplementary material, available online.).

Results

At a minimum 24-month (range 28 -36) follow-up, the patients who underwent ANAFAB repair achieved excellent realignment of the carpus (Figure 3 and 4), with a post-operative scapholunate gap of (median) 3 mm (Table1). Although preoperative pain was not formally quantified in all patients, it was noted to be quite variable and often only present under heavy load. At final review, the median pain score was 1 out of 10 (range 0–5) on the visual analogue scale, and all patients had a negative scaphoid shift test.

Owing to variation in the wrist position on lateral imaging, the scapholunate angle was determined to be the best measure of carpal realignment, and in all patients was close to or within the normal range (30°–60°). There was a recovery of more than 75% grip strength and range of motion (Table 1), with patients noting improvements in motion and strength between the 1 and 2-year review period. In most patients, the recovery of extension was nearly normal, but there was a modest (median 10°) loss of flexion.

Figure 3. Pre- and postoperative radiographs showing carpal realignment. Sca-Lun: scapholunate angle; Cap-Lunate: capitolunate angle).

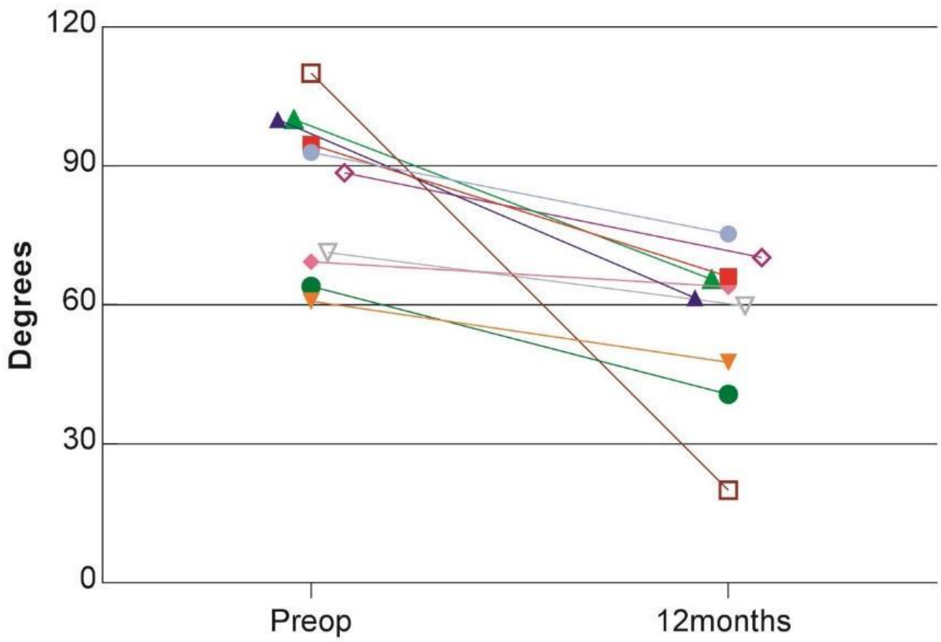

Figure 4. Scapholunate angle on lateral plain radiograph.

Although not part of the original review protocol, patients were asked about their ability to perform their normal sporting activities; specifically, their ability to perform push-ups. At 6 months postoperatively, all patients were able to perform at least three push-ups, although one man and two women did modify wall or kneeling push-ups. All patients advised they had been able to perform push-ups before their wrist injury.

Table 1. Scapholunate gap, grip strength and range of motion.

Parameter	Pre-op	3 months	6 months	12 months	24 months
Scapholunate gap in mm. Median [range]	3 [3-6]	3 [2-4]	2.5 [1.4-3.5]	2.8 [2-4]	3 [2-4]
Grip strength as % of other wrist. Median [range]	67 [25-100]	75 [40-100]	84 [40-100]	89 [68-100]	94 [20-100]
Flexion in degrees. Median [range]	60 [20-80]	30 [30-40]	40 [30-60]	50 [30-70]	50 [40-80]
Extension in degrees. Median [range]	60 [30-90]	40 [30-60]	50 [30-60]	60 [30-70]	60 [40-75]

(Scapholunate gaps were generally larger on three-dimensional (3 D) assessment, but only the two- dimensional radiographic measurements are shown to allow follow-up comparison, as 3D analysis (from computed tomography) was not generally used postoperatively. Variations with apparent decrease in gapping after 3 months may relate to variable positioning on plain radiographs.)

There were no wound issues or changes in the lunate suggestive of avascular necrosis. As K-wires were not used, the often- noted pin irritation and secondary surgery for wire removal was avoided. There was no loss of correction of the scapholunate coaptation or alignment in any of the patients; however, one patient developed an excessively flexed lunate whilst in the postoperative cast, with a secondary posterior distal radioulnar joint subluxation. When this was investigated by 3D CT quantitative analysis, the anterior portion of the lunate, which has a more prominent profile than the central or posterior regions, appeared to have caused a secondary ulnar carpal impaction, pushing the distal ulna head in a posteriorly displaced position relative to the radius and resulting in a secondary distal radioulnar subluxation. This was addressed by shortening at the ulna mid-shaft, which resulted in an immediate reduction of the distal radioulnar joint. The patient achieved a stable carpus with a correction of the scapholunate dissociation, but only a fair outcome overall.

Discussion

The ANAFAB reconstruction, based on the stable central column theory, aims to restore the anatomical mechanical constraints on both anterior and posterior aspects of the carpus. The preliminary results indicate that it restores carpal stability and grip strength without significant loss of motion. An important part of this study was the ability to quantify in 3D the pathological multi-planar displacement of the scaphoid, and define the extent of ligament disruption by identifying a loss of isometry between specific carpal bones (Sandow et al. 2014).

Many alternative reconstructive procedures have been suggested to address scapholunate dissociation. Although the SCCT has not been widely adopted as an accepted explanation of carpal mechanics, this concept was the basis of the ANAFAB reconstruction and the impetus to create a repair construct by combining selected components of existing repairs. An important reason for the SCCT not being widely accepted is that it fails to accord with the works of others (Kamal et al., 2016; Rainbow et al., 2015). Given that a reliable repair option for scapholunate instability has been elusive (Garcia-Elias, 2013; Sammer and Shin, 2012), an alternative approach such as the one based on the SCCT, may be a potential new solution. This study has shown that the ANAFAB appears to be at least as good as other procedures.

The FCR tendon is important in moving the distal carpal row, which normally pivots around an isometric constraint on the anterolateral margin of the trapezium and scaphoid (Moritomo et al., 2006; Sandow et al., 2014). To use the tendon as a replacement restraint is non-anatomical and, based on the SCCT of carpal mechanics, a flawed concept that is not likely to restore normal biomechanics. Further, the angle subtended by the FCR as it enters the drill hole in the scaphoid tuberosity adds a pronation moment, which may theoretically increase the abnormal motion and loading on the scaphoid.

Repairs that rely on free or transferred tendon weaves may be unable to functionally or anatomically match the original ligaments owing to their differing viscoelastic properties and revascularization and maturation time course (Hefti and Stoll, 1995). In the ANAFAB repair, the synthetic tape proved a durable stabilizing structure while soft tissue healing and maturation occurred. The FCR tendon weave in the ANAFAB procedure takes relatively little initial load; however, it provides a source of collagen to facilitate the progressive transition from synthetic tape to reformed ligament as healing progresses. As the synthetic tape is non-biodegradable it may cause longer term problems, but none were evident at the minimum 2-year follow-up.

Given the normal differential rotation between the scaphoid and lunate (Kamal et al., 2016; Rajan and Day, 2015; Sandow et al., 2014), reconstructions that attempt to restrain both the posterior and anterior region by applying a rigid central axis restraint (Lee et al., 2014; Rosenwasser et al., 1997; Ross et al., 2013), anterior and posterior scapholunate soft tissue connection (Corella et al., 2017; Ho et al., 2015; Kakar et al., 2017; Kakar and Greene, 2018) or by fusion (Hurkmans et al., 1996), may not be able to restore optimum, reliable or predictable wrist biomechanics.

The development of the ANAFAB procedure was the culmination of work to define the intercarpal isometric connection using computationally derived linkages (Papas and Sandow, 2001; Sandow et al., 2014). This showed that the wrist is composed of a complex array of variable biomechanical linkages. In an effort to reconcile this complexity, the connection between the proximal and distal rows has been described as a two-gear, four-bar linkage (Sandow et al., 2014). These findings were expanded into a theory to explain carpal stability and define critical linkages. By then using quantitative 3D motion analysis (True Life Anatomy, Adelaide, Australia) in the injured patients, the pattern of biomechanical defects could be characterized and reverse-engineered to propose a reconstructive solution to address the identified deficits.

The stable central column of the carpus requires the motion of the lunate to be controlled and to resist its natural tendency to rotate into extension (Rainbow et al., 2015). As the lunate does not have any direct tendon connections, this stability can be achieved by an anterior tether pulling proximally and, in particular, the long radiolunate ligament (Sandow et al., 2014), acting with a presumed posterior tether pulling distally. Work by Mathoulin (2017) and Wahegaonkar and Mathoulin (2013) has been pivotal in defining the connection of the lunate to the dorsal intercarpal ligament (DIC) (Viegas, 2001), which functions as the posterior distal tether for that bone. This role of the DIC is quite compatible with the concept of the SCCT. Surgical reattachment of the DIC to the lunate has been shown to be very effective in addressing wrist instability at the predynamic stage (Mathoulin 2017; Wahegaonkar and Mathoulin, 2013). However, the 'Mathoulin' approach did not fully address static scapholunate diastasis and additional stabilization procedures were required (Mathoulin, 2017). All patients in the current study had static scapholunate diastasis and instability; they were therefore in a different group to that managed by the reconstruction described by Mathoulin (2017).

A limitation of this study is that it was an observational retrospective review without a comparator. Although patients will generally present with activity related pain when seeking treatment, this was not formally quantified in all cases at the preoperative stage. Further, as the ANAFAB construct was a composite of various components of a number of other reconstructions, formal ex-vivo biomechanical analysis of the specific reconstruction technique was not undertaken before using the repair.

The ANAFAB procedure appears to have the ability to reverse the scapholunate diastasis and proximal scaphoid subluxation, but still retain functional motion. Significant load on the carpus and radius is generated during a push-up (Scordino et al., 2016; Smith et al., 2018). The ability of the ANAFAB reconstruction to allow patients to perform push-ups provides compelling evidence of its ability to restore longitudinal stability of the carpus without a significant loss of motion, indicating the successful restoration of functional carpal biomechanics.

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Conflict of Interest

Associate Professor Sandow has a commercial interest in the 3D imaging software used to quantify the ligamentous disruption and plan the repair technique.

Chapter Seven – Invited Presentations / Conference Proceedings

The Stable Central Column Theory of Carpal Mechanics — Midcarpal Stability Explained and Why Chimps Can't Throw Darts

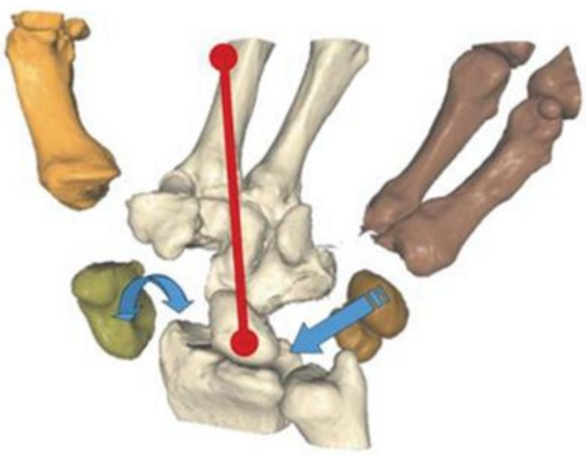
Michael Sandow [1]

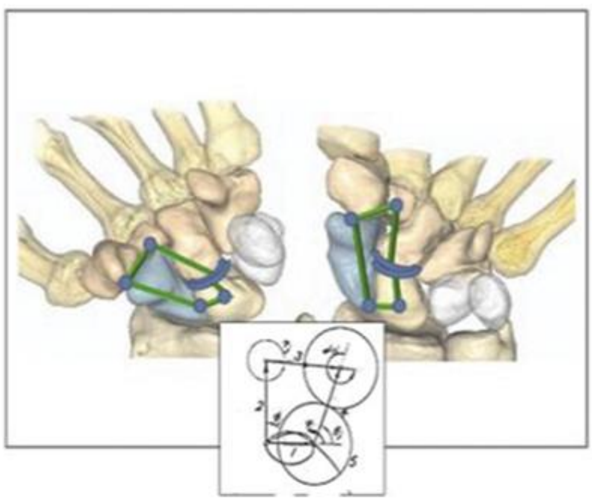
[1]Wakefield Orthopaedic Clinic and Royal Adelaide Hospital, Adelaide, Australia

Sandow MJ, Fisher TJ. Proximal Carpal Row Controls Midcarpal Alignment and Motion – The Offset Unitary Motion of the Rows Creates a Stable Carpus. Journal of Wrist Surgery. 2015; 04 - A021 DOI: 10.1055/s-0035-1545659
https://www.thieme-connect.com/products/ejournals/abstract/10.1055/s-0035-1545659
(Accessed 27 January 2019)

Introduction

The concept of the stable central column theory of carpal mechanics based on computationally derived isometric constraints has been previously presented, and was published in May 2014 (JHS-Eu May 2014). This theory characterizes wrist mechanics as a stable central carpal column with a lateral column stabilizer, a medial column translation restraint, and physiological pronation of the midcarpal axis.





The primary function of the wrist is to maintain a stable central metacarpal axis (2nd and 3rd) against which the more mobile thenar and hypothenar rays can act. The stability of the critical central column is achieved by its connection to the lateral column (scaphoid) as a two gear four-bar linkage. (Published with permission JHS-Eu, Sandow et al. 2014).

The trapezoid-shaped trapezoid places the trapezium anterior to the transverse plane of the radius and ulna, and thus rotates the principal axis of the central column to correspond to that used in the “dart thrower's motion.” This created a coronal axis at the radiocarpal joint and an oblique axis at the midcarpal joint.

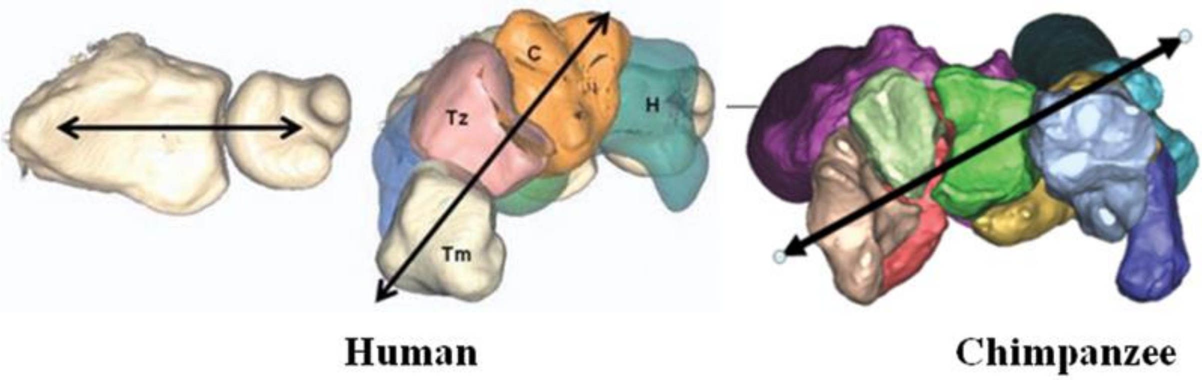
This paper presents the application of the theory to clinical cases as well as cross species comparison, in an attempt to explain midcarpal stability and the dart-throwing motion.

Materials and Method

The study was performed in two parts. (1) Clinical case examples who presented with midcarpal instability characterized by a midcarpal catch-up clunk were studied using dynamic 3D-spatial carpal bone analysis, and a reconstruction was performed based on the theory that midcarpal instability is due to a loss of the stability between the trapezium and scaphoid. (2) By comparing cross-species isometric constraints and carpal-bone morphology, the axis of the midcarpal joint was identified and the carpal motion of the human and chimpanzee characterized, with a theoretical proposal regarding carpal motion and function of Homo floresiensis.

Results

Four patients have undergone lateral column reconstruction to address midcarpal instability. In each patient, the medial column alignment and stability were improved, although complete anatomical correction was not possible in every case due to secondary stretching of medial interosseous ligamentous structures. Analysis of trapezoid morphology and isometric constraints of the lateral column demonstrated the origin of the more coronal midcarpal axis of the chimpanzee and explains the reason for the cross-species difference with respect to the ability to throw darts.



Conclusion

Midcarpal instability is due to a lateral column disruption which prevents the smooth transition from a flexed proximal row to an extended proximal row as the wrist moves from radial to ulnar deviation. The loss of a strong isometric connection to the volar trapezium creates a delayed extension of the scaphoid, thus delaying normal physiological proximal-row extension until an obligate and sudden lunate and proximal-row exertion correction, most likely initiated by the triquetrum as it glides up the volar aspect of the hamate. This loss of this carpal rhythm was corrected by restoring the lateral column integrity.

This, however, is unimportant when compared with the most important bone in evolution—the trapezoid. Without a “trapezoid shaped trapezoid”, dart (or spear) throwing, tool use, and the offensive or defensive use of a spear is impaired, as would be the survival of the species—unless one was stuck on a small island with no competitors.

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1. Sandow MJ, Fisher TJ, Howard CQ, Papas S. Unifying model of carpal mechanics based on computationally derived isometric constraints and rules-based motion - the stable central column theory. J Hand Surg Eur Vol 2014;39(4):353–363

Proximal Carpal Row Controls Midcarpal Alignment and Motion

Michael Sandow1, Thomas Fisher[2]

[1]Wakefield Orthopaedic Clinic & 2Royal Adelaide Hospital, Adelaide, Australia.

Sandow MJ, Fisher T. Proximal carpal row controls midcarpal alignment and motion. XXVI Congress of the International Society of Biomechanics 23 -27 July 2017 Brisbane, Australia https://isbweb.org/images/conferences/isb-congresses/2017/ISB2017-Full-Abstract-Book.pdf (Accessed 27 January 2019)

Introduction

As each individual’s wrist appears to have its own distinct biomechanics, the carpus has eluded simple explanation. The carpus moves with only 2 degrees of freedom – pitch (flexion / extension) and yaw (radial deviation / ulnar deviation), while largely preventing roll (pronation / supination).

This mechanical quandary can be addressed by applying the rules-based motion (RBM) concept. This states that the motion of a mechanical system, such as the wrist, is the net interplay of 4 rules – morphology, constraint, interaction and load [1].

Wrist motion is thus the composite outcome of these distinct rules. As the value or characteristics of each rule may varies, there is a matching complimentary variation in the other rules to achieve the final wrist motion and function.

The recently published Stable Central Column Theory (SCCT) of wrist mechanics [2] applies the concept of RBM to the carpus, and by using a reverse engineering computational analysis model, identified a consistent pattern of isometric constraints. There appears to be a clear pattern of constraint between the proximal row (Scaphoid-lunate-triquetrum) and the radius, and between the distal row (Trapezium-trapezoid-Capitate-Hamate) and the proximal row. This finding was expanded to suggest that the wrist functions a "Two-Gear Four-Bar" linkage.

This previous study assessed the isometric constraints in extremes of radial and ulnar deviation. The purpose of the current study was to further assess the motion of the various bones of the carpus using a 3D dynamic visualization model, in other directions and identify patterns of linkages.

Given the identified isometric constraints, the hypothesis was that the pattern and direction of motion of the proximal row, and the distal row with respect the immediately cephalad carpal bones or radius would be very similar in all directions of wrist motion. A further hypothesis was that the distal row motion direction was determined by the position of the proximal row, and this could vary dynamically as the wrist moved in particular directions.

Methods

3D models were created from 5 normal wrists that underwent CT scanning in multiple positions of radial and ulnar deviation as well as flexion and extension. Each carpal row (proximal and distal) was animated with the cephalad carpal bones or radius held immobile.
The rotational axis and position of each bone and each row was then compared in sagittal (Flexion-extension) and coronal (radial and ulnar deviation) motion. The DTM was not assessed.

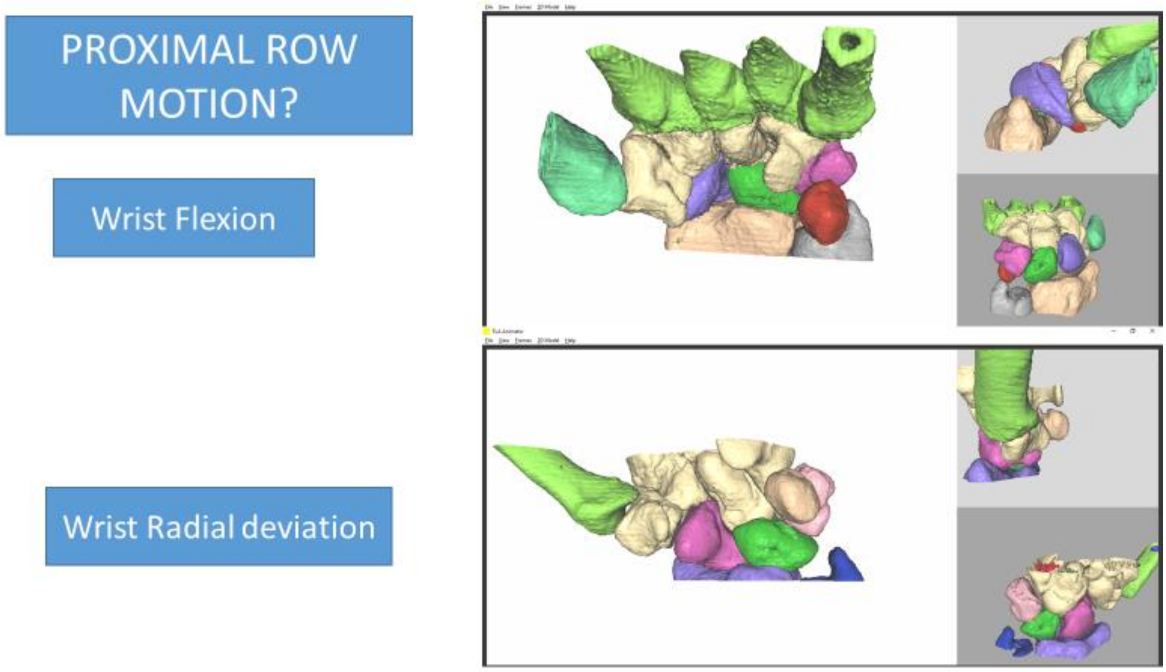
Results

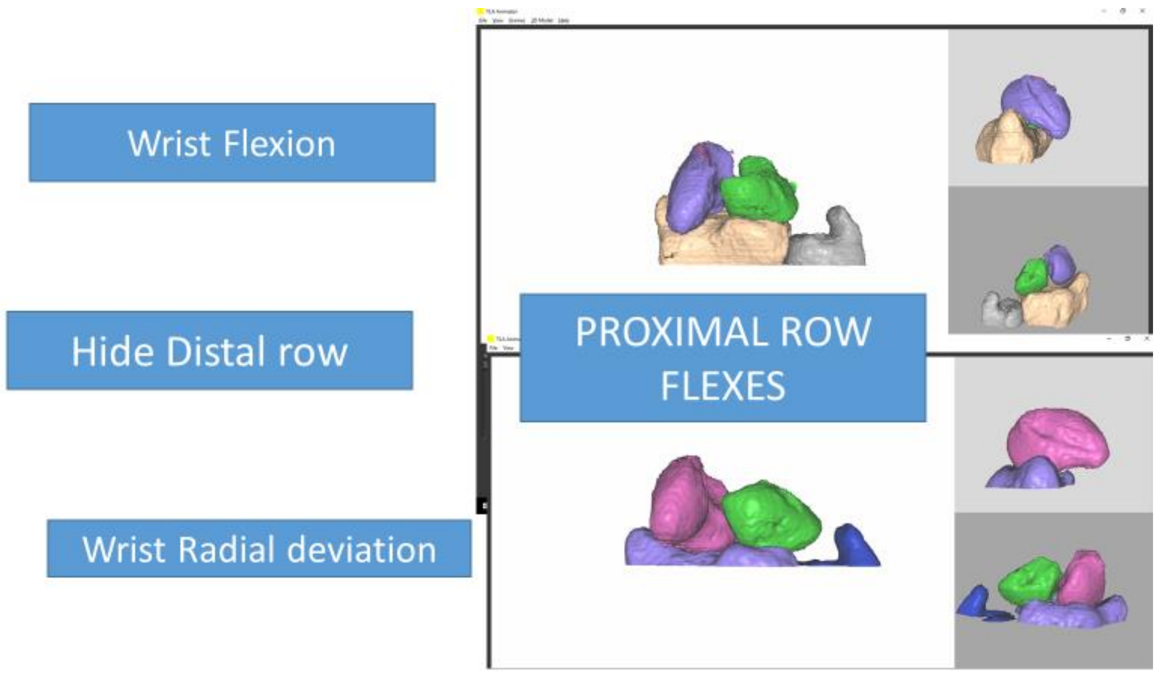
The proximal row moved in the same direction, but with a varying extent of the unitary arc during sagittal and coronal motion. The isometric constraints were consistent in both directions.

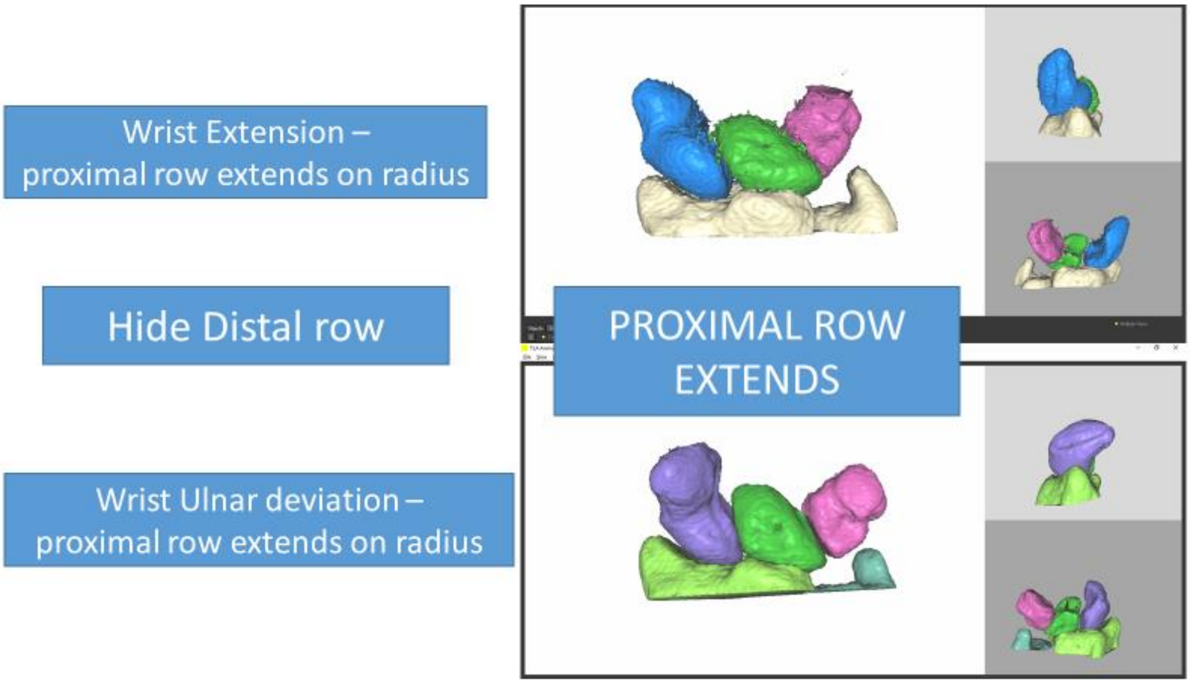
The distal row moved on an axis formed by a pivot joint laterally (between the trapezium and scaphoid), and a saddle joint medially (between hamate and triquetrum). This axis changed as the proximal row moved.

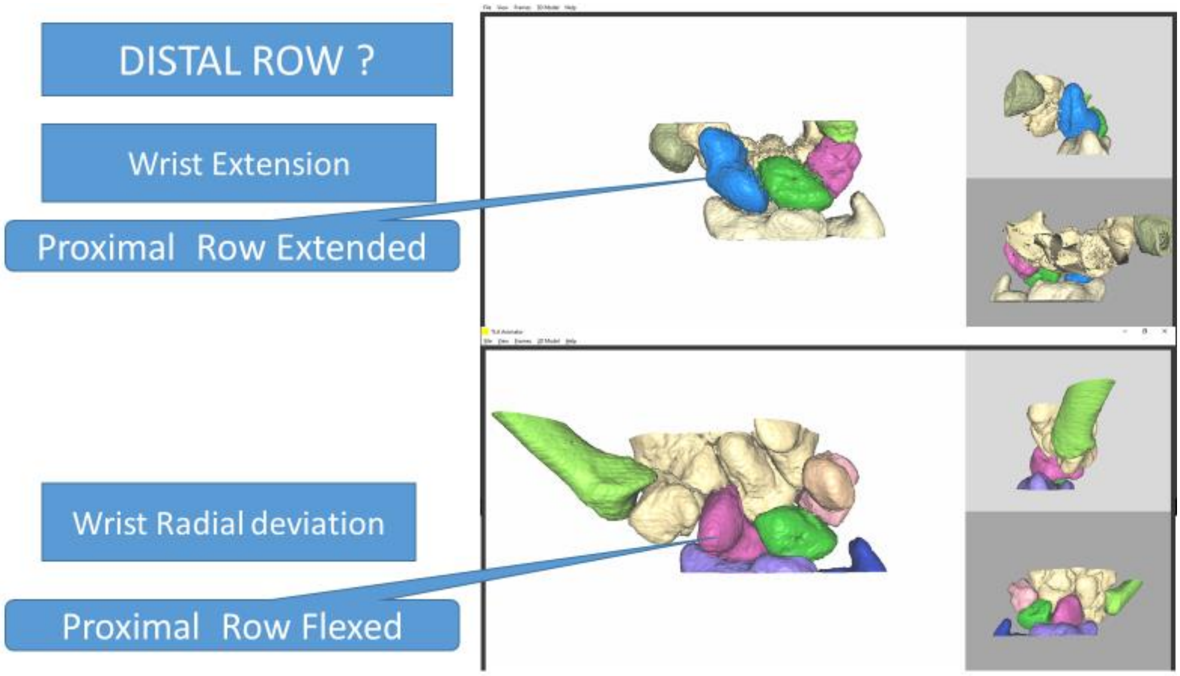
This created a distinct pattern of row motion to achieve the various required positions of wrist motion. On wrist radial deviation, the scaphoid (with the proximal row) flexed, and the distal row extended, whereas in wrist flexion, the scaphoid flexed (with the proximal row) and so did the distal row. The pattern was reversed in the opposite wrist movements.

While the general direction of motion of each row was consistent, the extent was quite variable.






Wrist Extension –
proximal row extends on radius
Hide Distal row
PROXIMAL ROW
EXTENDS
Wrist Ulnar deviation –
proximal row extends on radius


DISTAL ROW ?
Wrist Extension
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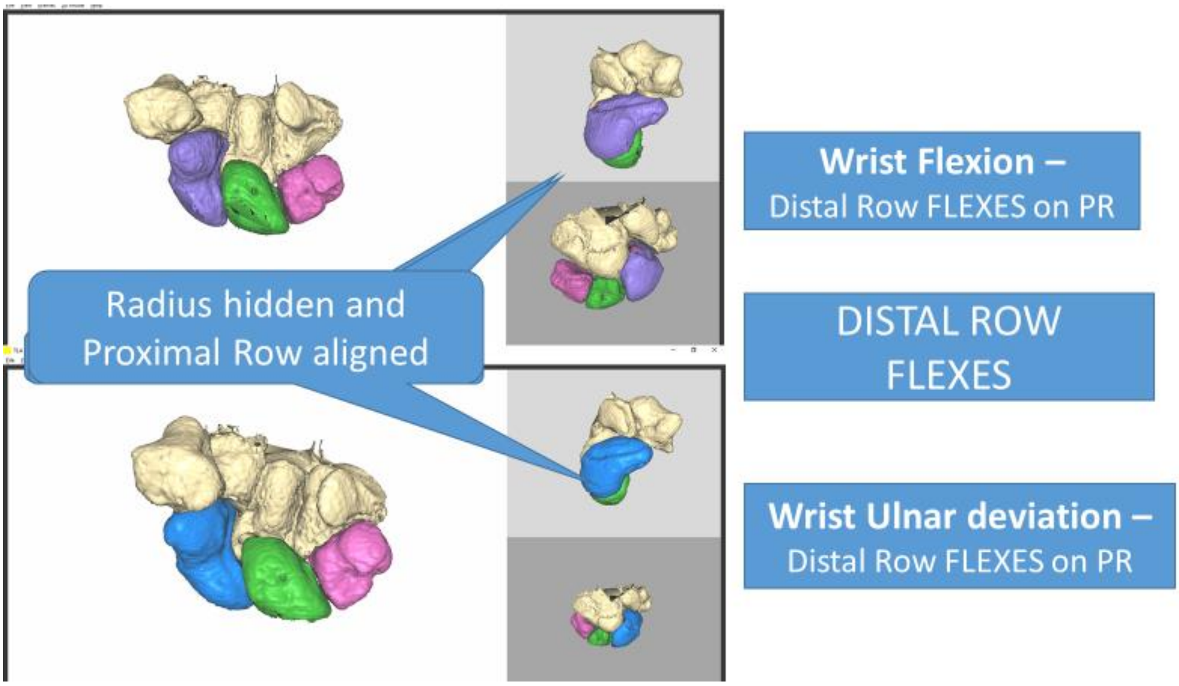
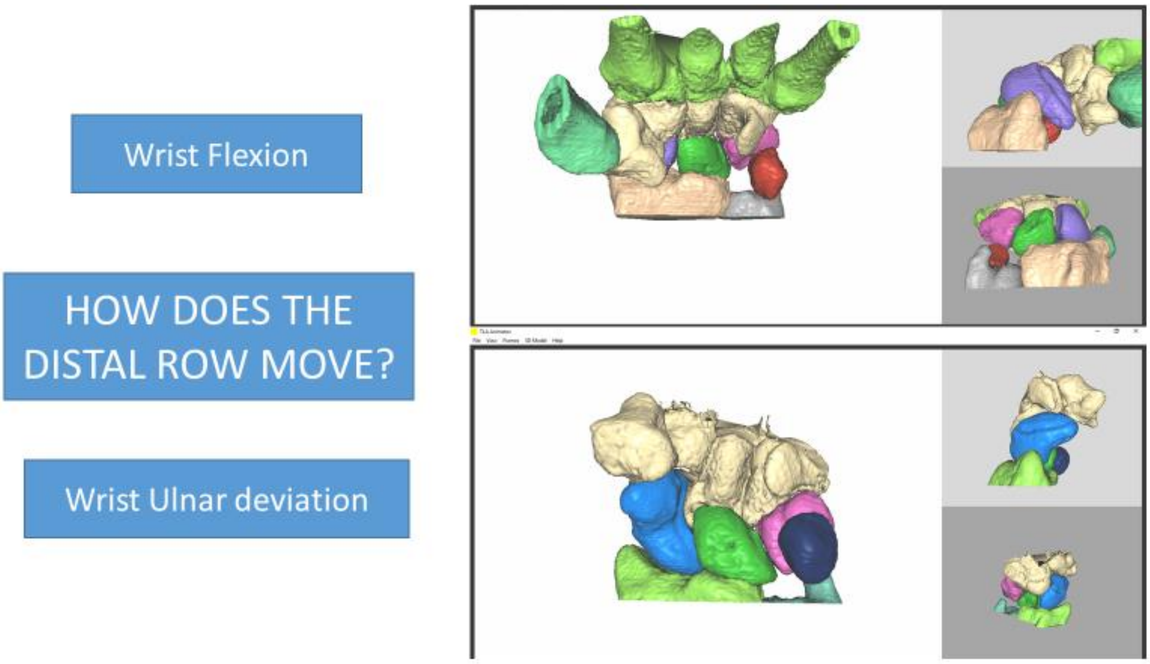
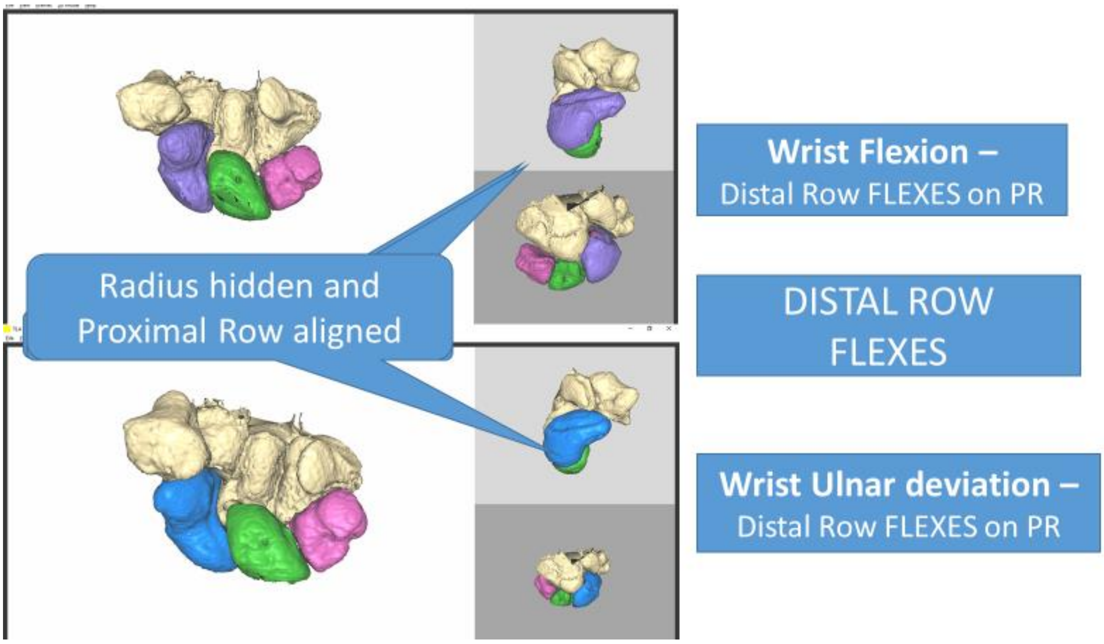
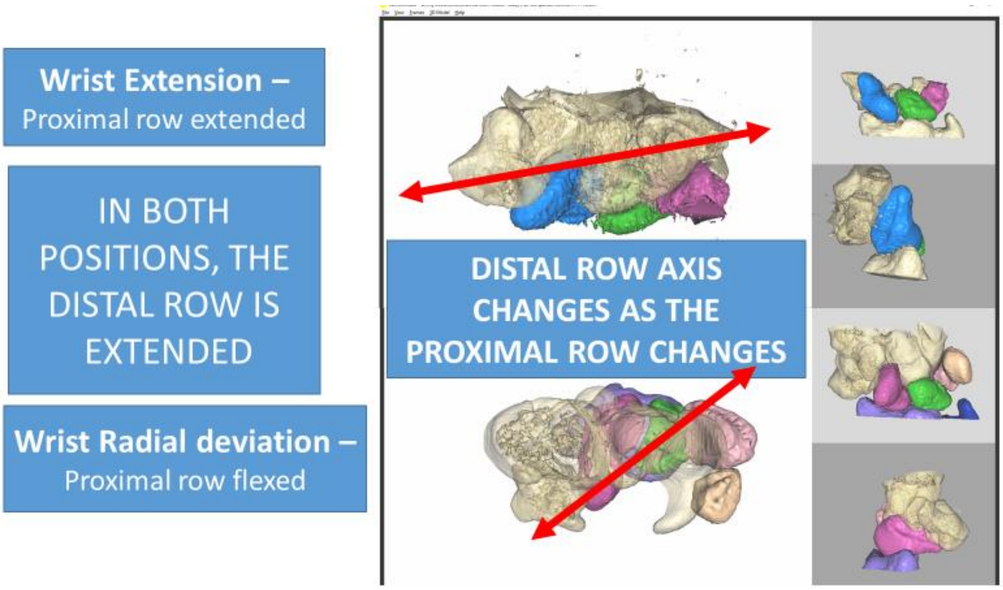
Wrist Radial deviation
Proximal Row Flexed


Radius hidden and Proximal Row aligned
Wrist Flexion – Distal Row FLEXES on PR
DISTAL ROW FLEXES
Wrist Ulnar deviation – Distal Row FLEXES on PR


Wrist Flexion
HOW DOES THE DISTAL ROW MOVE?
Wrist Ulnar deviation





Conclusions

The overarching concept in this work has been that by assessing general motion patterns, rather than focusing on specific axes and displacement measurements of each of the carpal components, a more useful theory to understand and treat wrist injuries can be developed.

As a more than 10-fold variations in the motion axes and excursion of various bone pairs between different individual has been reported [3], specific carpal bone kinematic analysis may not provide an effective pathway to explain both the mechanics of the normal wrist nor provide the ability to define disruption and consequent reconstructive solutions of an injured wrist.

Anatomical Volar and Dorsal Reconstruction (ANAFAB) For Scapho-Lunate Dissociation

Michael Sandow

Wakefield Orthopaedic Clinic, Adelaide, Australia

Sandow MJ. Anatomical volar and dorsal reconstruction (ANAFAB) for scapho-lunate dissociation. XXVI Congress of the International Society of Biomechanics 23 -27 July 2017 Brisbane, Australia https://isbweb.org/images/conferences/isb-congresses/2017/ISB2017-Full-Abstract-Book.pdf (Accessed 27 January 2019)

Introduction

The carpus is a complex mechanical linkage that is well adapted to perform a wide range of grasping, manipulative and propulsive functions. Previous work from our group, detailed the concept of a stable central column of the carpus which is a theory aimed to explain the identified computationally derived isometric constraints.

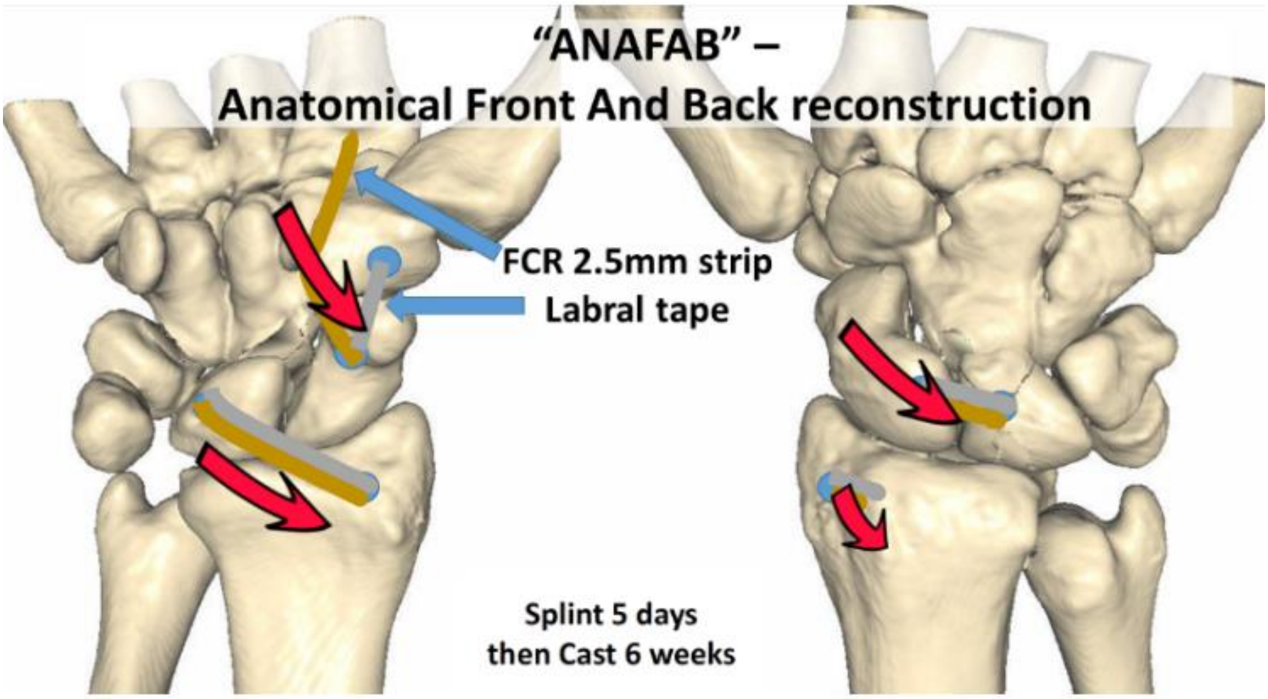
The process was to develop and then present a theoretical basis of wrist motion, identify the deficit in a particular pattern of injury, and then propose a solution based on the theoretical understanding of the cause of the biomechanical failure. This is then applied to injured patients to validate the proposition, and more importantly the theory of wrist biomechanics.

Scapho-lunate dissociation usually leads to excess scaphoid flexion, scapho-lunate diastasis, proximal scaphoid dorsal subluxation, plus pathological extension and ulnar translation of the lunate. This study reviews the efficacy of a reconstruction, based on the Stable Central Column Theory (SCCT) of Carpal Mechanics (reference), which aims to correct this disruption using a volar and dorsal approach with a hybrid tendon / synthetic tape weave (ANAFAB)

The purpose of this paper is to present the initial outcome indicating a successful translation of biomechanical theory into clinical solution.

Methods

The reconstruction was performed using a distally based strip of FCR tendon, supplemented by a synthetic tape that was passed from the volar trapezium to the scaphoid tuberosity, trans-osseously to the scaphoid dorsum, trans-osseously from dorsal to volar through the lunate and then volarly to the radial styloid where it was secured with an interference screw. Patients were immobilised in a cast for 6 weeks, but no stabilising wires were used.



Results

Ten patients have undergone the reconstruction and were assessed prospectively, including Scapho-Lunate (S-L) gap, pain, grip strength and carpal alignment.

At a minimum 6-month follow-up, the ANAFAB repair has achieved excellent realignment of the carpus, with correction of the S-L gap to (median) 3mm. Carpal realignment in most patients was within the normal range, and there has been a recovery of more than 75% grip strength and range of motion. Review is ongoing, with those patients followed the longest achieving further improvements in grip and motion.

Discussion

The ANAFAB procedure, based on the SCCT, has achieved a consistent recovery of carpal stability and grip strength, without significant loss of motion.

This is a theory driven, defect correction-based reconstruction that aims to restore the anatomical mechanical constraints on both volar and dorsal aspects of the carpus. However, further clinical experience is required to assess if this approach will provide a better long-term solution than we currently can offer our patients.

Reference

Sandow MJ, Fisher TJ, Howard CQ, Papas S. Unifying model of carpal mechanics based on computationally derived isometric constraints and rules-based motion - the stable central column theory. J Hand Surg Eur Vol. 2014 May; 39 (4):353-63.

Stable Central Column Theory of Carpal Mechanics

Sandow MJ. Stable Central Column Theory of Carpal Mechanics. Presented at International Wrist Investigators Workshop, ASSH ASM Las Vegas September 2019.
https://www.asshannualmeeting.org/servlet/servlet.FileDownload?file=00P0a00000mMZOAEA4
(Accessed 11th March 2019)

Background

The carpus is a complicated and functionally challenged mechanical system and advancements in the understanding have been compromised by the recognition that there is no standard carpal mechanical system and no typical wrist. This paper cover component of a larger project that seeks to develop a kinetic model of wrist mechanics to allow reverse analysis of the specific biomechanical controls or rule of a specific patient's carpus, and then use those to create a forward mathematical model to reproduce the unique individual's anatomical motion based on the extracted rules.

Objective and Methods

Based on previous observations, the carpus essentially moves with only 2 degrees of freedom - pitch (flexion / extension) and yaw (radial deviation / ulnar deviation), while largely preventing roll (pronation / supination). The object of this paper is therefore to present the background and justification to support the rules based motion (RBM) concept states that the motion of a mechanical system, such as the wrist, is the net interplay of 4 rules - morphology, constraint, interaction and load. The Stable Central Column Theory (SCCT) of wrist mechanics applies the concept of RBM to the carpus, and by using a reverse engineering computational analysis model, identified a consistent pattern of isometric constraints, creating a "Two-Gear Four-Bar" linkage. This study assessed the motion of the carpus using a 3D dynamic visualization model, and the hypothesis was that the pattern and direction of motion of the proximal row, and the distal row with respect the immediately cephalad carpal bones or radius would be very similar in all directions of wrist motion. To identify the unique motion segments, 3D models were created from 5 normal wrists that underwent CT scanning in multiple positions of radial and ulnar deviation as well as flexion and extension. Each carpal row (proximal and distal) was animated with the cephalad carpal bones or radius held immobile. The rotational axis and position of each bone and each row was then compared in sagittal (Flexion-extension) and coronal (radial and ulnar deviation) motion.

Results

The carpus would appear to have only two degrees of freedom, and yet is stable in those arcs, with the controlling motion loads applied proximally in the forearm. The proximal row moved in a singular arc, but with a varying extent of the unitary arc during sagittal and coronal motion. The isometric constraints were consistent in both directions. The distal row moved on an axis formed by a pivot joint laterally (between the trapezium and scaphoid), and a saddle joint medially (between hamate and triquetrum). This axis changed as the proximal row moved. This created a distinct pattern of row motion to achieve the various required positions of wrist motion. On wrist radial deviation, the scaphoid (with the proximal row) flexed, and the distal row extended, whereas in wrist flexion, the scaphoid flexed (with the proximal row) and so did the distal row. The pattern was reversed in the opposite wrist movements. While the general direction of motion of each row was consistent, the extent was quite variable.

Conclusion

The project overview and more specific review supports the Stable Central Column Theory of carpal mechanics and the carpus acting as a Two-Gear Four-Bar linkage, as well as the concept of RBM as a means to achieve a quantitative analysis of the normal and injured wrist. This provides a basis for the theory driven quantitative analysis and understanding of the normal and injured wrist. More sophisticated 3 Dimensional modelling will be required to better understand the specifics of carpal motion however the reverse engineering of the specific rules that define each individual wrist can then be applied to a mathematical model to provide a what if test of particular surgical interventions for a proposed injury and this provides one of the first examples of quantitative 3 Dimensional CT analysis, virtual surgical intervention and surgical planning and when the provided surgical solutions are then applied to the model an outcome analysis and expectations as well as prognosis can be defined.

This concept has allowed the theory to be extended to define the deficiencies in the injured wrist, and the solutions to address them.

This study supports the Stable Central Column Theory of carpal mechanics and the carpus acting as a Two-Gear Four-Bar linkage, as well as the concept of RBM as a means to achieve a quantitative analysis of the normal and injured wrist.

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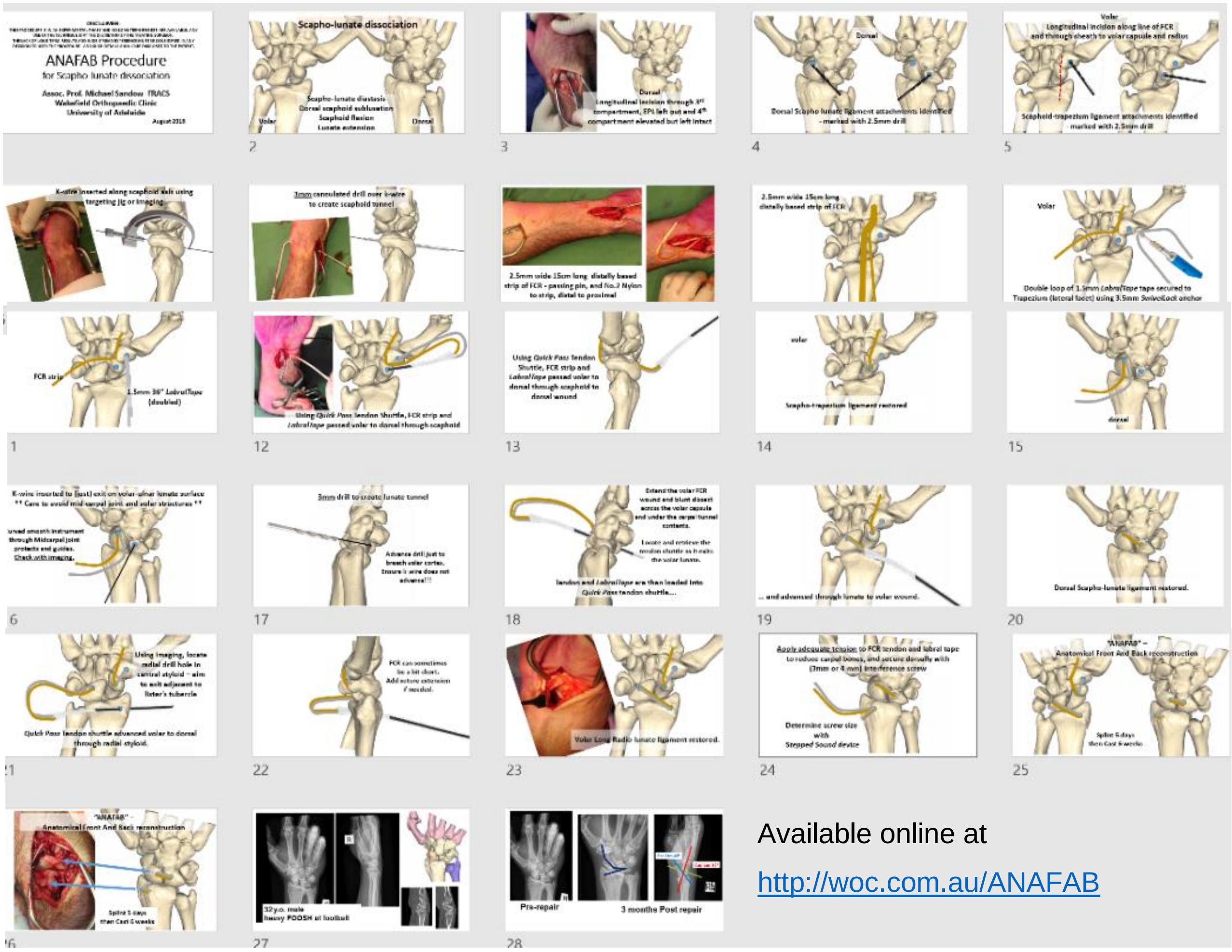
2. Sandow MJ et al. J Hand Surg Eur 39,353-63. 2014
3. Moritomo et. al J Bone Joint Surg Am. 88:611-21. 2006

- ## Why I do it this way and how I do it with technique video - ANAFAB Reconstruction

Sandow MJ. Why I do it this way and how I do it with technique video - ANAFAB Reconstruction. American Society for Surgery of the Hand, PRE-COURSE 05: Carpal Instability

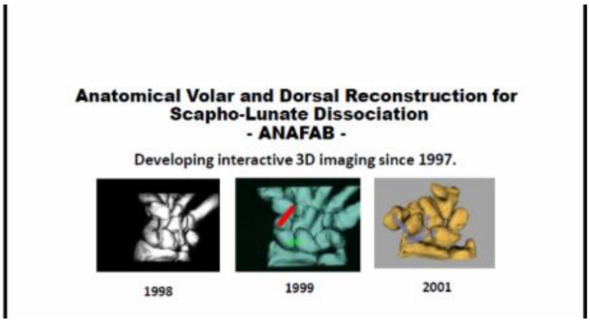
http://assh.force.com/annualmeeting/servlet/servlet.FileDownload?file=00P0a00000mN3O9EAK (Accessed 11th March 2019

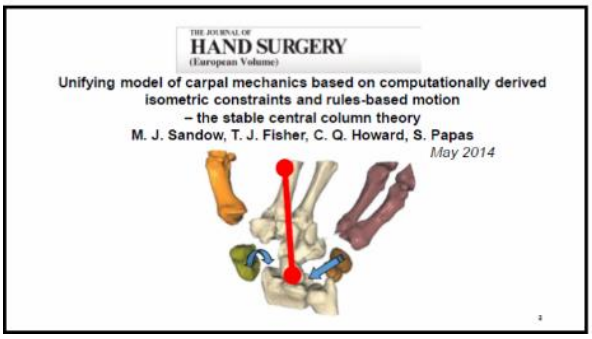


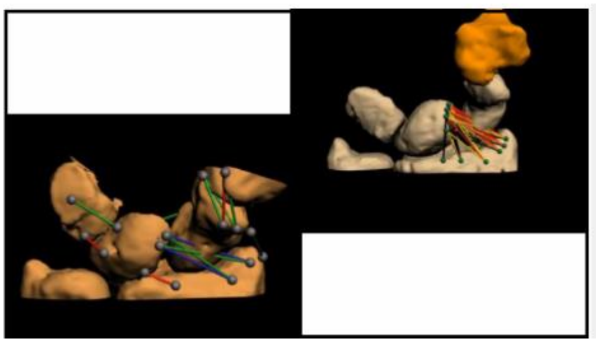
- ## Does the Stable Central Column Theory offer anything useful? It explains how the wrist works!!

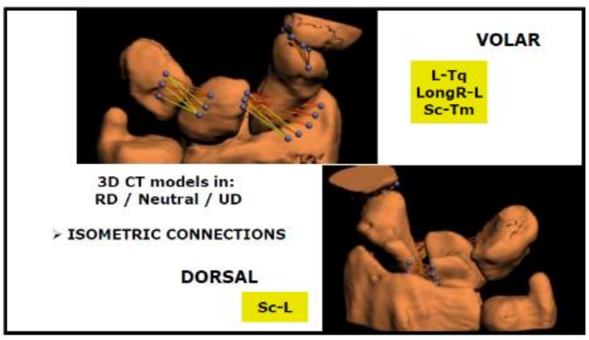
Sandow MJ. Does the Stable Central Column Theory offer anything useful? It explains how the wrist works!! Instructional Course: IC11: The 2019 Linscheid-Dobyns Instructional Course Lecture: The Critical Stabilizers of the Intercalated Segment. The stable central column and the critical ligamentous stabilizers.

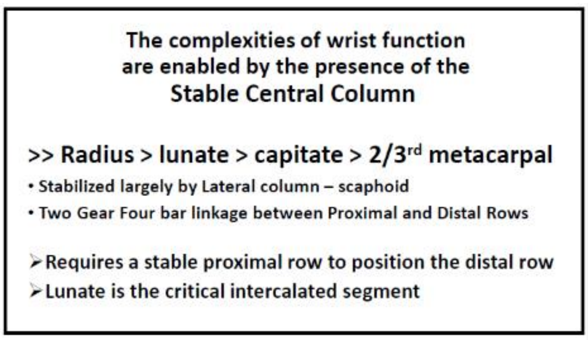
http://assh.force.com/annualmeeting/servlet/servlet.FileDownload?file=00P0a00000mMoDLEA0 (Accessed 11th March 2019)











Requires a stable proximal row
Lunate is the critical intercalated segment

Collapse patterns (simplified)

1. Lunate flexion or extension - DISI or VISI
2. Attached or not to the scaphoid – CID or CIND
   - CID – DISI
   - CIND – DISI
   - CID – VISI
   - CIND - VISI

Scapho-Lunate Injuries

- Frequently present late
- Late (> 3 months) vs Acute (> 4 weeks)

Late presentation

- More likely to have fixed displacement - irreducible
- More secondary deformity – additional attritional tears
- More degenerative changes

Acute S-L injuries

1. Carpal instability association with Radial fracture
2. As part of Multi-injury – Peri-lunate fracture dislocation etc.
3. Isolated Carpal Instability

Acute S-L Tears - THM

- Can occur as isolated carpal disruption, or part of wrist / radial fracture
- Undisplaced with fracture – pin in situ and manage fracture
- Isolated S-L tears / displaced S-L tears
  >>> needs assessment / reduction / fixation
- Three stage approach
  1. Assess and define disruption (Define Injury)
  2. Reduce displacement (Reduction Strategy)
  3. Stabilise displacement (Fixation Strategy)

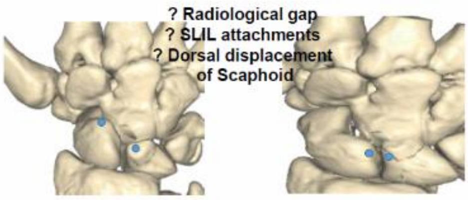
>> Volar and Dorsal Repairs as required
Anatomical Volar and Dorsal (ANAFAB)

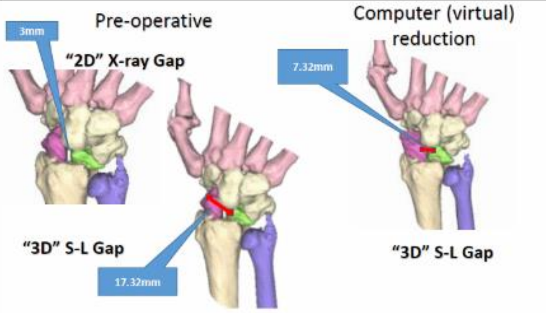
Acute S-L injuries / Tears

1. Assessment - What is the injury?
   1. Diagnosis of tissue disruption
   2. Understand mechanics and what is compromised
   3. What needs fixing
2. Reduction Strategy
   1. How to correct the displacement
   2. How to restore the anatomical relationship
3. Fixation Strategy
   1. How to hold the reduction
   2. Short and long term stabilisation

"Scapho-lunate" gap

Only measurable in 2D on x-rays and CT





S-L injury with Radial Fracture:

Initial treatment of a SLI of < 3mm does not always require treatment when accompanying a distal radius fracture.

Incidence and Functional Outcomes of Scapholunate Diastases Associated Distal Radius Fractures:
A 2-year Follow-Up Scapholunate Dissociation
Jonathan Lans, Alejandro Lasa, Neal C. Chen and Jesse B. Jupiter

1. **Reduced but S-L dynamic gap** >> treat radial fracture and pin S-L
2. **Gapped but reducible** >> primary repair of ligament with anchors and pin joint
3. **Gapped but not reducible** >> consider/treat as if it is primary S-L injury with secondary fracture
4. **Secondary degenerative changes** >> treat as chronic S-L injury

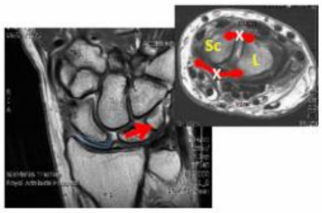
CID-DISI

Scapho-lunate dissociation
What to Do?

Volar capsulo-ligamentous - major restraint to the dorsal and volar translation of the carpus.

- **Volar capsule** –
  61% dorsal restraint,
  48% palmar restraint (of the radiocarpal joint)
- **Dorsal Radiocarpal ligament** –
  2% dorsal restraint,
  6% palmar restraint (of the radiocarpal joint)

Katz DA, Green JK, Werner FW, Loftus JB.
J Hand Surg Am. 2003;

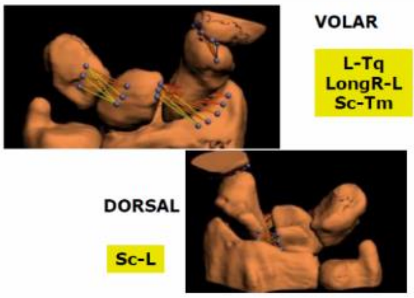


WHAT CAUSES DISI?

- **SLIL division alone ≠ DISI**
  - **Divided SLIL, RSC, LRL**
    - *Steve Lee et al, 2011*
- **Statistical association between SL instability and LRL injury**
  - *Van Overstaeten and Camus, 2016*

Scapho-lunate dissociation
What about the current repairs?

- Largely trial and error – not theory based
- Volar disruption largely ignored
- Do not address all the damage
- ** Each biomechanical deficit must be defined and addressed **

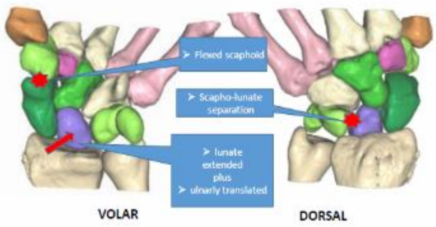


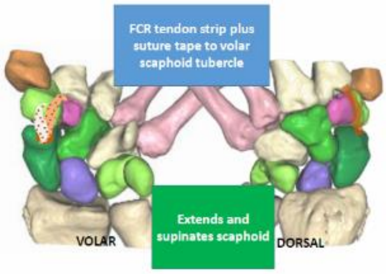
Scapho-lunate Dissociation / CID-DISI DORSAL

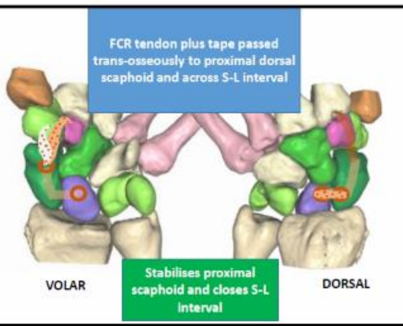
Injury spectrum:
- Scapho-lunate diastasis
- Scaphoid dorsal subluxation
- Scaphoid flexion
- Lunate extension / translation

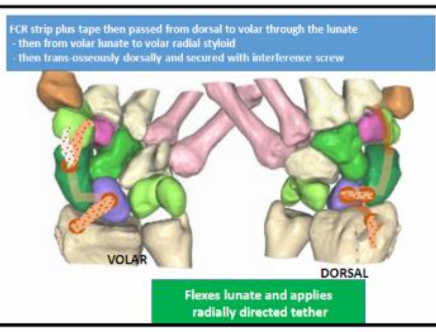
Critical 3
- STT
- dSLIL
- LRL

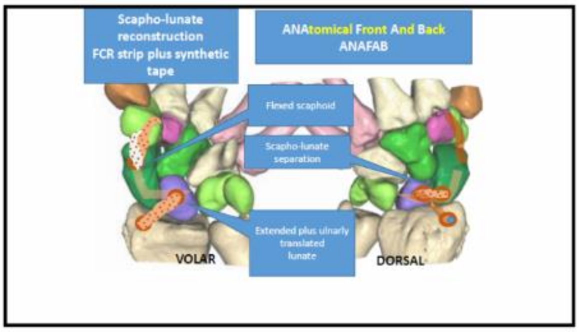
VOLAR

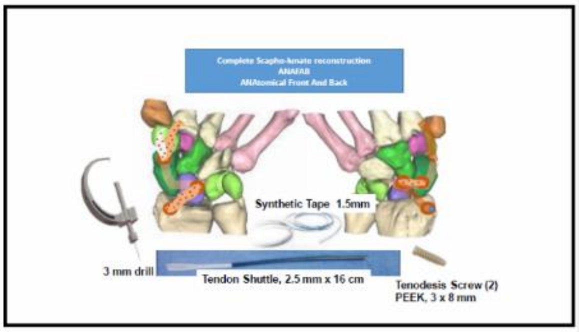


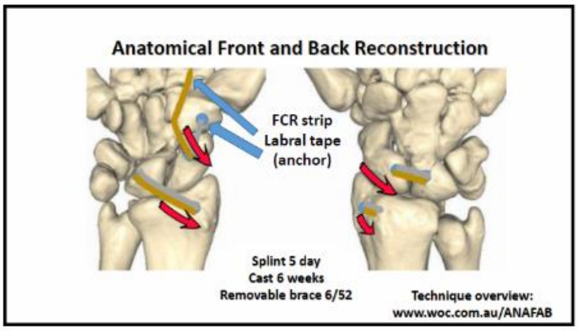







Scapho-lunate reconstruction FCR strip plus synthetic tape
ANAtomical Front And Back ANAFAB
Flexed scaphoid
Scapho-lunate separation
Extended plus ulnarly translated lunate
VOLAR
DORSAL

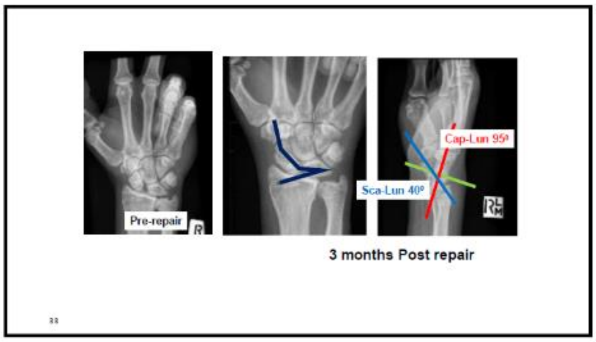

Complete Scapho-lunate reconstruction
ANAFAB
ANAtomical Front And Back
Synthetic Tape 1.5mm
3 mm drill
Tendon Shuttle, 2.5 mm x 16 cm
Tenodesis Screw (2)
PEEK, 3 x 8 mm


Anatomical Front and Back Reconstruction
FCR strip
Labral tape
(anchor)
Splint 5 day
Cast 6 weeks
Removable brace 6/52
Technique overview:
www.woc.com.au/ANAFAB

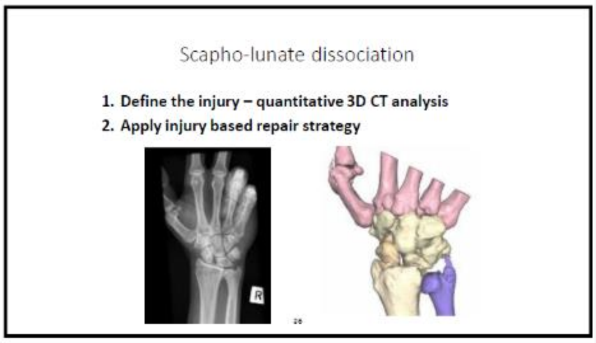

R
32 y.o. male
heavy FOOSH at football
30


1 week post op


Pre-repair
3 months Post repair


Cap-Lun 95º
Sca-Lun 40º
Pre-repair
3 months Post repair


6 months post ANAFAB


Scapho-lunate dissociation
1. Define the injury – quantitative 3D CT analysis
2. Apply injury based repair strategy
R

Scapho-Lunate Dissociation

Quantitative (3D) evaluation of:

- **dSLIL**
- **STT**
- **LRL**

} **CARPAL TRIFECTA**

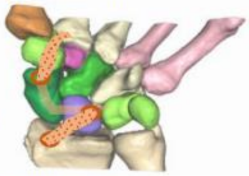
- **DCSS / DIC-L**

Apply injury based repair strategy

➢Repair is directed to the deficits

- Logic and Theory based

Scapho-Lunate Dissociation



- **dSLIL**
- **STT**
- **LRL**

}

Apply injury based repair strategy

➢Repair is directed to the deficits

- Logic and Theory based

Long term outcomes are needed

Stable Central Column **requires a** ***Stable Proximal Row***

Lunate is the critical intercalated segment

Collapse patterns (simplified)

1. **Lunate flexion or extension - DISI or VISI**
2. **Attached or not to the scaphoid – CID or CIND**

➢**CID – DISI**

➢**CIND – DISI**

➢**CID – VISI**

➢**CIND - VISI**

Acute S-L Tears - THM

- Can occur as isolated carpal disruption, or part of wrist / radial fracture
- Undisplaced with fracture – pin in situ and manage fracture
- Isolated S-L tears / displaced S-L tears

  >>> needs assessment / reduction / fixation
- Three stage approach
  1. Assess and define disruption (Define Injury)
  2. Reduce displacement (Reduction Strategy)
  3. Stabilise displacement (Fixation Strategy)

>> Volar and Dorsal Repairs as required

Anatomical Volar and Dorsal (ANAFAB)

Discussion – Can The Wrist Be Explained?

As detailed previously, the wrist has been difficult to characterise and this is largely related to the fact that most research has been empirical - carrying out multiple measurements of the motion of various components of the wrist both in vitro and in vivo situations then attempting to characterise the motion into patterns of movement.

To try to resolve this dilemma, a move away from the approach of exhaustively measuring how bones move with the forlorn attempt to find patterns, to an approach to assess what the wrist actually does and conceptually how it does it. This was a move from largely empirical to conceptual research.

The human wrist function is unique and places us at a distinct advantage regarding interacting with the environment. The wrist can be characterised as having three principle requirements (Figure 3);

1. To stably position the fingers and palm in space to create a required function for holding, grasping and throwing,
2. To create the 2nd and 3rd metacarpals as a stable central functional axis which is acted on by mobile thenar and hypothenar metacarpal anatomical units, and
3. Provide rotational and oblique gripping power which is powered proximally in the forearm to allow for a low-profile wrist.

In each anatomical or other motion system there are potentially six degrees of freedom (Figure 17). For the wrist these are pitch (flexion-extension), yaw (angled side to side), translation left and right, translation up and down, translation distally and proximally (or distraction or compression), and rotation (supination/pronation).

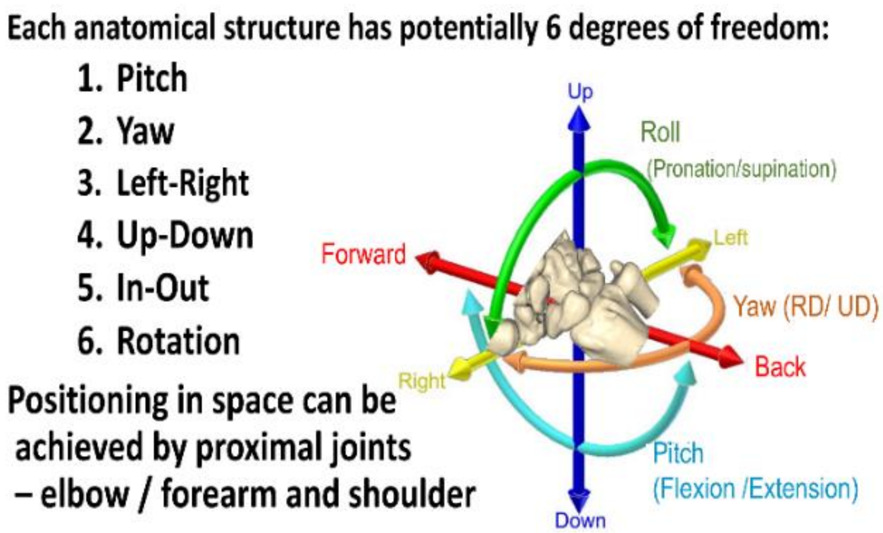


Figure 17. Degrees of Freedom of wrist.

The actual degrees of freedom through the wrist are not uniformly accepted, and in particular Garcia Elias strongly contends the wrist has actively controlled and resisted pronation and supination (Garcia Elias 2008). However, Sandow et al (2014) would argue that active control of carpal rotation is not likely given the position of the muscle powering this particular motion vector. The ligaments are largely positioned to resist rotation through the radio-carpal joint and deliver the rotational power generated by powerful muscles in the proximal forearm to the metacarpals.

It would appear the wrist has basically two degrees of freedom that are pitch (flexion/extension) and yaw (radial and ulnar deviation). All other movements are resisted including rotation (prono-supination) (Figure 18). While there is a certain amount of laxity within each of the joints, allowing some motion in other directions, this is only to the extent of the constraints and is not functionally useful nor under significant active control. The positioning in space of the wrist can be by proximal joints including the elbow, forearm and shoulder which have similarly a range or degrees of freedom.

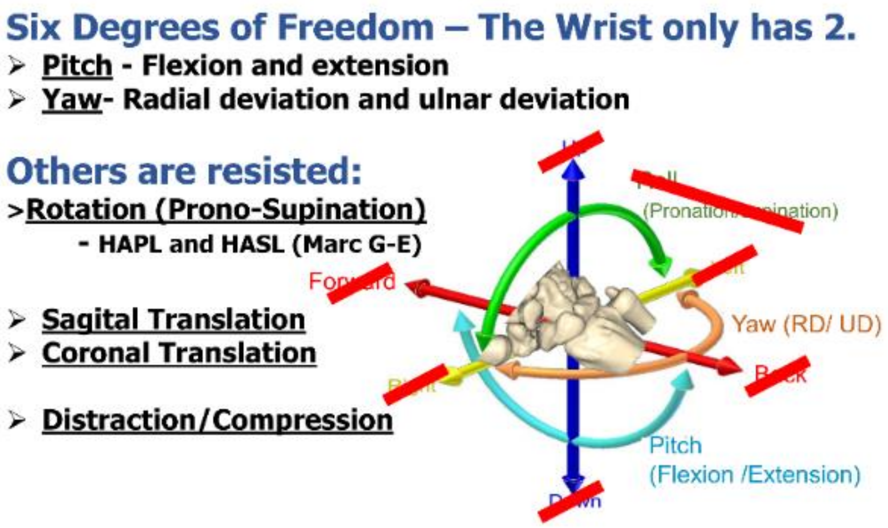


Figure 18. Of the 6 potential degrees of freedom, the wrist has only 2 – Pitch (Flexion and Extension) and Yaw (Radial and Ulnar deviation) – and all other degrees are resisted by a combination of bone shape and ligament attachments. (HAPL – Helical Anti-Pronation ligament, HASL – Helical Anti-Supination Ligament (Reference: Garcia-Elias 2008).

The rotational motion of the distal portion of the hand and wrist is largely directed through the forearm and powered by muscles proximal to the wrist. This maintains reduced profile of the wrist to increase its function but still provides good power proximally. This will be discussed further in subsequent sections.

It has been stated in the past that "form follows function", however it would certainly appear in the wrist that form enables function. While each wrist is different, the function itself is generally consistent.

Basic functional requirements

There are basically seven mechanicals prerequisites that the wrist must do to achieve required functional requirements.

1. **Adequate flexion and extension for holding and pushing (FLEXION/EXTENSION)**
2. **Adequate side to side rotation motion adjusting to holding different angles (RADIAL/ULNAR DEVIATION)**
3. **Delivery of powerful rotational force by resisting rotation through the radio-carpal joint (RESIST ROTATION)**
4. **Resist translation in coronal, sagittal and transverse planes (RESIST TRANSLATION /COMPRESSION/DISTRACTION)**
5. **Oblique power grip to improve holding, thrusting and throwing (ACHIEVE CO-LINEAR PALM AND FOREARM DURING USE)**
6. **Independent finger motion and wrist motion**
7. **Wrist must remain low profile in the distal extremity to increase functionality**

These various functional requirements must be achieved in the context of substantial biological constraints. The bones must be perfused and therefore vascular channels must attach to certain critical points of each of the bones, limiting the extent of surface articulation. Further, there are no axles in the human body and certainly no central pivot points, so the connection of the bones must only be by some form of external linkage.

Further to this there is substantial anatomical variation between the various bones.

Current carpal motion theories fail to achieve a consensus among researchers, are largely observational and thus poorly predictive, and are generally unable to test the effect of a particular intervention in one part of the carpus on overall wrist biomechanics. Consistent with this is the observation by Moojen et al. (2003) that '… a single functional model of carpal kinematics could not be determined' as well as work by Galley et al., (2007) and others (Craigen and Stanley, 1995; Garcia-Elias et al., 1995; Moojen et al., 2002) who showed that there is a 'spectrum of normal carpal kinematic motion'.

It has been difficult to reconcile the anatomical variability of the wrist as there is basically no average or typical wrist. A way forward may be to identify a generic wrist which includes the various bones which are of a general shape but can vary quite substantially. A generic structure can be defined as "characteristic of or relating to the class or group of things and not the specifics". This provides a handle on which to review the wrist.

The wrist has certain components that can each vary, but as detailed in the introduction, this embodies the concept of rules-based motion (RBM) (Sandow et al 2014, q.v. Chapter 2). The wrist biomechanics are therefore the result of a combination of:

1. Bone morphology
2. Constraints between the bones
3. Interaction between the bones
4. Load applied

Each component can vary but this will be matched by corresponding changes in the other components to create the same net outcome (Figure 19).

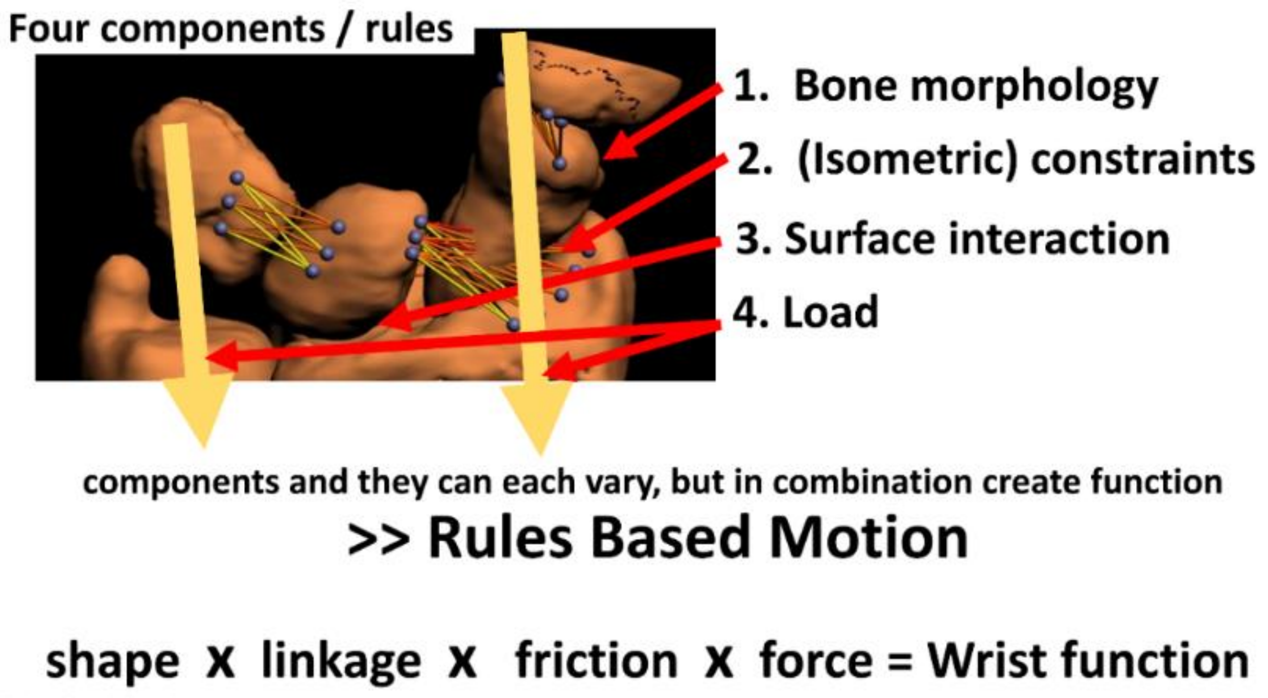


Figure 19. Rules Based Motion (RBM). There are four components or rules within a motion system such as the wrist, and each can vary. This individual component variation is offset or matched by changes in the other rule - which as a product creates a consistent net biomechanical outcome to achieve the required wrist function.

With this background, the various basic requirements (“Mechanical Prerequisites”) of the wrist can be explained in sequence.

1. Adequate flexion and extension for holding and pushing

A single linkage within the wrist given the constraints of vascular input and similar could probably only achieve approximately 45 degrees in each direction, so an approximate 90-degree arc of motion. The wrist requires 180 degrees arc of motion; therefore, a single linkage will not be adequate. This must then have a double linkage to achieve both 90 degrees of flexion and extension.

This will produce a potentially unstable proximal row but also requires a smooth transition between flexion and extension.

In the mechanical world this could be achieved by using a series of cylinders which each have a single axle (Figure 20). The pivot point at the "radial" end is fixed, but the pivot point on the "ulnar" end can move anteriorly and posteriorly to vary the alignment of the axes between the cylinders.

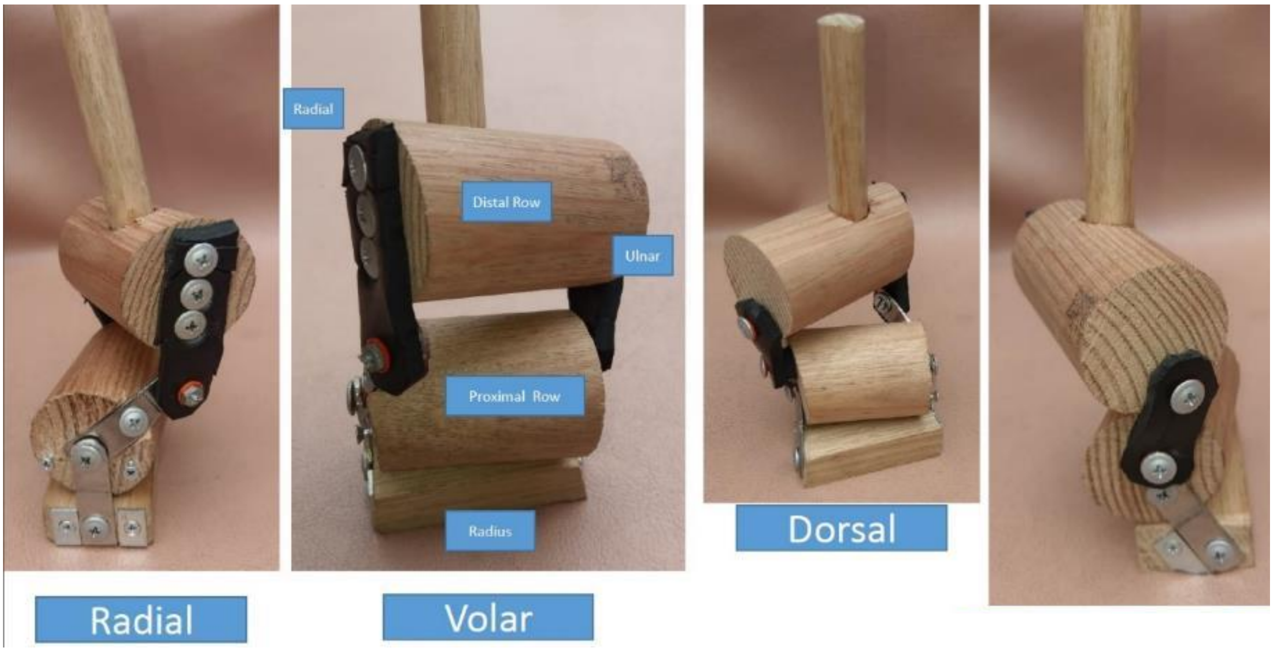


Figure 20. Wakefield Carpal Model - Model of the wrist as a series of single axle cylinders to allow adequate flexion and extension range.

When both cylinders move in the same direction, and the pivot points are in the same coronal plane, adequate cumulative motion is achieved to produce the required flexion and extension range (Figure 21).

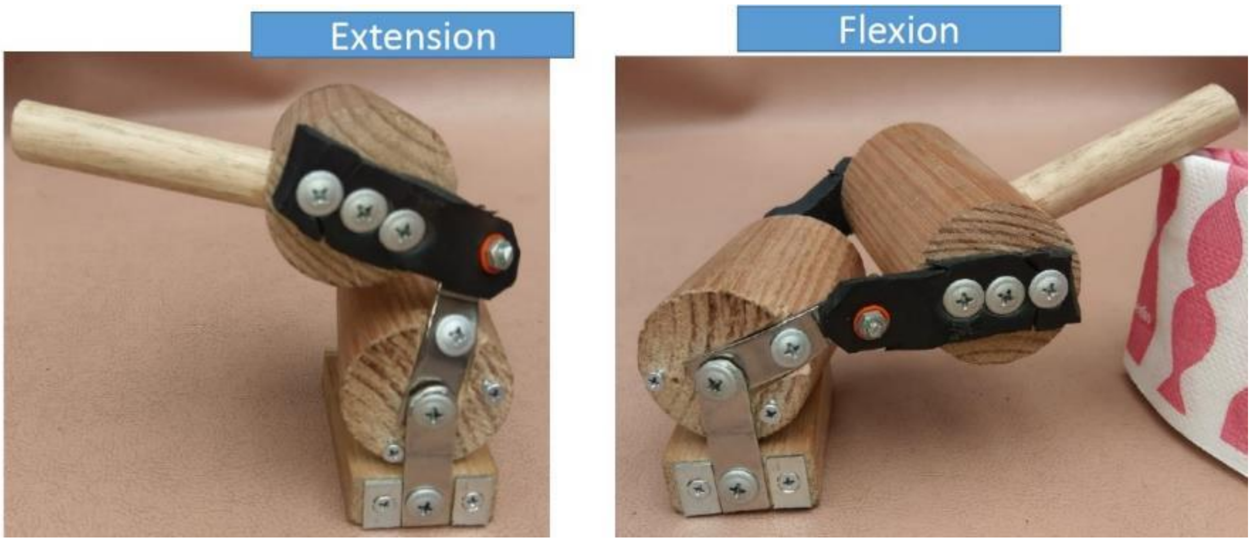


Figure 21. Wakefield Dowel Model showing both dowels moving in the same direction to achieve an adequate flexion and extension range.

There are however substantial biological constraints as noted previously and so this is not possible through non-biological axles.

Sandow et al 2014 (q.v. Chapter 2) demonstrated a clear pattern of connections between the various bones of the carpus, and so the proximal and distal rows of the carpus can move in a pattern similar to the dowels of the single axles Wakefield dowel model, but controlled by external linkages.

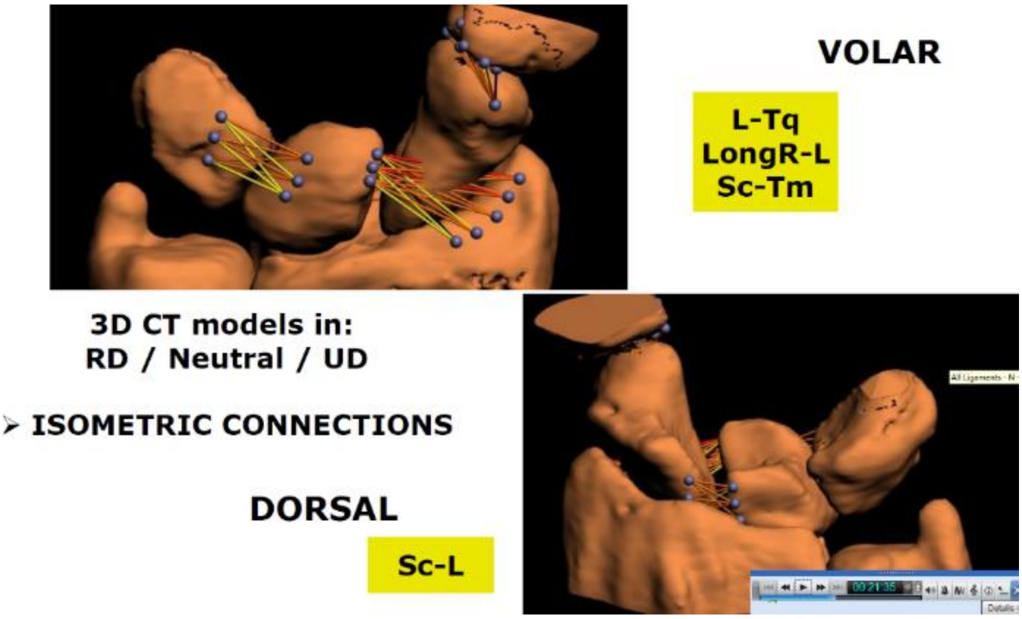


Figure 22. Isometric connections between and within the proximal carpal row and the radius.

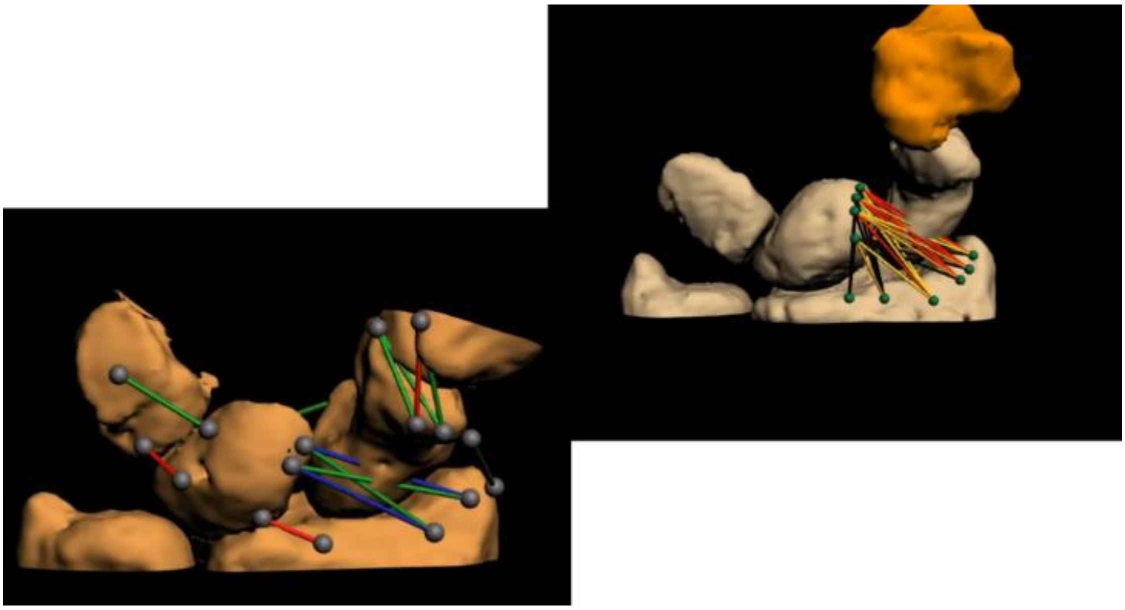


Figure 23. Clear connections between proximal carpal bones and the radius have been demonstrated by Sandow et al (2014), which allows notional flexion and extension of the proximal row, without a central axle.

Each carpal row is constrained by external linkages in the form of ligaments, and achieves the required uni-axial motion by a combination of the bones translating and rolling. What is of interest in subsequent research is that the isometric constraints are identical for flexion and extension as well as radial and ulnar deviation.

The proximal and distal rows can therefore be stylised as consisting of cylinders, having a single axis of rotation, but controlled by external linkages (Figures 22 - 24).

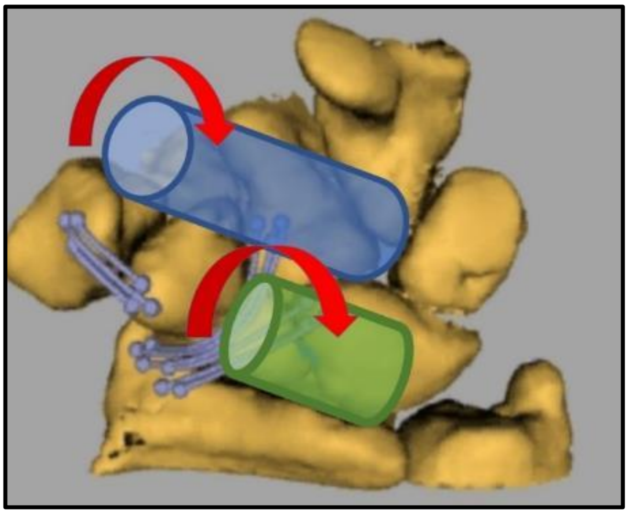


Figure 24. Proximal and distal carpal rows stylised as single axis cylinders.

This process would readily explain the adequate range of flexion and extension, with the flexor and extensor tendon acting on the distal row, with the proximal acting as an intercalated segment, controlled by external linkages and allowing motion by a combination of ligament constraint obliquity and sagittal translation (Sandow et al 2014).

However, this double in line uniaxial motion arrangement does not allow side to side motion - and the distal row cannot act like a universal joint, as the motor control is in the proximal forearm.

2. Allow side to side motion adjusting to holding different angles

The fixed position single axis cylinders, as discussed above and in the mechanical world, would achieve adequate range of flexion and extension, but would not achieve the offset motion required for radial and ulnar deviation.

The wrist cannot be a universal joint as this would be rotationally unstable. In the mechanical world this side to side motion could be achieved by the cylinders having a variable offset which would change the alignment of the axle of the distal row. The mechanical arrangement that would allow this motion would be for the proximal dowel to retain its single arc of motion in the same axis, but the distal dowel rotates in the opposite direction and with an offset axis. In the model, the “radial” side of the proximal dowel has a fairly fixed pivot point or connection of rotation, but the “ulnar” side can move to change the offset of the two dowels. This would mean that each dowel still only moves in a single arc, but their axes can be variably offset.

By then changing the offset, and having each dowel move in an opposite direction, side to side motion can be achieved (Figure 25)

Thus, flexion of the proximal row with extension of the offset distal row will achieve radial deviation, and conversely extension of the proximal row with flexion of the offset distal row will achieve ulnar deviation (Figure 25).

Again, as noted in the biological world this is not possible because there are no axles and the bones are constrained by external ligaments. This has been demonstrated in the computational isometric connections.

This explanation reconciles with the observation that the isometric attachments originally identified in yaw, or radial and ulnar deviation, are identical to those isometric relationships seen in flexion and extension (Figure 15 and 27).

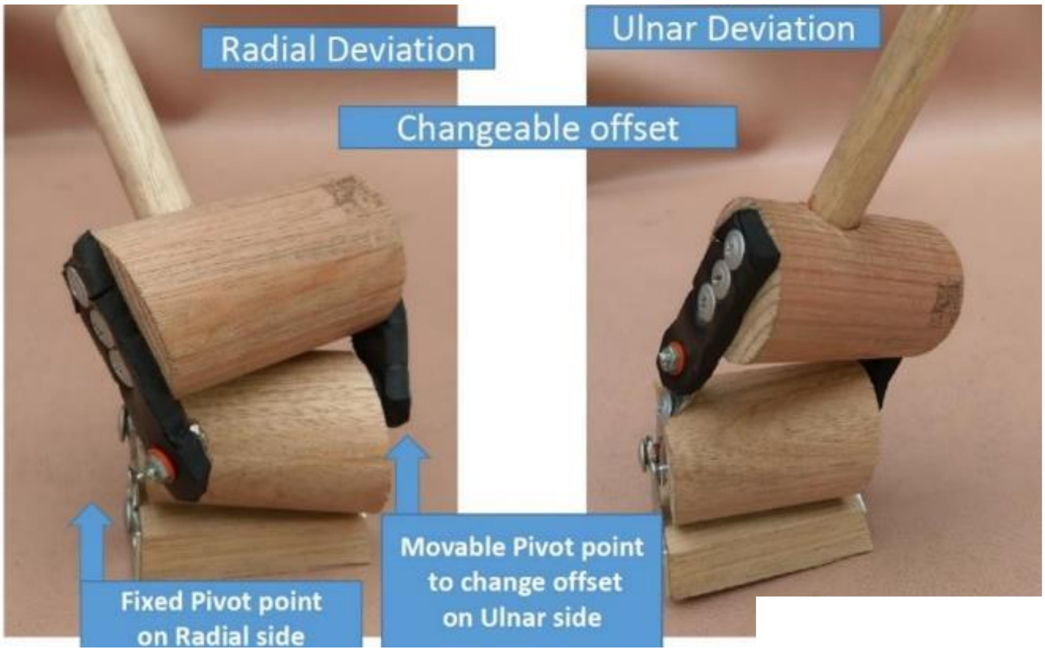


Figure 25 and 26. Wakefield Carpal Model - Cylinders RD/UD. Offset of the axes of each "row" achieved by the variable pivot point on ulnar side with the cylinder/dowels moving in opposite directions.

This means that there is a single set of isometric constraints, that control the motion of each row as a single axis with respect to its more caudal connection – for the proximal row this is the radius, and for the distal row this is the proximal row.

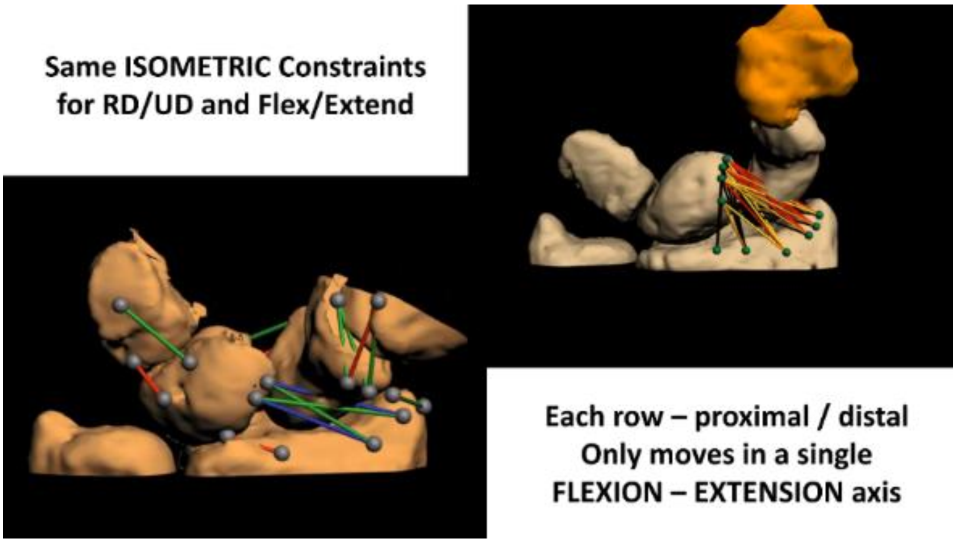


Figure 27. Isometric connections are the same for radial and ulnar deviation and for flexion and extension, indicating that each row has a unitary arc of motion with respect to its caudal neighbour.

The wrist however could be stylised as a series of proximal and distal cylinders (Figure 28).

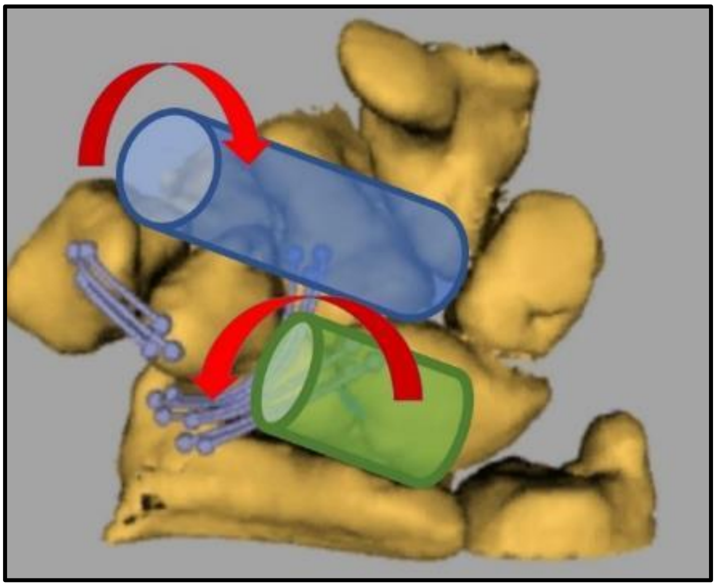


Figure 28. Proximal and distal row, stylised as offset single axis cylinders moving in opposite directions to achieve radial and ulnar deviation.

With the dynamic modelling capabilities of the TLA software, the motion of the wrist can be analysed by moving each row sequentially. This is artificial as the motion of each row would move concurrently, making it difficult to appreciate the specific relationship of the rows as they move.

The following diagrams (Diagrams 29 A-I) demonstrate the stylised sequential motion of the wrist in flexion and radial and ulnar deviation.

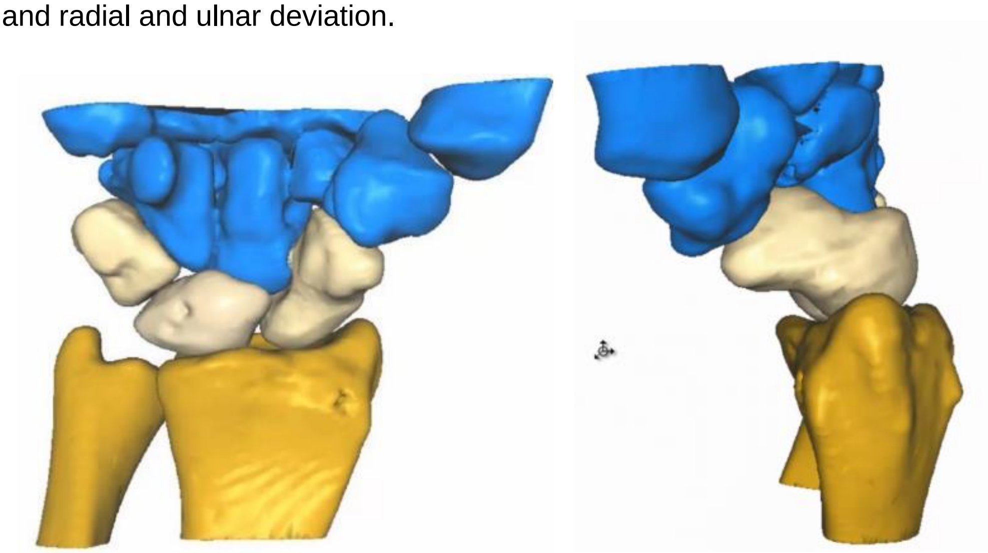


Figure 29 A. "Generic" wrist 3D model in neutral position, separated into radius and ulnar (tan), proximal row (brown) and distal row (blue).

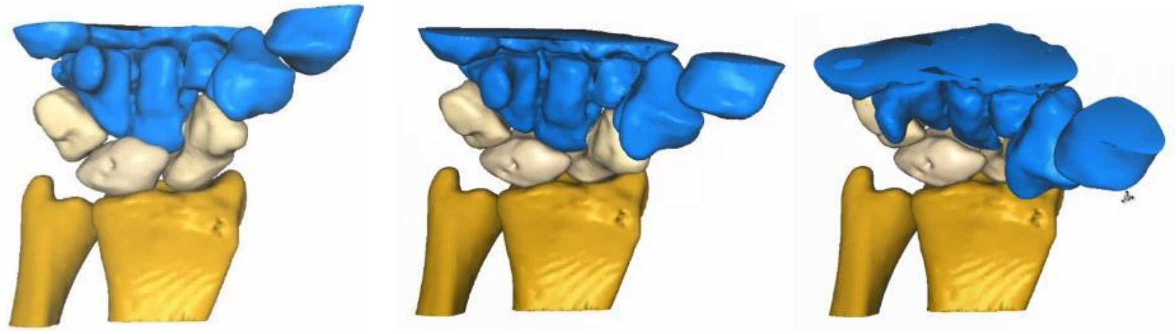


Figure 29 B. Wrist flexion – Anterior view – a. Neutral, b. Proximal row flexed, then c. distal row flexed

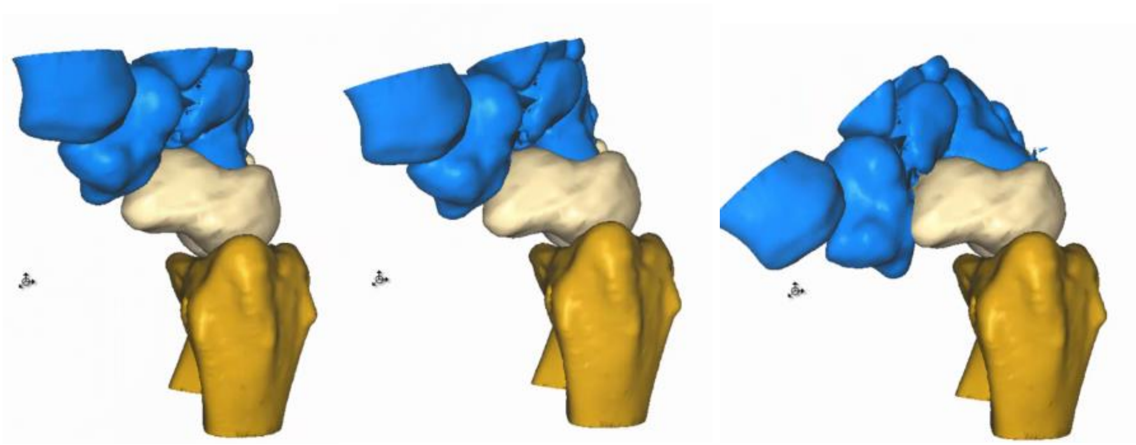


Figure 29 C. Wrist flexion – lateral view – Neutral position, then proximal row flexed, then distal row flexed

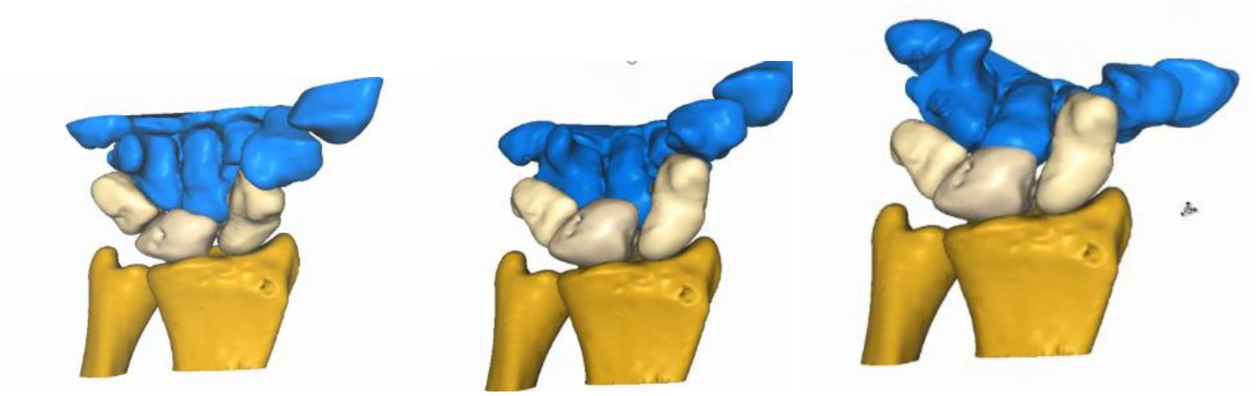


Figure 29 D. Wrist extension – Anterior view – a. Neutral, b. Proximal row extended, then c. distal row extended

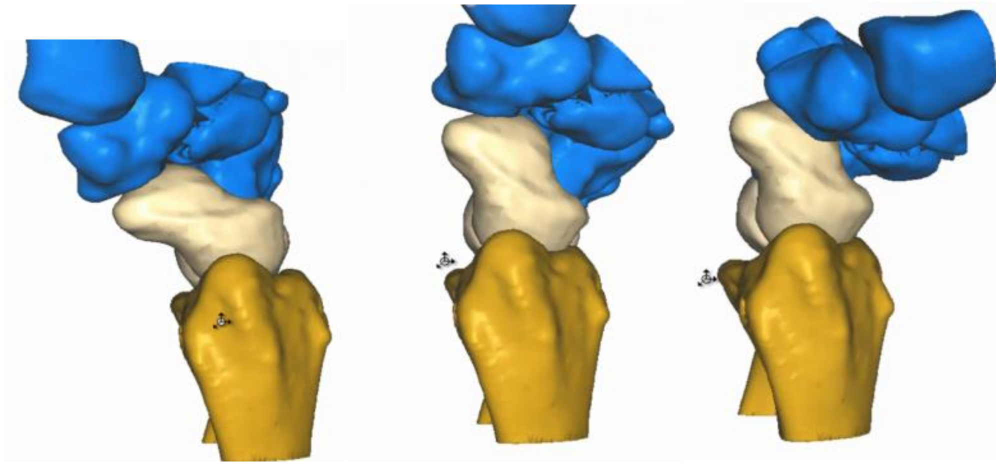


Figure 29 E. Wrist extension – Lateral view – a. Neutral, b. Proximal row extended, then c. distal row extended.

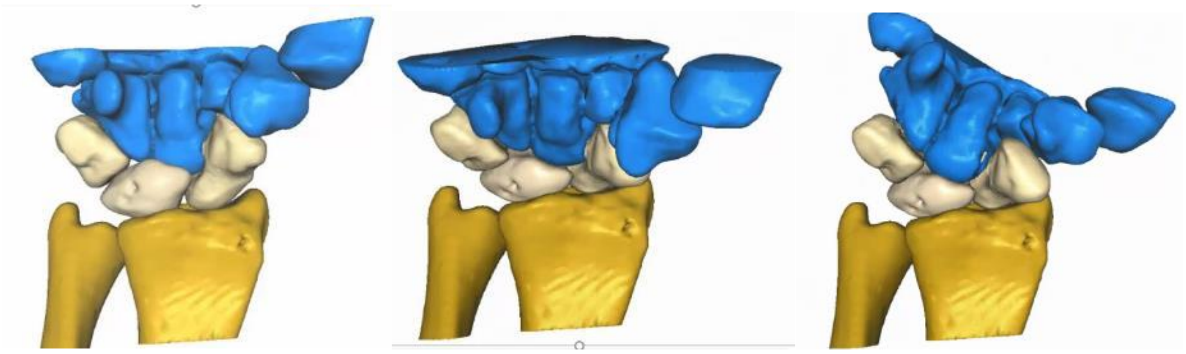


Figure 29 F. Wrist Radial deviation – Anterior view – a. Neutral, b. Proximal row Flexed, then c. distal row extended

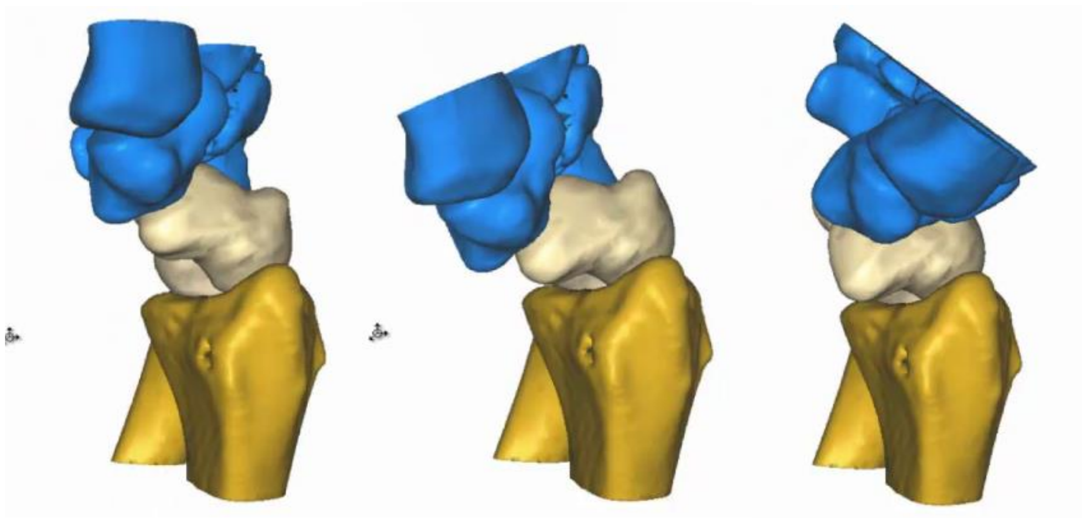


Figure 29 G. Wrist Radial deviation – Lateral view – a. Neutral, b. Proximal row Flexed, then c. (offset) distal row extended

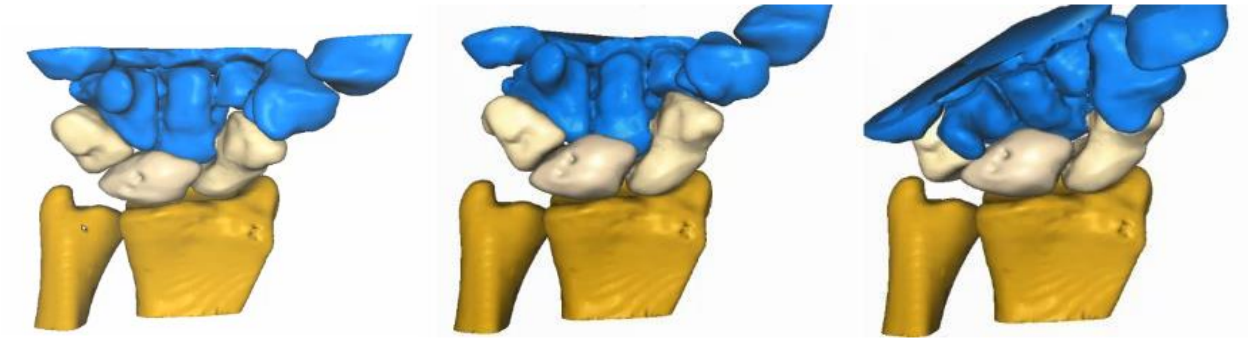


Figure 29 H. Wrist Ulnar deviation – Anterior view – a. Neutral, b. Proximal row Extends, then c. (offset) distal row Flexes.

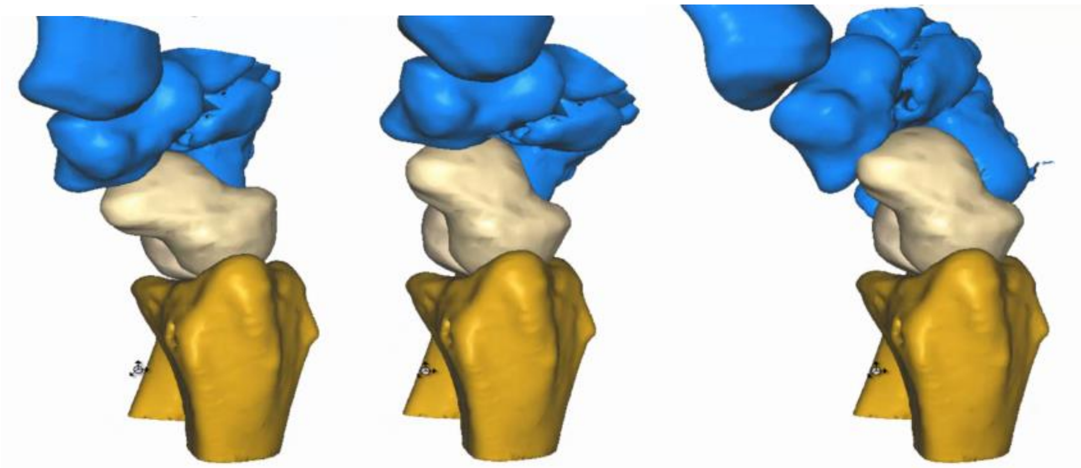


Figure 29 I. Wrist Ulnar deviation – Lateral view – a. Neutral, b. Proximal row Extends, then c. (offset) distal row Flexes.

In summary, the wrist consists notionally of two single axis cylinders with variable offset:

- When cylinders are in line and moving in the same direction, the wrist moves into flexion and extension.
- When the cylinders are offset and moving in opposite directions, the distal carpus moves into radial and ulnar deviation.

The mobility of the triquetrum allows the distal row to change its alignment with the proximal row. These findings are quite consistent with the work of Moritomo et al (2004) who identified the distal row as moving and connecting to the position of the scaphoid (Figure 30).

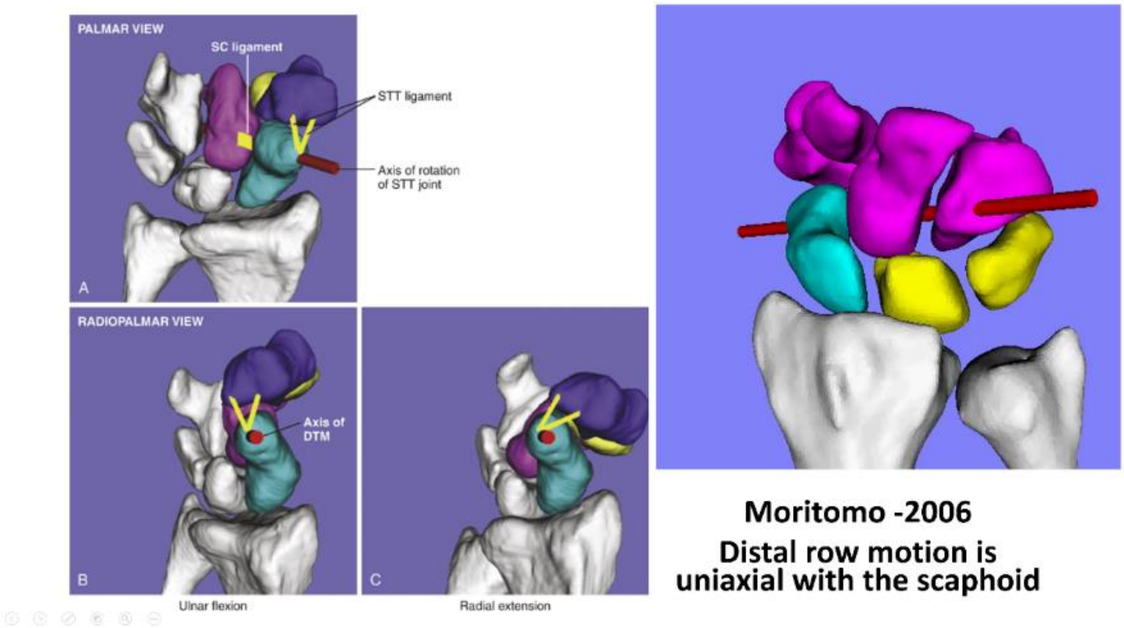


Figure 30. Distal row is linked to the proximal row (Moritomo et al 2006)

The carpus can thus be seen as two carpal rows that are linked, but variably offset. Each only moves through a singular arc of motion, but the combined binary output of the variable offset alignment creates the required two degrees of freedom (Figure 31).

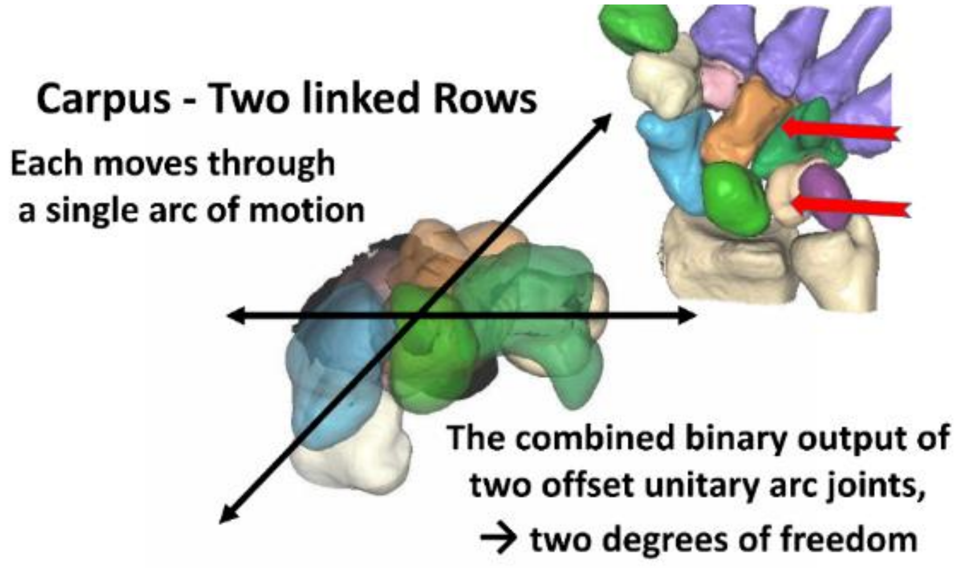


Figure 31. The wrist can be seen as two linked rows. Each which moves in a single arc of motion. The binary output of the two offset joints creates the required two degrees of freedom. (Sandow et al 2014).

The pivot points between the proximal and distal row are the key to understanding the ability to create the two degrees of freedom. On the radial side, the connection between the distal and proximal row forms a pivot point similar to the distal radio-ulnar joint – a trochoid, rotatory or ginglymoid joint.

On the medial aspect, the rows are connected more by a saddle joint, much like the basal joint of the thumb. When combined with the anterior and posterior mobility of the triquetrum, this articulation allows spatial and axis changes in the motion arc, thus allowing the offset binary motion of the two rows (Figures 32A and B)

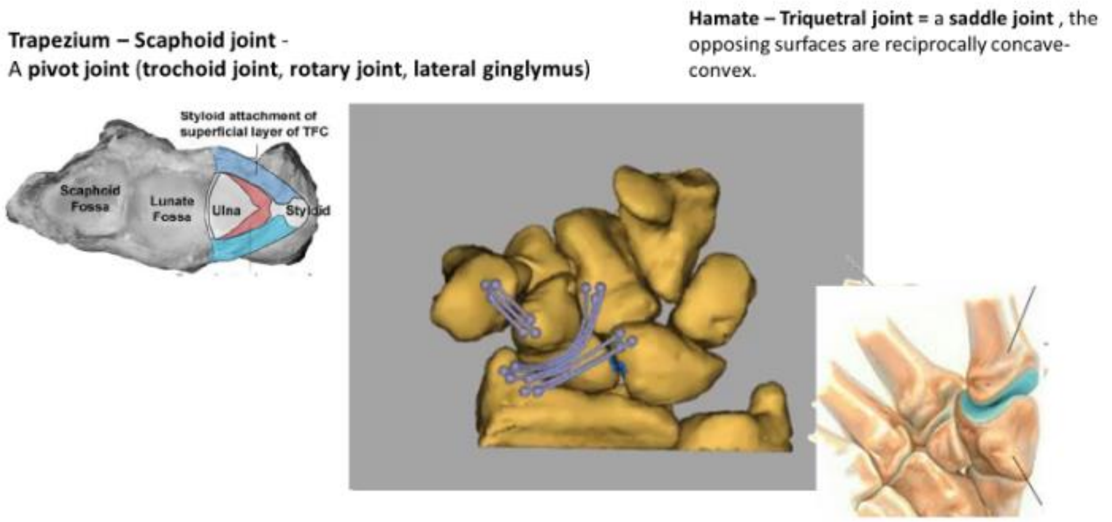


Figure 32A. On the radial side, the connection between the distal and proximal row forms a pivot point similar distal radio-ulnar joint – a trochoid, rotatory or ginglymoid joint.

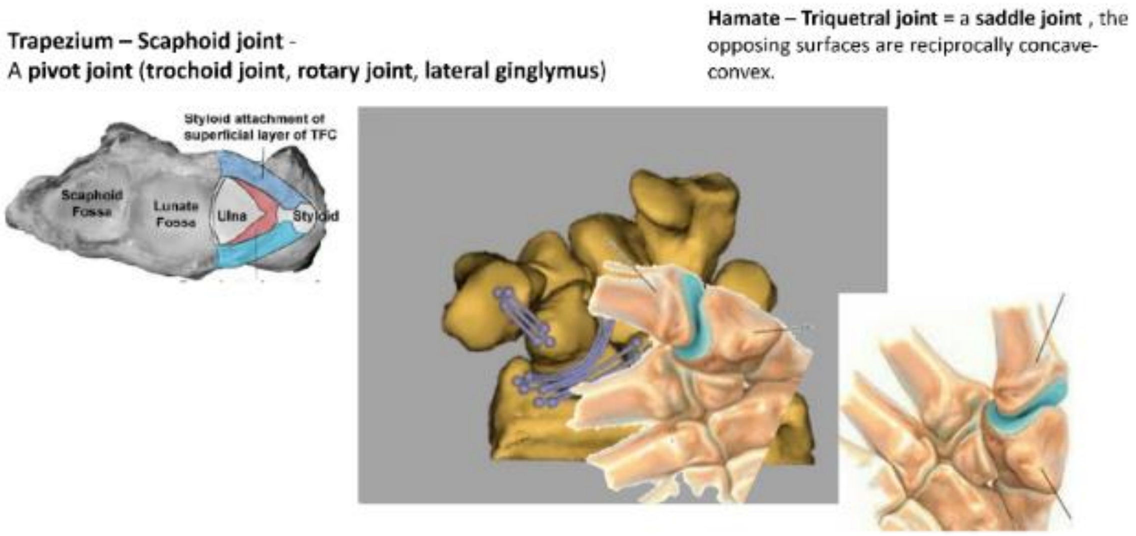


Figure 32B. On the medial aspect, the rows are connected more by a saddle joint, much like the basal joint of the thumb.

The proximal and distal rows are linked together in a form of two-gear four bar linkage. Such a linkage is well described in other anatomical systems, and creates a powerful connection between the rows (Figure 33).

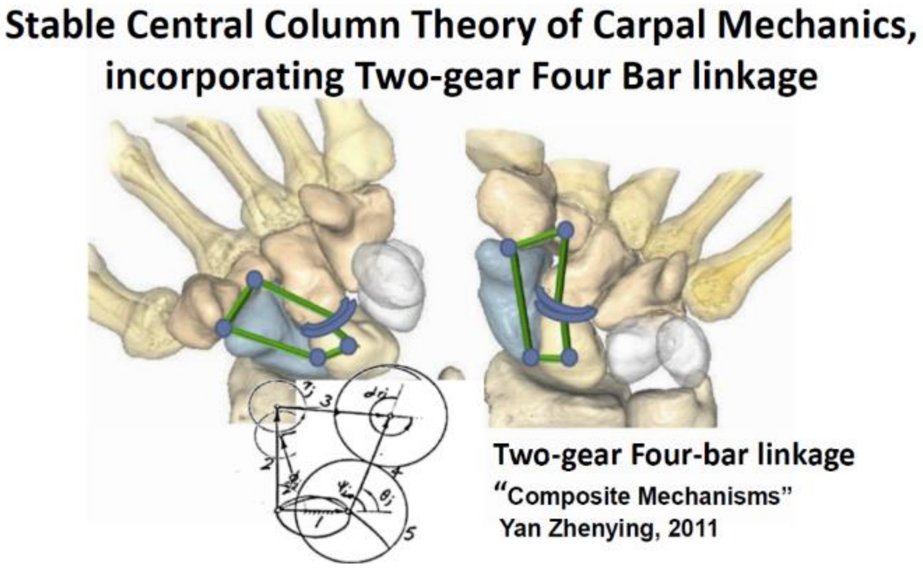


Figure 33. Two gear four bar linkage (Sandow et al 2014).

This concept of the differential but interdependent motion of the proximal and distal rows is supported by recent work by Akhbari et al (2019). They agreed that the wrist can be regarded as a two-degree freedom of movement joint due to a kinetic reduction of the individual motion of actual carpal bones.

Consistent with the observations by Sandow et al (2014) (q.v. Chapter 2), they (Akhbari et al, 2019) demonstrated that the bones of the distal row move largely as a single unit during wrist motion. They identified greater differential motion between bones of the proximal row in different wrist arcs of motion, however during each specific anatomical motion axis the differential motion was minimal.

Differential motion between the bones of the proximal row is critical to allow for the variable offset of the more stable distal row during each of the two-degrees of freedom. This allows the axis formed between the lateral pivot point (formed by the connection between trapezium and scaphoid) and medial articulation (formed largely between the hamate and triquetrum) to pronate and supinate, which thus defines the axis of motion of the distal row.

As part of the stable central column theory, the lunate is placed between the scaphoid and triquetrum, and it is attached firmly to only one side of the adjacent bone – to the scaphoid dorsally, and the triquetrum volarly. This alternating attachments of inter-row intercarpal ligament (Figure 42 A and B) is critical to allow the lunate to remain relatively axially immobile while the adjacent bones move. This allows the proximal row to change shape to create the shifting pivot points to allow the variable offset of the distal row.

What must be stressed however is that while these articulations can be described as a notionally consistent linkage, there is considerable variations in terms of actual angles of displacement and specific axes of rotation. The concept of rules-based motion however provides the justification for acceptance, and perhaps the means to provide some explanation on how there can be such variation of the actual individual carpal bone motion and yet a functional outcome that we see as a stable wrist, with only two- degrees of freedom.

3. Deliver powerful rotational force

The muscle loading of a joint, and in particular the wrist, is generally perpendicular to the motion vector, and the location of such rotational loading via strong muscles cannot be at the level of the wrist to avoid extremity bulk.

A joint such as the hip which is largely a universal joint has large muscles to control its rotation, however this would make the wrist dysfunctionally bulky and so therefore the delivery of rotation power must be more proximal.

This is achieved by the arrangement of the carpal ligaments preventing rotation and therefore as the forearm rotates and as such the radius rotates around the ulnar, the carpus is rigidly constrained in a rotational manner to the distal radius but still is able to carry out flexion and extension as well radial and ulnar deviation in the two other degrees of freedom (Figure 34).

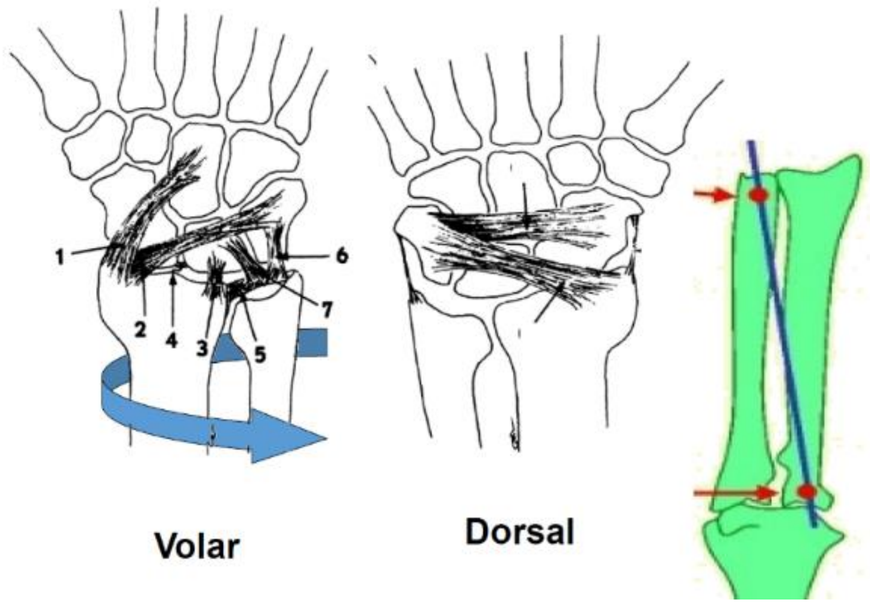


Figure 34. Pronation/Supination is restrained by obliquely positioned ligaments to resist rotational force.

This concept is not fully consistent with the more dynamic rotational control proposed by Garcia-Elias (Garcia Elias 2008).

The biological constraints require external linkages and this is achieved through a series of external linkages creating an oblique connection with translation facilitating rotational and stable motion of the carpus.

4. Resist translation in coronal, sagittal, transverse and longitudinal planes

The function of the wrist is to deliver load to the second and third metacarpal, and resist all but pitch and yaw.

Strong obliquely oriented ligament combined with an enveloping capsule prevent coronal and sagittal translation. The oblique hoop arrangement of the radial to triquetral ligament restraint on the dorsal and volar aspects (Figure 35) is critical to prevent ulnar translation of the carpus on the radius.

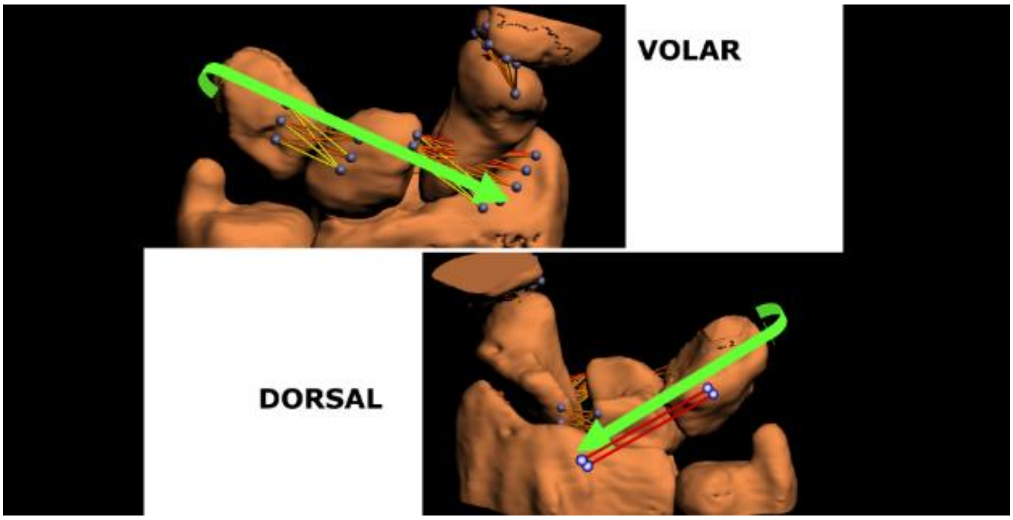


Figure 35. Restraint to ulnar translation due to volar and dorsal oblique ligaments (Sandow et al 2014).

While the short radio-lunate ligament has been previously regarded as limited to lunate extension (Garcia-Elias 1997), it is more appropriately positioned as a restraint to distraction (Figure 36).

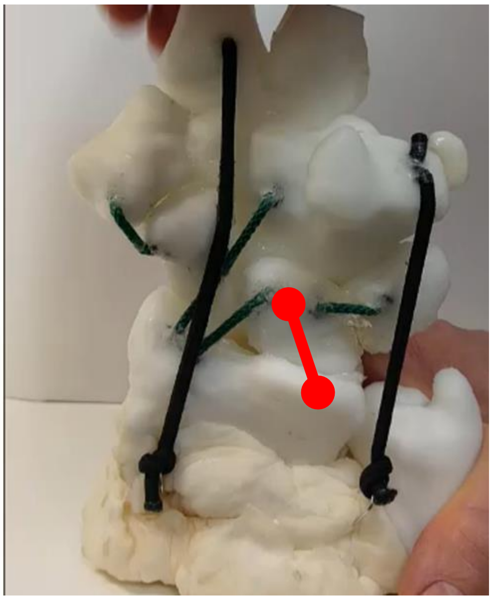


Figure 36. Short Radio-lunate ligament (red line) becomes taut with the wrist in slight ulnar deviation, thus resisting distraction.

5. Oblique power grip to improve holding, thrusting and throwing

One of the unique characteristics of the human wrist is the ability to achieve oblique power grip which requires alignment of the palm with the forearm, not a variable flexion of the fingers, as will be present in the primate. This requires flexion and ulnar deviation of the wrist and places the palm co-linear with the forearm. This is achieved by pronation and flexion of the distal row on a stable proximal row to achieve the so-called dart throwers motion.

This is achieved by the pronation of the distal row on the proximal row so that the distal row has a resting position approximately 45 degrees to the coronal access of the radius and ulnar. This is achieved through the shape of the trapezoid as detailed in the paper on the SCCT (Sandow et al 2014), and this translates the trapezium forward bringing the thumb out from the coronal plane of the forearm. This has a number of mechanical advantages, including oblique power grip and improved opposition of the thumb, substantially increasing overall improved function (Marzke 2009)

In contrast, the chimpanzee (Pogo) wrist lacks the functionality of the human carpus. A review of the carpal anatomy is relevant as the chimp trapezoid is more triangular, the trapezium is more in a coronal plane and the primate lacks the oblique power grip so characteristic of the human wrist. It has been well described previously (q.v. Chapter 7) (Figure 37-38).

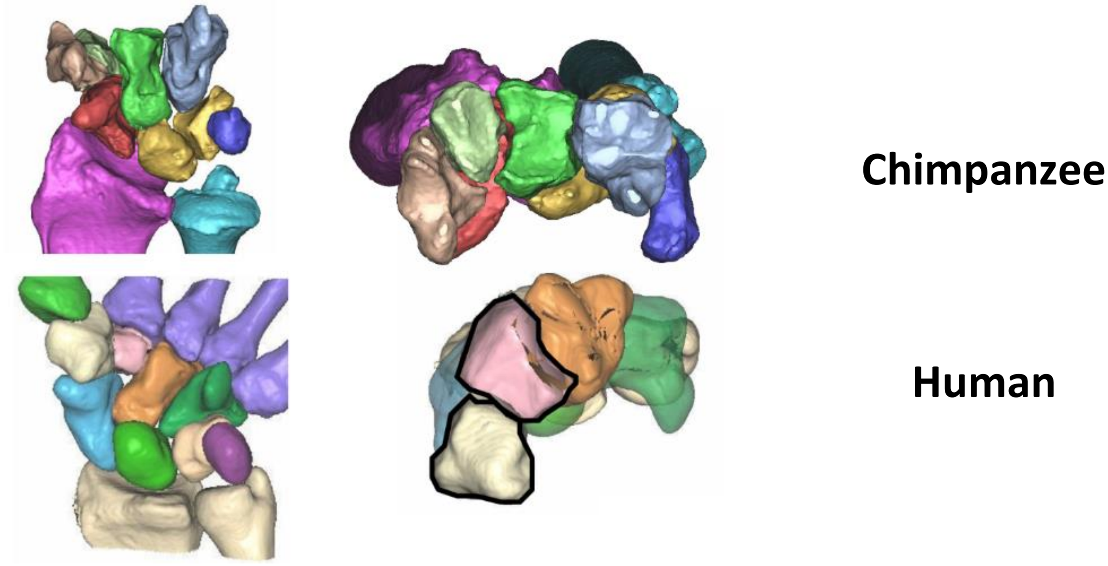


Figure 37A. The chimpanzee trapezoid (lime green) is triangular which does not translate the trapezium (tan) significantly forward, and out of the coronal plane compared to the human trapezoid (pink) with its more trapezoid shape.

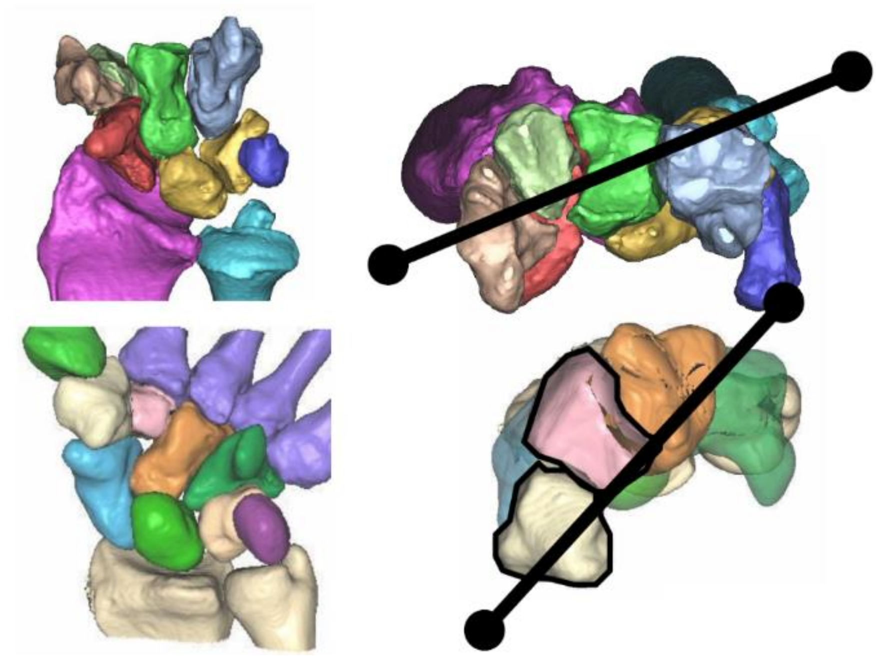
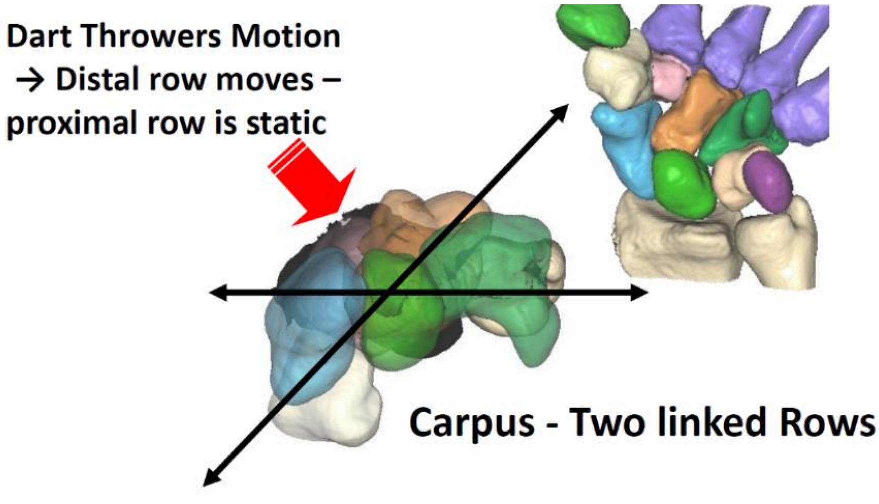


Figure 37 B. Due to the differing shape of the trapezoid, the distal row of the human is pronated by approximately 45 degrees compared the Chimp, thus allowing oblique power grip.



Future 38. This translates to the ability to perform the so-called Dart Throwers motion.

6. Independent finger and wrist motion

The characteristics of the wrist are that the fingers need to be positioned in space and allow independent motion of the fingers. This is achieved by flexor and extensor tendons being positioned on the immediate maximum volar and dorsal aspect and the so called four corners, with the flexor tendons positioned almost centrally in the carpus (Figure 39).

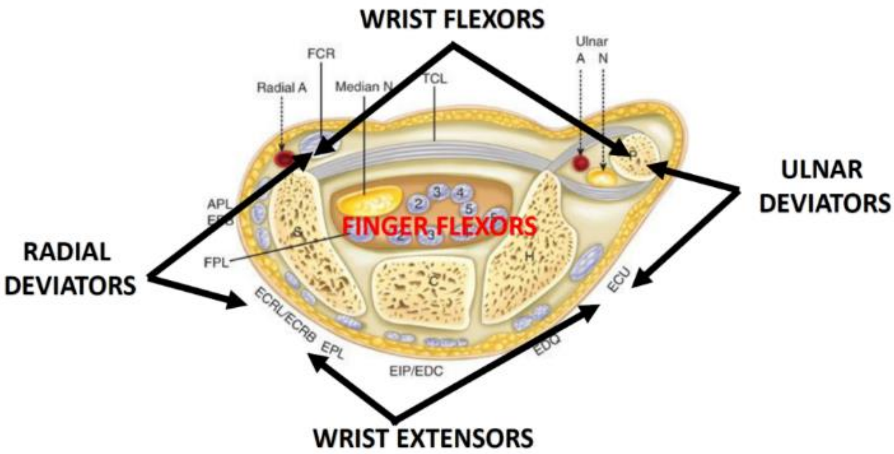


Figure 39. The wrist and finger muscles are arranged optimally to achieve controlled motion and power. FPL- Flexor pollicis longus, APL – Abductor pollicis longus, EPB – Extensor pollicis brevis, ECRL – Extensor carpi radialis longus, ECRB – Extensor carpi radialis brevis, EIP – Extensor indicis proprius, EDC – Extensor digitorum communis, EDC – Extensor digit quinti, ECU – Extensor carpi ulnaris, Ulnae A/N – Ulnar artery and nerve, TCL – Transvers carpal ligament, Median N – Median nerve, FCR – Flexor carpi radialis, Radial A – Radial artery.

By sequentially contracting either both wrist flexors (Flexor carpi ulnaris and flexor carpi radialis muscles), or the extensors of the wrist (Extensor carpi radialis longus / brevis, and extensor carpi ulnaris muscles), the wrist will flex and extend respectively. Conversely, by contracting the radial wrist muscles, or the ulnar sided wrist muscles, the wrist will radially or ulnarly deviate respectively. The finger flexor muscles and tendons (Flexor digitorum profundus and Flexor pollicis longus) create a powerful contractile force for gripping, and because of the central location in the carpus, are minimally affected by the actual alignment of the wrist in the usual functional range.

The position of the flexor tendons down the central axis of the carpus allows the wrist to adopt a wide range of motion without substantially compromising the capabilities of the flexor muscles. The extensors, which are largely to lift the fingers from the palm and not generally required for strong power grip, are positioned dorsal to the central axis. When the wrist is in flexion the extensors have little function but to restore the wrist to its neutral position.

A more detailed discussion of the interplay of the intrinsic muscles and subtle impact on wrist position during rehabilitation following tendon repair and wrist reconstruction is outside the scope of this document. However, the anatomical positions of the muscles and tendons of the wrist allow independent finger and wrist motion.

7. Low profile distal extremity

To optimise the independence and function of the fingers, the distal upper extremity must have a narrow profile. Muscles acting as part of a force couple are best if working close to perpendicular to the motion direction. To achieve this, strong muscles are positioned in the forearm to power the long flexor tendons, the long extensor tendons as well as the radial and ulnar deviator muscles of the wrist. Forearm rotation is achieved by strong oblique muscles principally positioned proximally through the supinator, the biceps tendon as well as the pronator quadratus and the pronator teres. The strong rotational load in the forearm muscles is then delivered to the carpus which resists as discussed previously.

The wrist can achieve strong flexion and extension, as well as independent sideways motion of radial and ulnar deviation, while maintaining a slim distal profile (Figure 40).

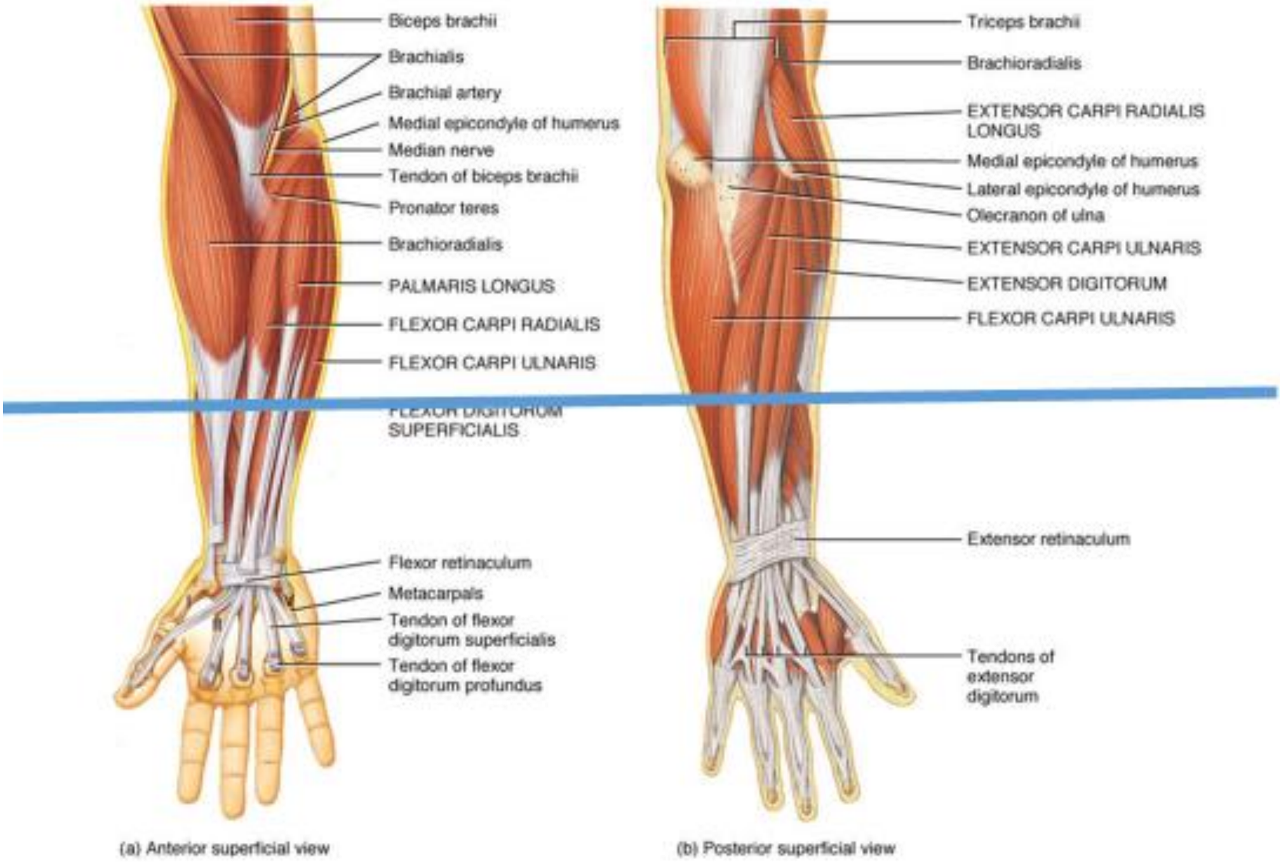


Figure 40. Muscles acting on the wrist to create finger and wrist motion are mostly positioned in the proximal half of the forearm to create a slim distal extremity, but still with powerful motion control.

Functionality Summary

The complexities of wrist function are enabled by the presence of a stable central column which delivers load from the radius to the lunate to the capitate and to the 2nd and 3rd metacarpals. This is largely stabilised by the scaphoid as detailed in the stable central column theory, and the connection between the proximal and distal rows can be seen as a notional two gear four bar linkage (Sandow et al 2014) (Figure 41).

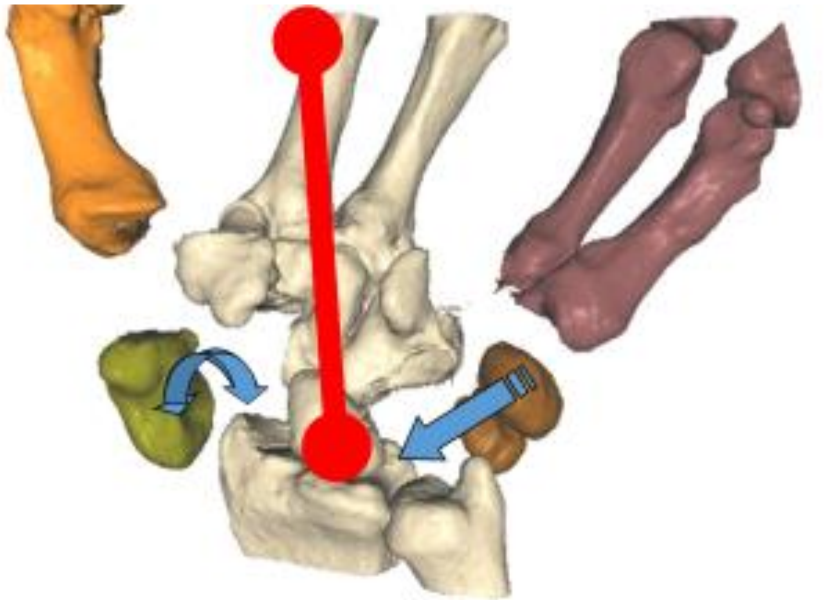


Figure 41. Stable Central column of the carpus. Radius > lunate > capitate > 2/3 metacarpal. (Published with permission JHS-Eu, Sandow et al. 2014).

The seven basic functional requirements (Figure 42) are therefore enabled by a combination of “Rules Based Motion” driving a stable central column, with variable offset of the proximal and distal rows.

1. Adequate flexion and extension for holding and pushing (FLEXION/EXTENSION)

2. Adequate side to side rotation motion adjusting to holding different angles (RADIAL/ULNAR DEVIATION)

3. Delivery of powerful rotational force by resisting rotation through the radio-carpal joint (RESIST ROTATION)

4. Resist translation in coronal, sagittal and transverse planes (RESIST TRANSLATION /COMPRESSION/DISTRACTION)

5. Oblique power grip to improve holding, thrusting and throwing (ACHIEVE CO-LINEAR PALM AND FOREARM DURING USE)

6. Independent finger motion and wrist motion

7. Wrist must remain low profile in the distal extremity to increase functionality

Figure 42. The seven basic requirements of the wrist are enabled by the stable central column.

The key in this situation however is that the proximal row must remain stable and the lunate remains a critical intercalated segment.

The lunate has a tendency to extend but is pulled volarly by the long radial lunate ligament and is pulled distally at the dorsum by its connection to the dorsal capsular ligamentous scapho-lunate septum which is then connected to the dorsal intercarpal ligament.

Recent work by Mathoulin has provided important insights into the controlling effect of the connections between the lunate and the DIC (Mathoulin et al 2017). This is covered in Sandow and Fisher (2019).

Reviewing the arrangement of the ligamentous constraints present an emerging pattern. The apparent volar and dorsal alternating inter-row connection presents a pattern that provides stability and yet allows for a change in shape of the rows.

This is matched by a complimentary connection on the opposite side where there is the interrow connection with a connection to either the distal or caudal row. This create the matching inter row connections (Figure 43 A and B).

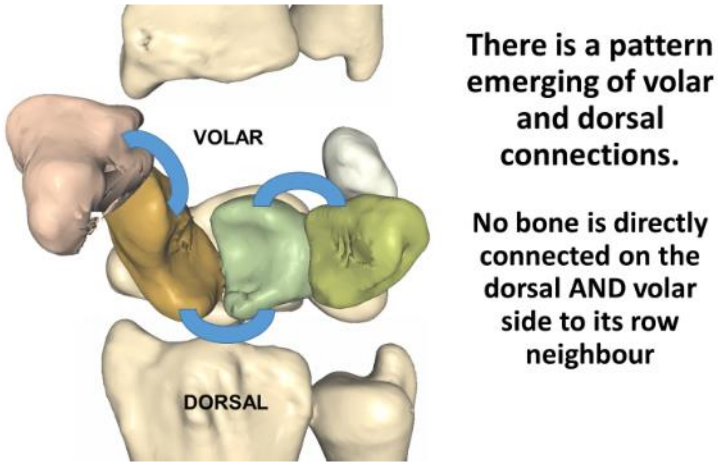


Figure 43 A. The connection between the carpal bone created an alternating volar and dorsal intra-row connection that provides stability and yet allows for a change in shape of the rows.

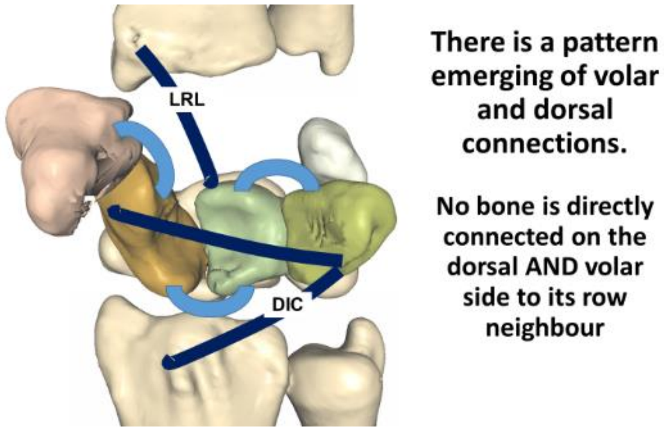


Figure 43 B. This is matched by a complimentary connection on the opposite side where there is the inter-row connection to either the distal or caudal row. This creates a pattern of reciprocating inter-row and intra-row connections.

Therein emerges a pattern between the connections of the proximal to distal row. The critical factor of the wrist is that the proximal row must remain stable to set up the positioning of the distal row. No bone in the proximal row is strongly connected at both its volar and dorsal aspect, and forms an alternating pattern between volar ligament constraints on the trapezium scaphoid and then dorsally between the scaphoid and lunate and then volarly again between the lunate and triquetrum.

This is matched by further ligamentous constraints which span to either the opposite joint or further across the carpus, but not to its adjacent carpal bone. This allows the specific shape of the distal articulating surface of the proximal row to change and it is able to flex and extend under control of the distally loaded distal row via the various wrist flexor and extensor muscles. The lunate therefore is an intercalated segment which is not attached to tendons but is a passive mobiliser acted upon by the distal row which moves under the load of the extensor and flexor tendons. The distal row pivots rigidly around its connection to the scaphoid and is connected to the scaphoid strongly by the trapezium on its lateral side but articulates with a mobile triquetrum on its ulnar side. It is the translation of the triquetrum which adjusts the pivot point of the medial aspect of the carpus which thus adjusts the offset of the distal row with respect to the proximal row. The proximal row is therefore critical to the motion of the distal row.

Oblique power grip

One of the critical aspects of the wrist is that the human wrist can create an oblique power grip where engagement of the palm and fingers in gripping. The variable offset of the stable distal row allows the two degrees of freedom, but as the axis between the two rows changes, this provides a variable offset.

Trapezoid shaped trapezoid pushes the lateral end of the distal row into pronation and the trapezium is strongly connected to the scaphoid as a lateral pivot point. The mobile triquetrum on the mid aspect slides dorsally and volarly to change the offset of the medial pivot point of the distal row, thus by changing the offset allowing for two degrees of freedom. The oblique power grip is achieved by flexing and extending of a pronated distal row. This ability of the human wrist to align itself with the forearm to improve throwing and gripping capabilities is critical to human wrist function. This is facilitated by the offset axis between the distal and proximal rows as detailed above and largely due to the trapezoid pushing the lateral pivot volar to the coronal access of the carpus and radius and ulnar, and the mobility of the triquetrum to allow for a variable offset.

The dart throwing motion is typically an isolated mid carpal motion on a stable proximal row, where the proximal row sets the starting point of the distal row which then moves through a motion from radial extension to volar flexion in the characteristic dart thrower or oblique power grip position. The carpus can therefore be seen in a conceptual form to have two degrees of freedom - pitch and yaw which is achieved through a stable central column. The lunate is the intercalated segment which connects the radius to the capitate to the 2nd and 3rd metacarpals around which the thenar and hypothenar muscles move (Figure 16). The distal and proximal rows appear to be connected by a notional two gear four bar linkage and the whole mechanical system can be defined by the rules-based motion concept. The distal row is a solid block of bones actively controlled at each corner and as noted sits on a stable proximal row that controls its axial alignment (Figure 44).

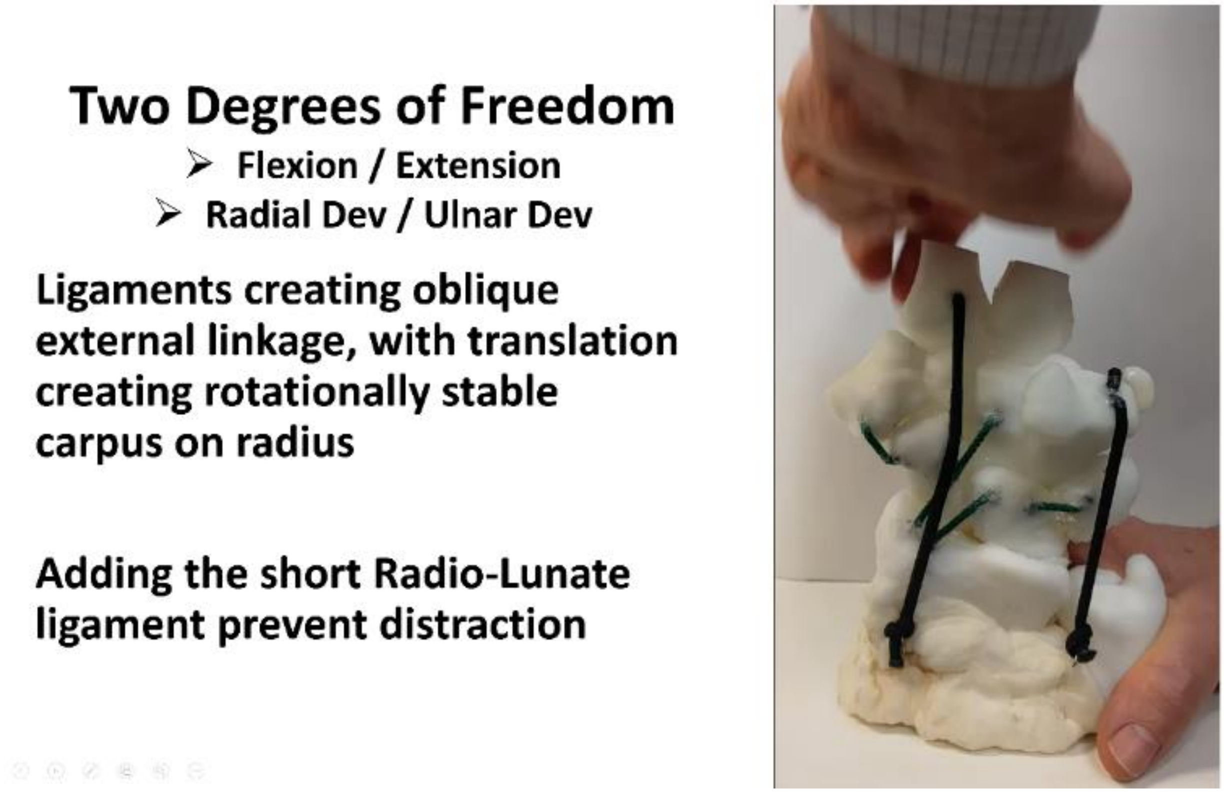


Figure 44. Applying the 3D printed bones, and then adding the ligamentous constraints and notional tendon tension can re-create a stable yet mobile wrist. This is reanimation of the extracted rules, and is a major validation of the original intent. This is the "holy grail" event.

The lunate is further stabilised by the connection to DIC (Figure 45 and 46). This creates a stabilising force couple for the central column that allows motion coupled with stability.

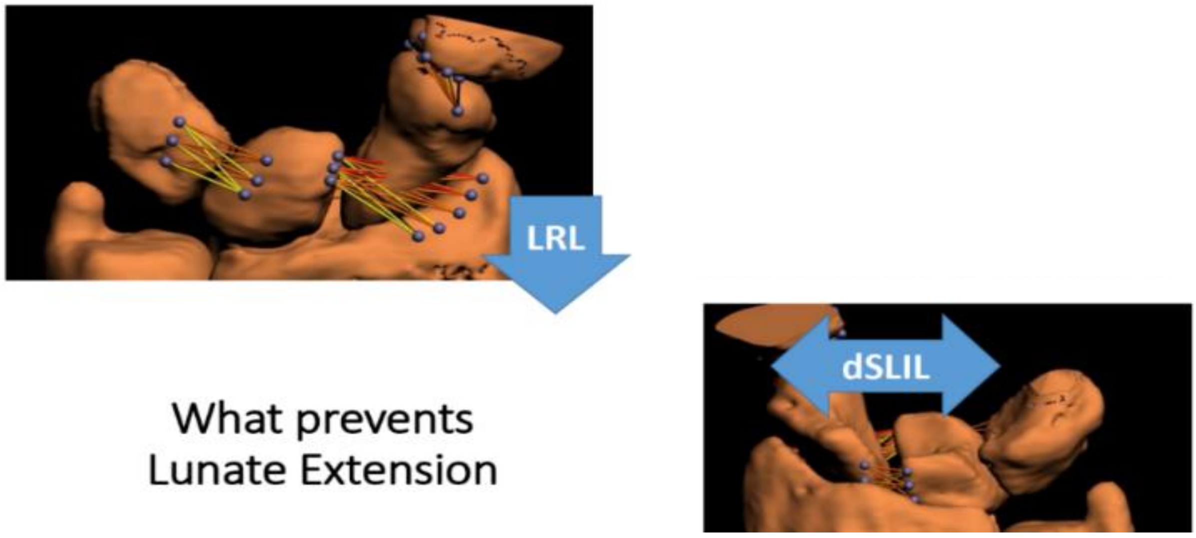


Figure 45. The lunate has a balanced force couple with the LRL (long radio-lunate ligament) creating a volar proximal load to pull the lunate into flexion thereby preventing the natural tendency of the lunate to rotate into extension, which is balanced by the connection of the lunate dorsally to the DCSS (Dorsal Capsulo-Scapholunate Septum) creating a stable well aligned and reactive intercalated segment – the lunate.

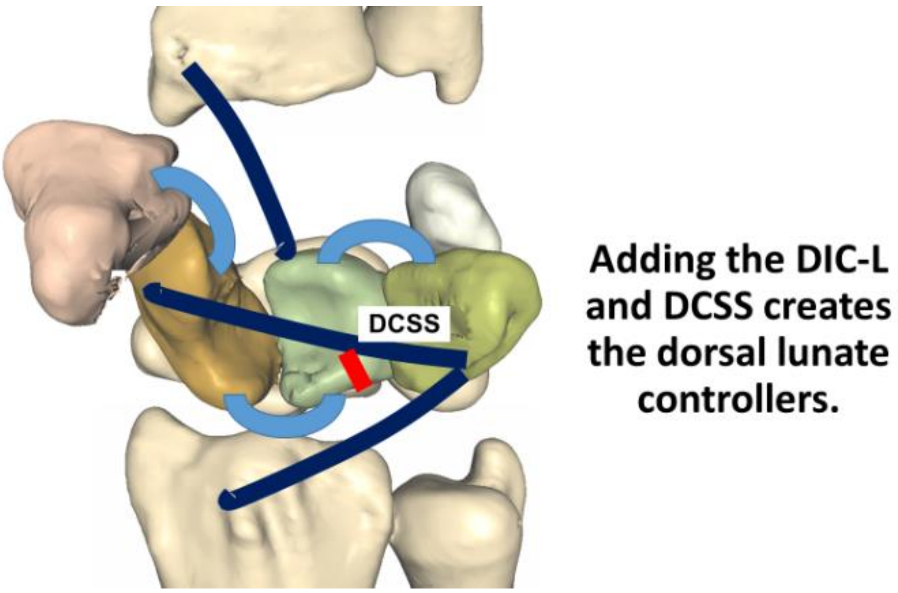


Figure 46. Adding the dorsal lunate connection to the DIC creates an additional constraint to the control of the central column via the lunate.

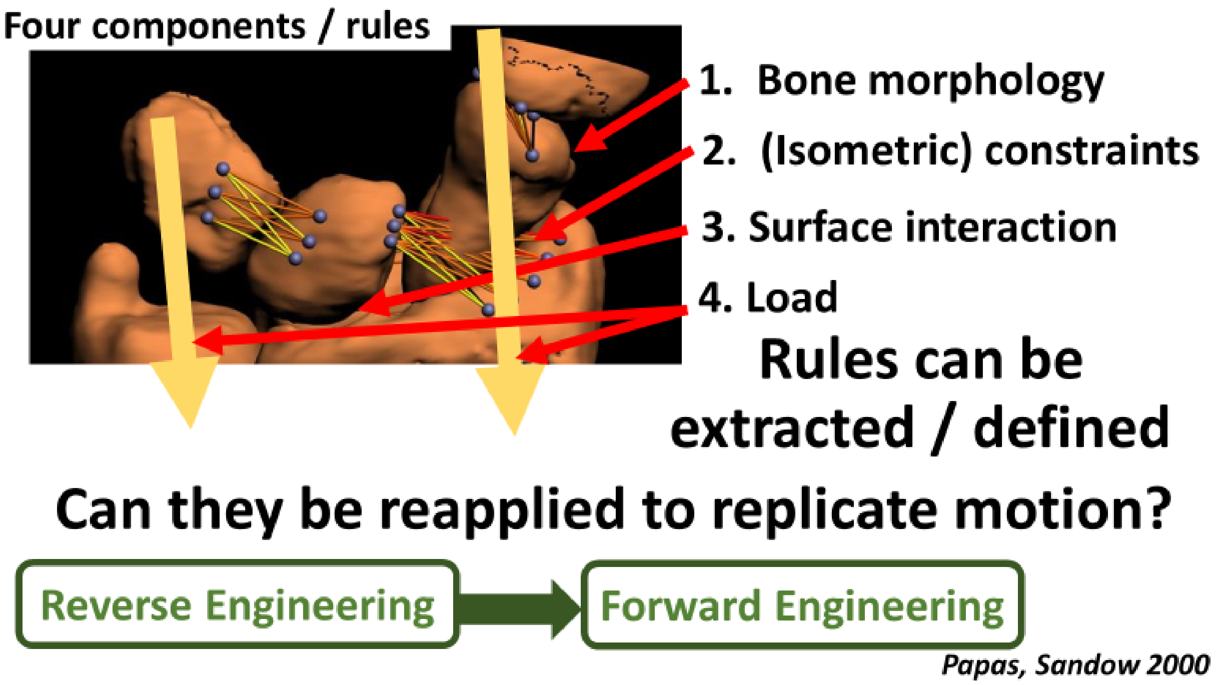


Figure 47. The original concept was to create a reverse engineering process, to identify the important rules that control a dynamic system and reapply the identified rule to recreate motion.

The concept therefore was to identify the rules and then re-apply them to re-create motion (Figure 47). The true test of this concept is to see if this is possible to be re-created. In this process, the bones were 3D printed (Figure 48), the computationally derived constraints applied (Figure 49) and simulated tendon attached (Figure 50).

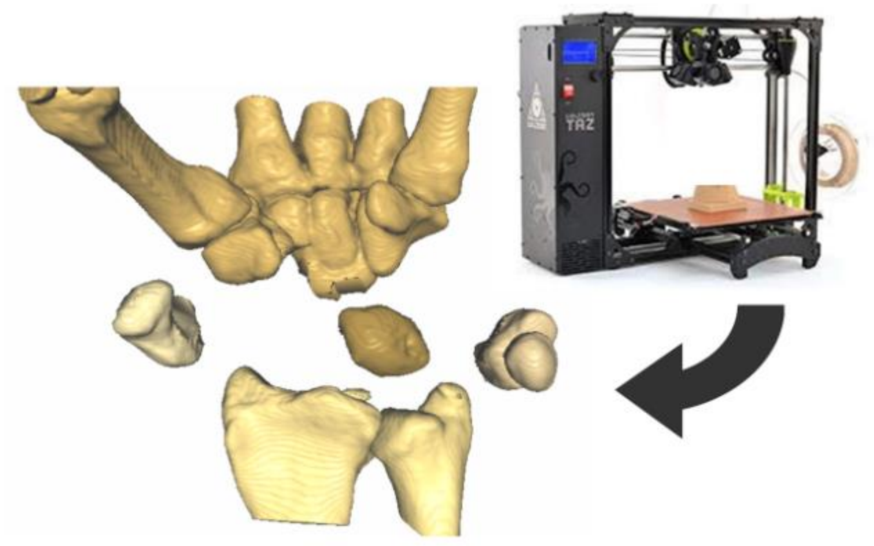


Figure 48 A. The selected wrist having identified the bone morphology and isometric connections can be printed using existing 3D printing technology.

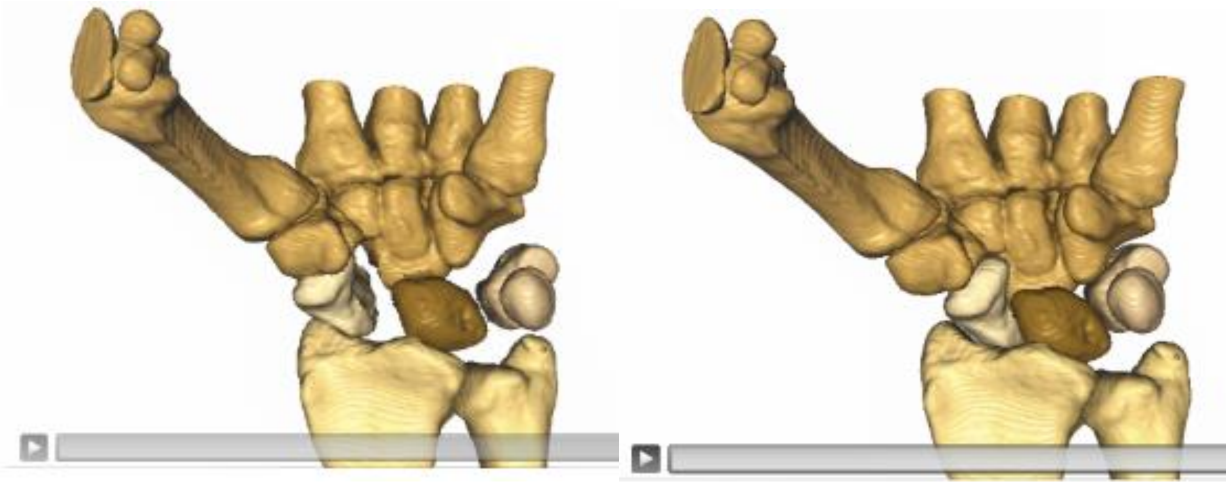


Figure 48 B. Bone printed and re-aligned.

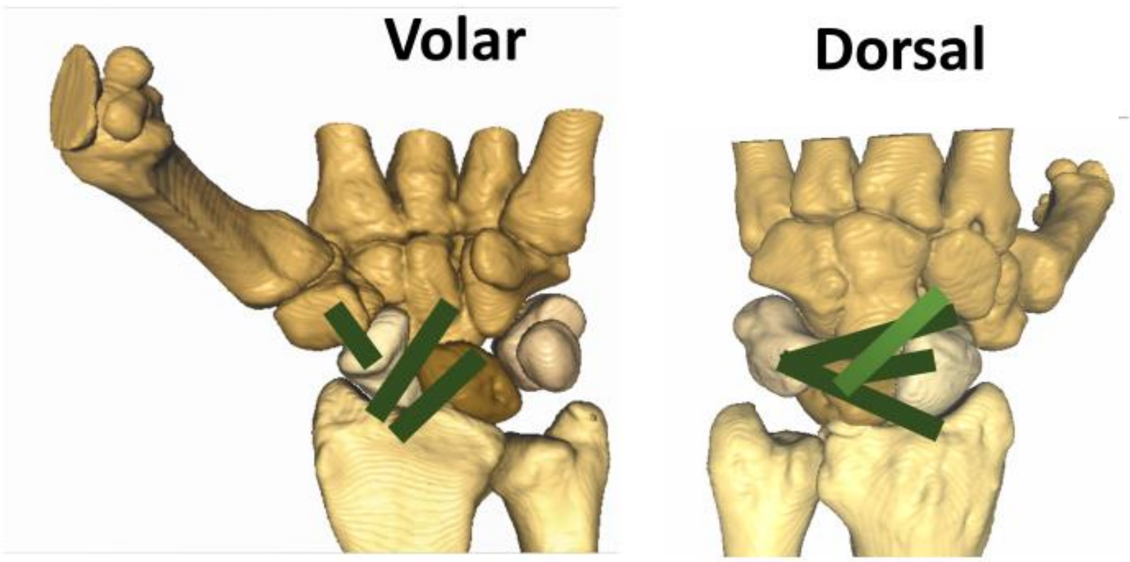


Figure 49. Computationally derived Isometric identified and re-applied.

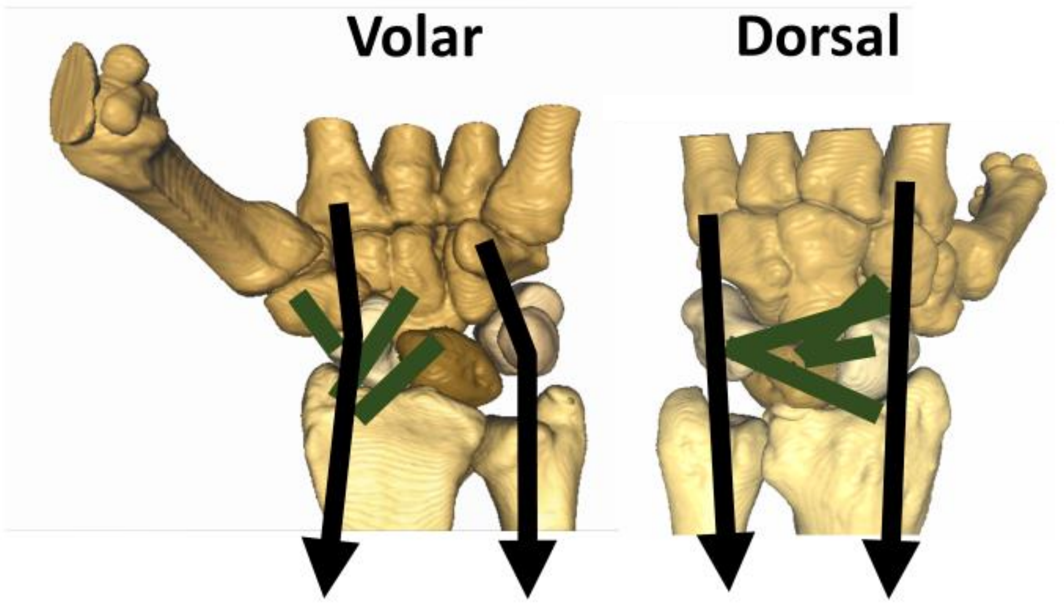


Figure 50. Notional tendon load points are added.

By applying load to the re-configured carpus, motion can then be created under its own RULES (Figure 51).

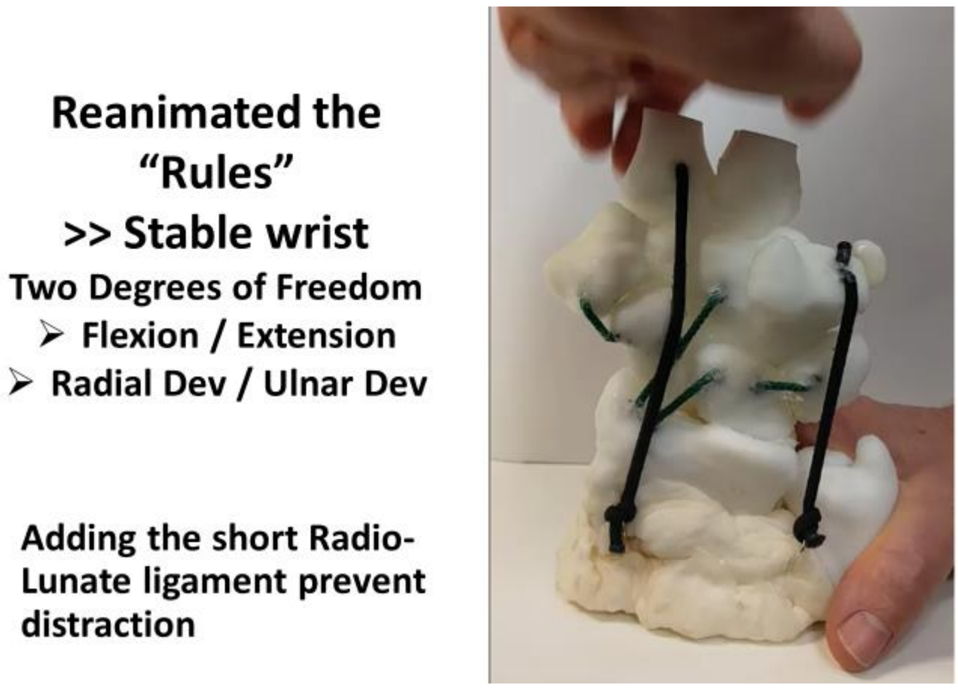


Figure 51. Re-applying the 3D printed bones, adding the computationally derived isometric constraints, and adding the notional tendon load creates a stable mobile wrist – quite stunning and validation of the concept of reverse engineering > forward engineering > reanimation, which support the whole notion of a stable central column - a relative biomechanical correlation to Kock's postulate.

Carpal Disruption –
What Happens When Things Go Wrong?

The question is "can this conceptual approach be used to explain what happens when the wrist fails?"

The longitudinal stability of the proximal row is critical to the stability of the carpus and it is the lunate which is the critically intercalated segment. The lunate has a tendency to collapse into extension but can on occasions rotate into flexion. The lunate is normally attached strongly to the scaphoid on the dorsal aspect and so various instability patterns can be categorised by separation or not from the scaphoid to have two broad patterns of either dissociated (separated from the scaphoid - CID (carpal instability dissociative)) or non-dissociated (still connected to the scaphoid – CIND (carpal instability non-dissociative)). As part of an instability pattern, the lunate can collapse into flexion (VISI - volar intercalated segmental instability) or extension (DISI - dorsal intercalated segmental instability).

The four patterns of instability of the central column can therefore be seen as CID/DISI, CID/VISI, CIND/DISI and CIND/VISI.

For the lunate to collapse into extension the structures that would normally prevent such motion need to be disrupted. The lunate is attached strongly to the scaphoid dorsally but also volarly to the radius by the long radial lunate ligament. The lunate is also pulled dorsally by the DCSS (dorsal capsule ligamentous scapho-lunate septum) (Figure 45).

As the proximal row is usually stable in its transverse aspect, for a scaphoid lunate gap to develop, both the volar and dorsal constraints need to be disrupted (Figure 52).

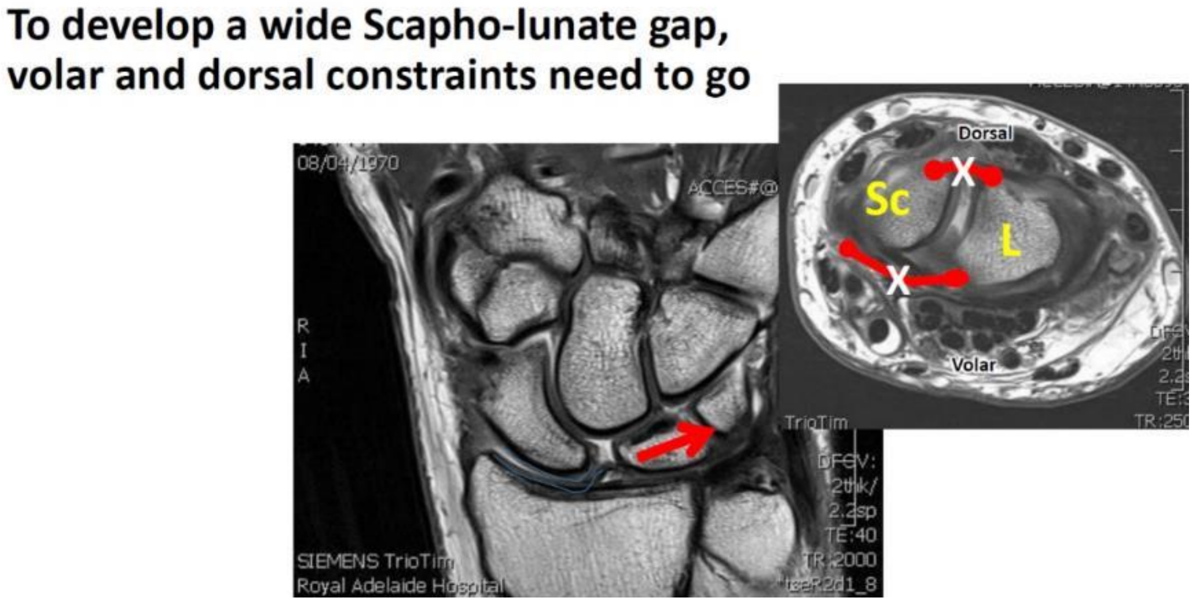


Figure 52. For scaphoid- lunate dissociation, the lunate must move away from the scaphoid, or alternatively, the scaphoid must move in a radial direction. For the lunate to displace, both the dorsal and volar stabilising ligaments must fail.

As detailed above, the longitudinal stability of the proximal row is critical and so if the lunate is separated from the scaphoid then this develops a dissociative pattern (CID) and can then move into flexion or extension. When the volar long radial lunate ligament is disrupted and there is a loss of the stabilising effect of the DCSS, the lunate will go into extension and the scaphoid flexes. This creates a CID/DISI collapsed deformity (Figure 53).

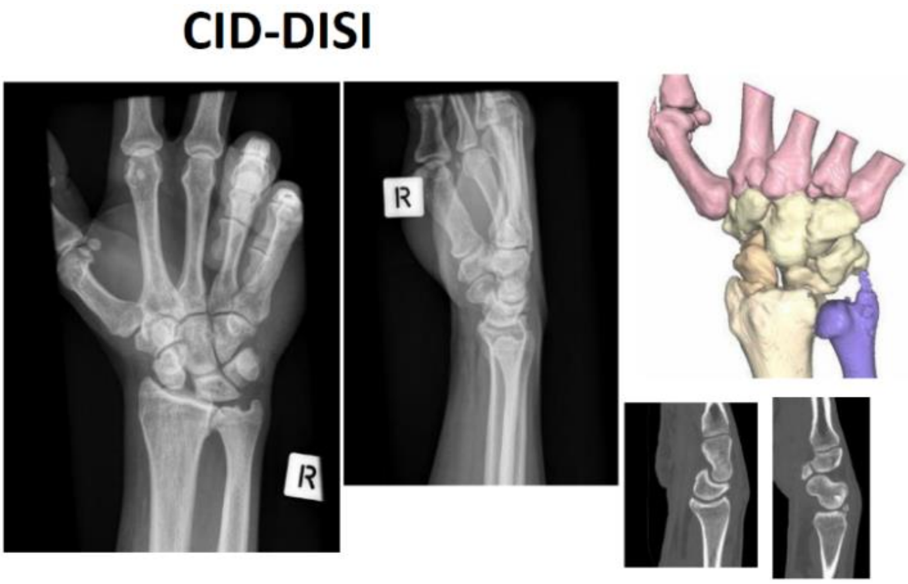


Figure 53. A fall on outstretched hand created an injury that includes a scaphoid flexion, scaphoid-lunate diastasis, and lunate extension.

Can this conceptual approach be applied to understanding and addressing the more common scapho-lunate dissociation instability pattern?

In the typical scapho-lunate dissociation, there is generally a flexion of the scaphoid, diastasis between the scaphoid and the lunate, and extension and ulnar translation of the lunate. Three critical ligaments would appear important on the basis of the stable central column theory work to control this motion. These include the scaphoid trapezium ligament, the dorsal scapho-lunate ligament and the long radial lunate ligament (Figure 54).

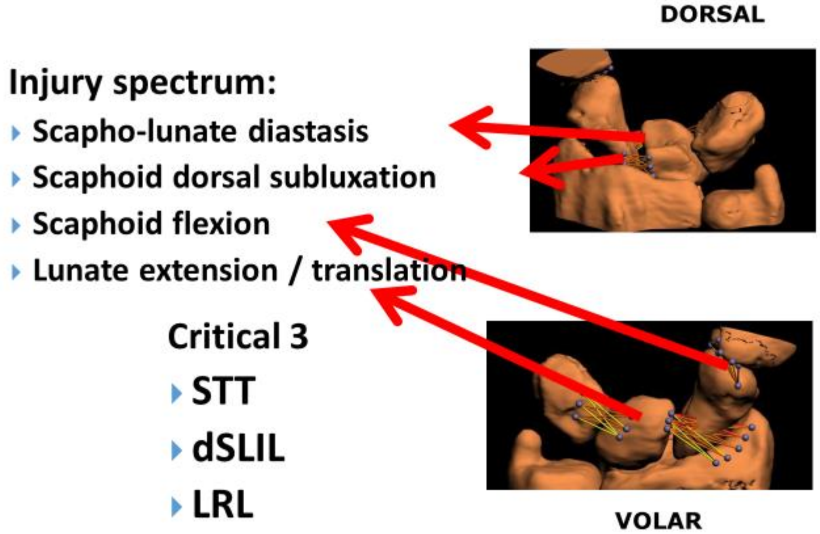


Figure 54. Although the scapho-lunate dissociation can occur as a spectrum, the key elements are Scapho-lunate diastasis, Scaphoid dorsal subluxation, scaphoid flexion, and lunate extension and ulnar translation.

The anatomical front and back reconstruction (ANAFAB) described in Chapter 4 addresses the scapho-lunate dissociation of the classic CID/DISI pattern (Figures 55 -58).

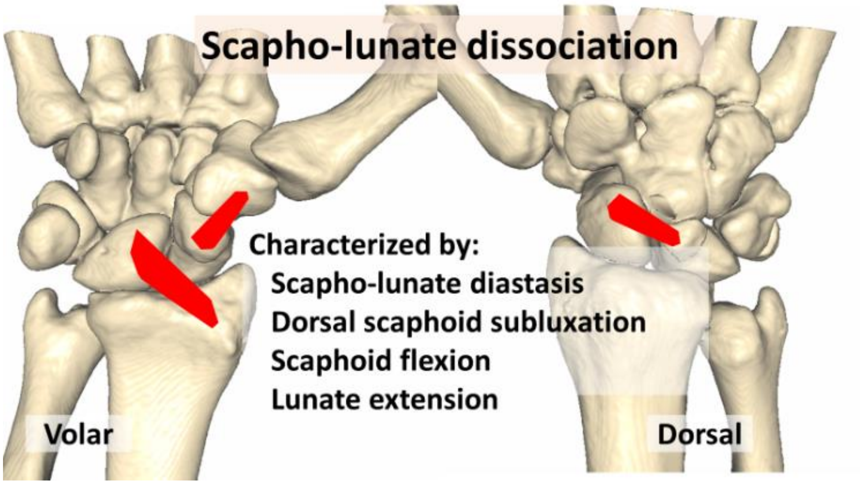


Figure 55. The deficits in scapho-lunate instability include Scapho-lunate diastasis, Scaphoid dorsal subluxation, scaphoid flexion, and lunate extension and ulnar translation.

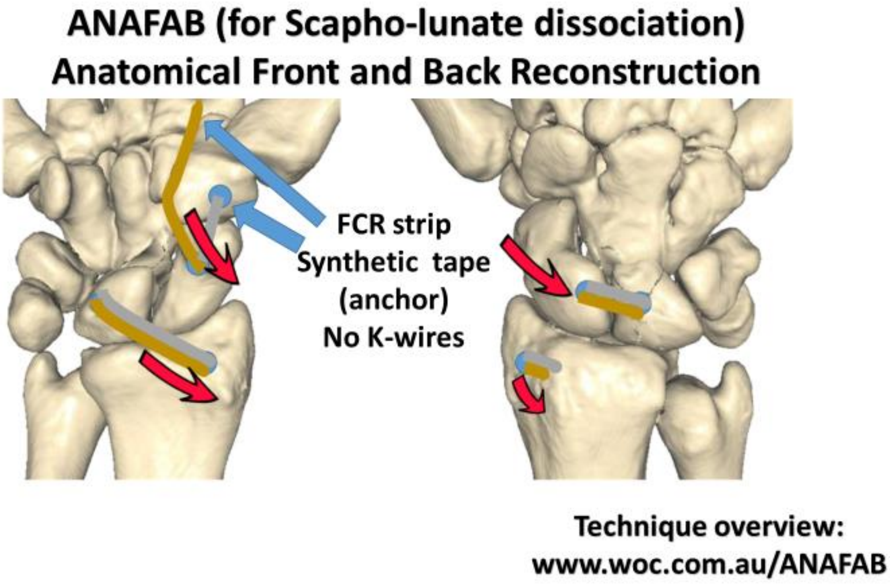


Figure 56. The ANAFAB procedure aims to addressed identified deficit.

The ANAFAB procedure appears to have the ability to reverse the scapholunate diastasis and proximal scaphoid subluxation, but still retain functional motion. Significant load on the carpus and radius is generated during a push-up. The ability of the ANAFAB reconstruction to allow patients to perform push-ups provides compelling evidence of its ability to restore longitudinal stability of the carpus without a significant loss of motion, indicating the successful restoration of functional carpal biomechanics (Sandow and Fisher 2019, q.v. Chapter 6).

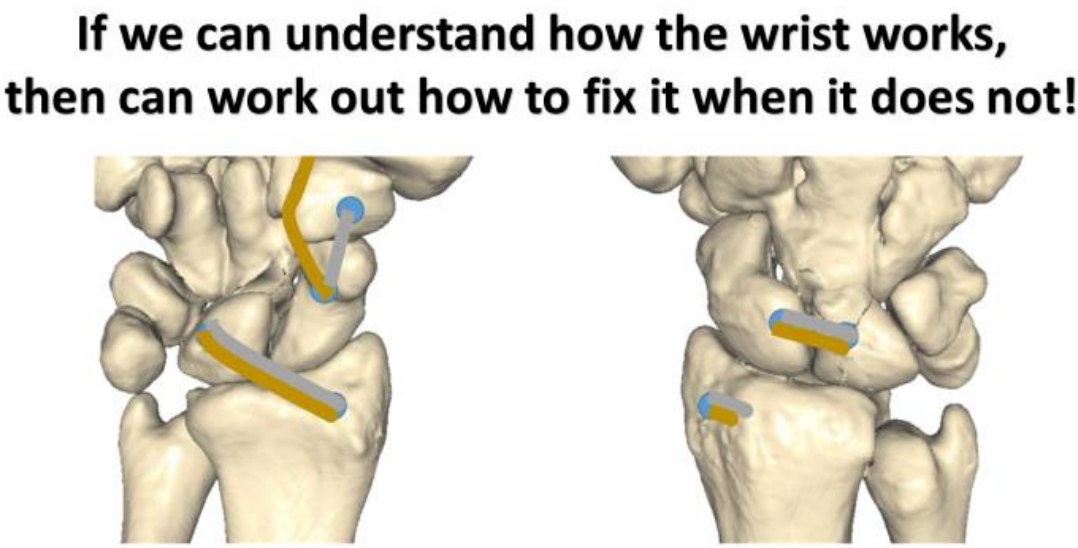


Figure 57. The ANAFAB reconstruction addresses the major recognised deficit in wrist injuries. Based on a conceptual true theory of carpal mechanics and deficits, this reconstruction delivers a solution that was not previously possible.

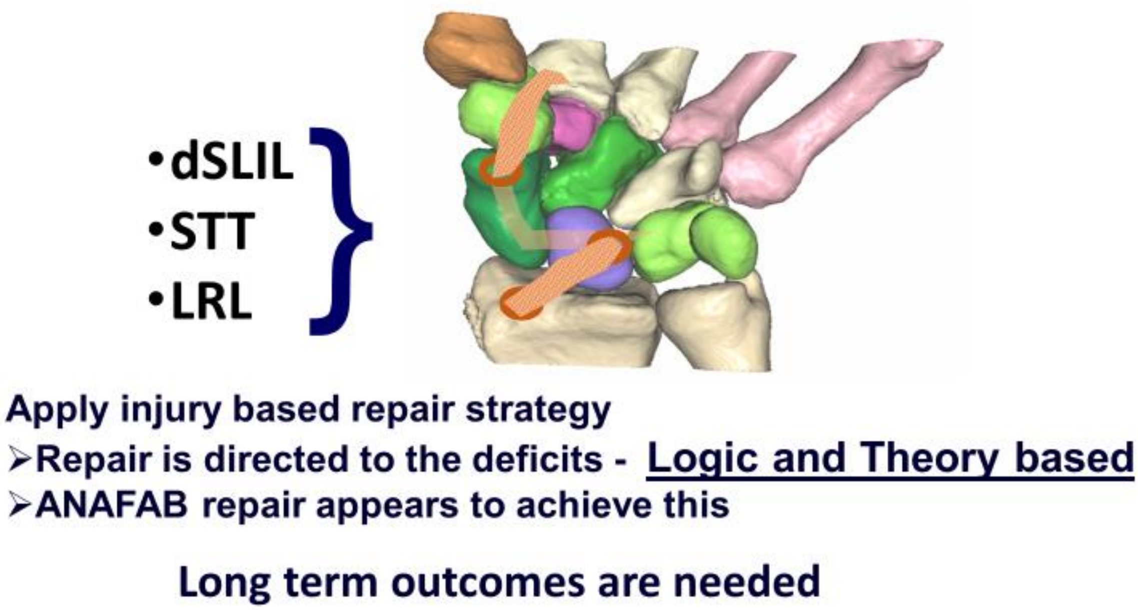


Figure 58. The ANAFAB provides a logic and theory-based solution to scapho-lunate dissociation.

The application of a logic and theory based diagnostic and therapeutic solution has successfully addressed the standard scapho-lunate instability pattern. This was the original goal of the project. The approach is therefore to use a quantitative analysis of the constraints in an injured wrist, to compare the findings to the expected pattern and then use that to propose a reconstructive strategy.

By using a theory-based approach, deviations from the anticipated pattern of injury can be reconciled against a different spectrum of ligamentous disruption.

As noted above, the lunate has a tendency to collapse into extension but is generally held in flexion by both the volar long radial lunate ligament and the dorsal DCSS as well as the scapho-lunate ligament. In an isolated DCSS injury, the lunate can tilt into extension, however as the dorsal scapho-lunate ligament remains intact, the scaphoid can be pulled into extension by the extending lunate.

The longitudinal stability of the proximal row is critical for wrist function and if both scaphoid and lunate move into extension, then this indicates that the scapho-lunate has non-dissociated so this creates a CIND/DISI. The question is how does this reconcile with the stable central column theory as the long radial lunate ligament is known to be quite critical?

On preliminary examination, as the scaphoid goes into extension, as part of a CIND/DISI collapsed deformity, the scaphoid moves radially, as does the lunate. This translates the lunate radially thus creating a physiological lengthening in the long radial lunate ligament allowing the lunate to go into extension while the long radial lunate ligament remains intact. Therefore, pathological lunate extension can occur with an intact long radial lunate ligament but only if the scaphoid moves radially allowing increased radial translation of the lunate. This therefore creates the CIND/DISI deformity, which implies the disruption of the DCSS. Further work is required in this area, however, by applying the stable central column theory, a potential explanation can be presented and tested.

The question then arises, as to what normally prevents pathological scaphoid extension?

If reviewing anecdotal operative experience, removal of the trapezium (as part of a reconstruction for an arthritic first carpo-metacarpal joint) does not create excessive scaphoid extension. It would therefore be likely that the scaphoid trapezium ligaments are not the primary restraints to scaphoid extension. A review of previous literature (Berger 1997) identifies a strong ligament between the capitate and the scaphoid and this may represent a prime restraint to scaphoid extension. However, more work is required to validate this suggestion.

A recent clinical case has shown that when the CIND/DISI pattern develops, there is a rotation of the scaphoid away from the capitate and trapezoid which would be consistent with loss of connection between the capitate and scaphoid, thereby allowing excessive and pathological scaphoid extension.

It would therefore appear that the distal scaphoid is certainly bound by the STT (Scapho-Trapezium-Trapezoid) ligamentous complex, however it is the connection between the scaphoid and the capitate that is a critical linkage in preventing excessive scaphoid extension.

This project had as its initial goal to find a solution to the classic instability pattern of scapho-lunate dissociation. By developing a theory on how the stable central column of the carpus is maintained, observed deviation from the typical anatomical arrangement can be tested against the theory to identify a particular pattern of restraint to explain the resultant collapse pattern.

The critical stabilising effect of the DCSS is quite consistent with the Stable Central Column Theory of Carpal Mechanics and surgical restoration of the CIND/DISI pattern may require restabilisation of the dorsal connection of the lunate to the dorsal intercarpal ligament as well as attempts to stabilise the scaphoid. This particular instability pattern is outside the remit of the current research, and is now a work in progress. However, application of the theory of the stable central column and characterisation of which particular structures may have been disrupted, an appropriate and successful management should be possible.

This work thus completes the first part of the journey into the understanding of the normal wrist and the therapeutic resolution of the dysfunctional carpus. The application of a logic and theory-based approach to the less common patterns of wrist dysfunction will extend the capabilities of the wrist surgeon, and improve the outcome for patients who develop such maladies.

Future application of this work

While this project has largely centred around identifying a unifying concept of carpal mechanics and applying this to address the most common form of carpal disruption, scapho-lunate dissociation, the pathological motion of the lunate into flexion is another whole area of wrist instability which will need to be dealt with separately. However, the stable central column provides a basis on which to expand the understanding of the wider carpal biomechanics and assess the deficit and thereby propose and test potential solutions.

As detailed in the introduction, this project was part of a bigger study to develop a kinetic model to explain the carpus, and to develop a reverse engineering, then forward engineering and then ultimately a "what if" testing environment to assess reconstructive options to address the dysfunctional carpus.

While the characterisation of the "Rules" that control the carpal biomechanics have been achieved, the reapplication of such rules has only been possible by laboriously 3D printing of each of the individual carpal bones of a specific patient or subject and then applying the static and dynamic constraints. As a proof of concept, this has been very successful.

However, the next big advance will be the development of the technology to allow the application of the individual rules in an interactive and interconnected multi-body animation virtual environment to complete the reverse then forward and ultimately "what if" process.

Conclusion

• The wrist explained.

The wrist is a complex and intricate, but highly specialised biomechanical system. There exists great variation between individuals, and a reliable and unified explanation on which to base an understanding of the normal mechanical performance has been elusive. Even more challenging has been the assessment and understanding of what may fail in dysfunction, and how to address such failure. Past repairs have been largely unsuccessful in predictably restoring mechanics of the wrist. The stable central column theory of carpal biomechanics provides a unified concept that can be applied to address the pathological disruptions within the carpus.

As is noted previously, theories cannot be proven but can be validated, justified or replaced and they must be predictive and testable. This work represents a major advance both in the understanding of what constitutes a theory that can be applied to the carpus, as well as how such a theory can be applied to characterise a mechanical disruption and determine a logic and theory based reconstructive solution.

The complexities of wrist function are enabled by the presence of the Stable Central Column, which creates a stable linkage from the radius to the lunate to the capitate and ultimately to the 2nd and 3rd metacarpals. Components of the wrist, and in particular the bone morphology, ligamentous and tendon attachments, can each vary, but in combination creates the required wrist function and represents, possibly the first described, example of Rules Based Motion.

Marc Garcia-Elias (2013) has been quite famous in describing the attempts in understanding the carpus as a "Long and Winding Road", given the vagaries of progress which have frustrated multiple attempts to understand and address carpal mechanics and their deficiencies. The analogy of the long and winding road suggests that the journey to sort out the wrist does not have a clear end point, and the journeymen travels the pathway of exploration looking for the next most likely productive option or opening – but without a clear vison of where they are going.

A more logical approach would be to address the challenge of the wrist as akin to planning a journey to somewhere where you want to be. A journey is best planned by starting from where you want to finish, even though the destination is a little imprecise, it is still conceptually evident. The termination point is defined, even if not in great clarity, and then planned backwards having some better indication about where you want to finish up.

A proposed analogy is climbing a tropical mountain where the traveller may have some idea of where they want to be but can't see it, however they know roughly where they wish to finish. This is distinct from aimlessly heading down a "long and winding road". If the traveller roughly knows where they are heading and have anticipated some of the obstacles, they are more likely to take the correct fork in the trail. The journeyman will likely be most successful if they have planned out their journey with an end point in mind.

The journey to identify the critical biomechanical restraints of the wrist by using a reverse engineering technology and then identifying a means of restoring them to the pathologically injured wrist would appear to have achieved its goal, at least in one part of the wrist. In the case of scapho-lunate diastasis and collapse of the central column, applying a logic based reconstructive volar and dorsal surgical solution (ANAFAB) (Sandow and Fisher 2019), carpal function has been successfully restored in the majority of this group of patients.

Further work is now required to address other areas of pathology in the wrist, but the stable central column theory, and the arrangement of isometric constraints provides a useful basis on which to further study the complex biomechanics of the wrist. The SCCT however is still just a theory, and as is the case, the best thing that can happen to a theory, is to be replaced by a better theory.

However, at least wrist researchers and surgeons now have a true theory on which they can approach the dysfunctional wrist. This has been provided by a shift from the aimless measuring so typical of the empirical research approach, to a more logic based conceptual methodology.

This over 20-year journey may well have answered the opening question – "Can the wrist be explained?" The application of computer based quantitative analysis appear to be able to explain carpal biomechanics and identify therapeutic solutions for wrist dysfunction.

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Appendices

Appendix 1: Peer Reviewed Publications and Chapters

Publications

1. Sandow M, Fisher T Anatomical anterior and posterior reconstruction for scapholunate dissociation: preliminary outcome in ten patients. J Hand Surg Eur Vol. 2019 Nov
2. Sosnowski MR, Dinh Q, Sandow M. First Report of Eutypa lata Causing Dieback and Wood Canker of Pomegranate (Punica granatum) in Australia- Plant Disease, 2019
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Appendix 2: Inventions / Intellectual Property Patents

Suture anchor

MJ Sandow – United States Patent App. 13/578,798, 2013 - Google Patents

When ligaments or tendons detach from associated bone, or become damaged by way of being torn, surgical intervention can be used to assist repair and reattachment (restoration). An anchor in the cortical portion of the bone is provided which is used to secure a suture …

Cited by 25 Related articles All 2 versions

Animation Technology

Australian patent - 2001237138 Animation technology -

Applicant: Macropace Products Pty Ltd; True Life Creations (SA) Pty Ltd

Inventors: Papas, Sam; Sandow, Michael John

Priority date: AUPQ6001A – 03-3-2000

Patent granted: 05-03-2001

https://patents.google.com/patent/AU3713801A/en (accessed 19th September 2019)

United States Patent 7,236,817-B2 Granted: 26th June 2007

https://patents.google.com/patent/US7236817 (accessed 19th September 2019)

US007236817B2

(12) **United States Patent**
Papas et al.

(10) **Patent No.: US 7,236,817 B2**
(45) **Date of Patent: Jun. 26, 2007**

(54) **ANIMATION TECHNOLOGY**

(75) Inventors: **Sam Papas**, Adelaide (AU); **Michael John Sandow**, Adelaide (AU)

(73) Assignees: **True Life Creations (SA) Pty Ltd.**, Adelaide, South Australia (AU); **Macropace Products Pty Ltd.**, Adelaide, South Australia (AU)

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PCT Pub. Date: **Sep. 7, 2001**

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A61B 5/05 (2006.01)

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(58) **Field of Classification Search** .... None
See application file for complete search history.

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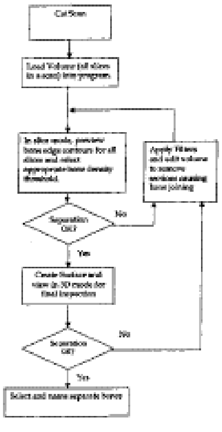
Primary Examiner—Eleni Mantis Mercader
Assistant Examiner—James Kish
(74) *Attorney, Agent, or Firm*—Klauber & Jackson

(57) **ABSTRACT**

A method for creating an animated image of the bones of a body part is described. The steps include converting Computed Axial Tomography (CAT or CT) scan and Magnetic Resonance Imaging (MRI) 2-dimensional cross-sectional images (slices) into 3-dimensional images of individual bones (FIG. **1**). A first ordered series of slices of a body part in a first position is converted into a 3-dimensional representation of the skeleton of the body part and then a second ordered series of slices of the same body part in a different position is converted. The converted images are then used to create a step frame animation of the movement of the skeleton of the body part. Additional ordered series of slices of the body part in other intermediate positions could be used in the step frame animation. The steps of the method may also include the process of separating the bones if they are depicted as co-joined in a slice (FIGS. **6** and **7**). The method can also include the identification of isometric points (FIGS. **8** to **11**) on the separated bones to aid a clinician in the diagnosis of a problem or abnormality as well as assist in the application of "what if" surgical procedures on the digital representation of the skeleton of the scanned body part. The method can also include steps that create movement of the bones of the body part by applying rules of motion for one or more points on the separated bones of the scanned body part.

12 Claims, 6 Drawing Sheets



ANIMATION TECHNOLOGY

ANIMATION TECHNOLOGY

This invention relates to 3-dimensional analysis of the human skeleton and in particular provides a method for improved clinical diagnosis and repair of associated soft tissue injuries and abnormalities using existing imaging equipment.

BACKGROUND

Computed Axial Tomography (CAT or CT) scan and Magnetic Resonance Imaging (MRI) technologies provide detailed 2-dimensional cross-sectional images or "slices" of the human body. The 2-dimensional slices are viewable by clinicians and a diagnosis can be made.

Of more usefulness to clinicians is the provision of computed 3-dimensional images of the human body.

CAT/CT and MRI equipment is highly specialised and the digital output of each "slice" is typically provided in proprietary digital image format for use by the manufacturers image manipulation software and hardware to produce 2-dimensional and computed 3-dimensional representations for display on a screen constructed "slices" produced by the CAT/CT and MRI equipment. These images are referred to as solid-form images and can be made to depict bones, ligaments, blood vessels, muscles and tendons according to various settings available on the imaging equipment.

Each set of images typically only depicts the stationary condition of the part of the patient being examined.

Thus, analysis of the information provided by such images can only provide a limited part of the clinical basis for a diagnosis as to the problem or abnormality associated with the scanned body part.

The discussion herein providing some background to the invention is intended to facilitate a better understanding of the invention. However, it should be appreciated that the discussion is not an acknowledgment or admission that any of the material referred to was published, known or part of the common general knowledge as of the priority date of the application.

The invention described in this specification provides a means and method for the visualisation of information generated by current CAT/CT and MRI equipment. This will enable more accurate and "what if" manipulation of the digital image of a 3-dimensional representation of the scanned body part so as to improve the accuracy of diagnosis by the clinician. It will also improve the probability of the success of planned corrective surgery via manipulation of the three-dimensional representation and analysis of the resultant movement.

BRIEF DESCRIPTION OF THE INVENTION

In a broad aspect of the invention, a method of producing 3-dimensional visualisations of digital representations of cross-sectional slices of a vertebrate animal or human body part includes the steps of:

a) obtaining a first ordered series of slices of a portion of said body part in a first position;

b) applying one or more filters to each of said digital representations of said first ordered series of slices to identify the skeletal portions of said body part;

c) converting said first filtered series into a 3-dimensional representation of the skeleton of said body part in said first position;

d) obtaining a second ordered series of slices of said portion of said body part in a second position different to said first position wherein said first and said second position of said portion of said body part is representative of extremes of the achievable movement of said portion of said body part;

e) applying one or more filters to each of said digital representations of said second ordered series of slices to identify the skeletal portions of said body part;

f) converting said second filtered series into a 3-dimensional representation of the skeleton of said body part in said second position;

g) combining said 3-dimensional representations to form a step frame animation having as many steps as there are ordered series of slices.

A yet further aspect of the method includes the further step of:

h) obtaining a one or more further ordered series of slices of said portion of said body part in a one or more further positions;

i) converting said further filtered series into a 3-dimensional representation of the skeleton of said body part in said further positions;

j) combining said 3-dimensional representations to form a step frame animation having as many steps as there are ordered series of slices.

In a yet further aspect of the invention the method includes the further step of:

k) selecting a plurality of points on two or more skeletal object s in each said 3-dimensional representation; and

l) analysing whether the distance between pairs of said points on different skeletal objects are isometric, if the distance between pairs of points remain the same or within a predetermined variance of distance during said step frame animation.

In a further aspect of the invention comparing the changes, if any, of the distances between predetermined pairs of points with expected changes, wherein the result of said comparison provides assistance to a clinician to form a diagnosis regarding the body part.

In a further aspect of the invention wherein the isometric points determined equate substantially to the fixation location of the ends of ligaments associated with said portion of said body part and the further step of:

m) comparing the isometric points determined to predetermined isometric points of a typical or contra-lateral body part and if said isometric points vary, a clinician may infer a problem or abnormality and a degree of problem or abnormality associated with one or more ligaments associated with said portion of said body part.

In a further aspect of the invention step b and/or e includes a filter that allows an anatomically knowledgable medical professional to adjust the bone selection criteria of said filter until a representation of adjacent bones shows that said adjacent bones are separate from one another.

In a further aspect of the invention wherein the digital representation of slices of a vertebrate animal or human body part is provided by CAT/CT or MRI apparatus.

In another broad aspect of the invention a method of producing 3-dimensional visualisations of digital representations of cross-sectional slices of a vertebrate animal or human body part includes the steps of:

a) obtaining a first ordered series of slices of a portion of said body part in a first position;

b) applying one or more filters to each of said digital representations of said first ordered series of slices to identify the skeletal portions of said body part;

c) converting said first filtered series into a 3-dimensional representation of the skeleton of said body part in said first position;

d) obtaining a second ordered series of slices of said portion of said body part in a second position wherein said first and said second position of said portion of said body part is representative of extremes of the achievable movement of said portion of said body part;

e) applying one or more filters to each of said digital representations of said second ordered series of slices to identify the skeletal portions of said body part;

f) converting said second filtered series into a 3-dimensional representation of the skeleton of said body part in said second position;

g) applying to one or more points on the skeleton of said body part of each said 3-dimensional representation, one or more rules based animation constraints;

h) creating a 3-dimensional animation of the movement of said body part according to said constraints.

Specific embodiments of the invention will now be described in some further detail with reference to and as illustrated in the accompanying figures. These embodiments are illustrative, and are not meant to be restrictive of the scope of the invention. Suggestions and descriptions of other embodiments may be included but they may not be illustrated in the accompanying figures or alternatively features of the invention may be shown in the figures but not described in the specification.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** is a front view of the radius and carpal bone;

FIG. **2** depicts a front view of a 3-dimensional representation of the radius and carpal bone;

FIG. **3** depicts a flow diagram of an embodiment of the steps performed to create a visual representation of separate bones of a scanned body part;

FIG. **4** depicts the wrist in extreme radial deviation;

FIG. **5** depicts the wrist in extreme ulnar deviation;

FIG. **6** depicts cross-section A-A of FIG. **1** showing a portion of a poly frame representation of co-joined bones overlayed on the cross-section;

FIG. **7** depicts a portion of a poly frame representation of separated bones overlayed on the cross-section of FIG. **6**;

FIG. **8** depicts a front view of a wrist showing isometric points between the scaphoid and the trapezium bones while the wrist is in extreme radial deviation;

FIG. **9** depicts a front view of a wrist showing isometric points between the scaphoid and the trapezium bones while the wrist is in extreme ulnar deviation;

FIG. **10** depicts isometric points of the lateral carpal column of the wrist in extreme radial deviation; and

FIG. **11** depicts the same isometric points of those in FIG. **8** with the lateral carpal column of the wrist in extreme ulnar deviation.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

By way of example only an embodiment of the invention will be described herein using the bones of the hand as the scanned portion of the human body. However, this should in no way limit the application of a suitable scanning apparatus and the methodology of the invention to just that part of the body. Indeed it is possible that the method can be used on any portion of any vertebrate animal or human.

By way of assistance various bones of the hand and in particular, the wrist are referred to throughout this description, so a brief explanation of the various bones of the wrist is provided herewith.

FIG. **1** depicts an image obtained from a CT scan workstation of the wrist also referred to as the carpus. This image is merely a computer generated 2-dimensional representation of the 3-dimensional information collected by the scanning apparatus. The bones depicted are as they are seen from one point of view and it is not possible to observe their individual or interrelated movement.

This view shows the palm facing orientation of the wrist. The distal end of the radius **12** is shown at the lower left-hand side of the image. The distal end of the ulnar **13** is shown at the lower right-hand side of the image.

Central within the carpus lies the lunate **14** (a crescent shaped bone) which appears, from motion studies possible with the method of the invention, to be extremely mobile in flexion, extension and translation, even though it is clearly a load bearing bone and remains well aligned under such load.

Adjacent to the lunate **14** towards the metacarpal **16** of the thumb (pollex) lies the scaphoid **18** (a boat-shaped bone) which is the most lateral bone in the proximal row of the carpal bones. The scaphoid not only translates but also rotates during lateral motion of the wrist.

Above the scaphoid **18** and below the metacarpal **16** of the thumb lies the trapezium **20** (an irregular four sided bone).

Various features of the invention will be described by closely examining images of the carpus and in particular the lunate **14**, scaphoid **18** and the trapezium **20** bones of the carpal column. However, it should be understood that this body part and these particular bones are used by way of example only. Only by exercising the invention can the complex interrelationship between various bones and their surrounding body parts become more apparent.

The 2-dimensional image provided by FIG. **1** can be generated in a conventional manner using any one of the medical imaging apparatus currently available. Amongst them, the most commonly used are Computed Axial Tomography (CAT) and Magnetic Resonance Imaging (MRI).

CAT scanning involves the creation of cross-sectional images of a portion of the human body made by accurately rotating an X-ray source and recording the image captured with a radially opposite detector. The cross-sectional image is referred to as a "slice" and although of some use to the clinician, a single slice image may be more useful if arranged as a series of adjacent slices, which are simultaneously made available for viewing by the clinician. Computers are used to create a 3-dimensional representation and an example is displayed in FIG. **2**.

The 3-dimensional representation of the scanned portion of the human body is provided in a 2-dimensional form as a result of a digital transformation of an ordered series of all of the available slices recorded by the CAT equipment. Such images are generated by transforming the different densities of materials recorded in the slice into representations of the various bodily elements bone, tendons, veins etc. FIG. **2** is an example of this but the body part represented is unitary, that is none of the identifiable bones can be separated from the representation for analytical or other purposes.

Similar visual representations are available from MRI equipment where selectively detectable nuclear magnetic resonance of protons produces proton density maps of selected portions of the human body.

The radiant flux densities emitted by these types of equipment are sufficient to provide adequate quality slices for clinical use. For both the abovementioned equipment, flux densities are ever decreasing such, that it has only been recently possible for multiple images to be taken at the same time while maintaining the radiation dosage into the person below safe levels. Such a development thus makes it possible to capture the scanned body portion in multiple positions.

The equipment that provides 3-dimensional representations of the slices is proprietary and inextricably linked to the slice generating equipment. Therefore it tends to be expensive and lacks the ability to provide clinically useful options.

The point of view provided in the 3-dimensional representation can be changed about a reference point chosen within the 3-dimensional space occupied by the representation. The point of view can be any point on a sphere of any diameter about the chosen reference point and by appropriate manipulation the clinician can observe the static relationship of each bone with another. The bones as displayed, are in the position they had during the capture of the CT slices used to create the image.

Clearly, such a view can be very useful for a clinician as an abnormality can be more readily identified as it may be observed from many perspectives unlike the 2-dimensional view of FIG. **1**.

However, the image is static, it does not indicate in any way how the bones move in their damaged state nor does the image allow comparison with the movement of a contra healthy limb.

These limitations are part of the problem addressed by the invention. A patient presenting with a problem is physically assessed by a medical professional and if warranted a particular body part is scanned using CAT/CT or MRI equipment. If should be noted however, that the invention is not limited to only these types of scanning equipment.

Referring to FIG. **3**, which depicts a preferred embodiment of the steps performed to create a visual representation of separated bones of a scanned body part.

Scanned information is collected and made available as a series of DICOM (Digital Imaging and Communications in Medicine) formatted image slices of the limb or body part requiring investigation by the medical professional.

DICOM formatted output is available from most CAT/CT and MRI equipment. The DICOM format has become popular with medical users as a result of the pressure placed on medical equipment manufacturers to provide a vendor independent digital imaging format. Version 3.0 is currently in place.

The DICOM image slices provided are representative of the body part while in a predetermined position.

In this embodiment, the example provided and illustrated in FIG. **4** is of the extreme radial deviation of the wrist. This position of the wrist is achieved by placing the wrist and palm onto a flat surface and moving the hand in the direction of the thumb to its fullest extent. This brings the thumb **16** radially about the wrist and laterally of the radius **12**. The series of slices, which are taken at about 1 mm distances apart, can total about 50-60 in the example given, ie. 5-6 cm's of the wrist is scanned for investigation.

A further step is to record a second series of DICOM formatted image slice data for the same limb or body part in a second position. In this embodiment the second position is the extreme ulnar deviation as depicted in FIG. **5**. This position is achieved by moving the palm and wrist in the direction of the little finger to its fullest extent. This brings the little finger in an arc towards the ulnar **13**.

It is also possible for a plurality of intermediate positions to be recorded. Five intermediate positions have been found adequate for advanced aspects of the invention to be described later in the specification.

Alternatively, and in accord with the usefulness of extending and flexing the wrist for movement and other analysis, the first and second positions could be full extension and flexion of the wrist.

Extension and flexion of the wrist is achieved for the purposes of scanning, by placing the little finger or the thumb (but preferably the little finger) onto a flat surface with the palm of the hand vertical with respect to the flat surface from which the scanned image is detected. The fingers and thumb are kept in constant spatial relationship with each another while the hand is flexed (turned inwards) to its extreme and then moved to an extension position (bent backwards).

Again, it is possible for a plurality of intermediate positions to be recorded.

In this embodiment, DICOM formatted slices of the various positions are preferable, but other formats can be adapted, as required, for the purposes of this invention.

The next step is to convert the raw DICOM formatted slices to a 3-dimensional surface representation, which depending on the application program used could output stereo lithographic formed files (typically having a .stl file type).

Alternatively, the conversion could take the DICOM formatted slices to a .dfx or .igs file format.

Each set of slices for each position recorded by the CAT or MRI apparatus is converted according to the following steps to provide a 3-dimensional surface representation of the body part that comprises individual bones capable of being represented independent of each other and shown moving according to their actual motion.

However, to achieve that goal, it is in this embodiment, required to have each slice previewed by an appropriately skilled medical professional.

Each DICOM image is provided as a rasterized DICOM format data file and each pixel in that file will have a numerical value representative of the density of the tissue. DICOM files are typically viewed as a grey scale representation and use a 16-bit value representative of density. Hence each pixel has a numerical value and by way of its method of is representative of a grey scale value of tissue density. In the inventor's experience, a numerical scale of 0 to about 1400 is representative of the number if grey scale values evident in the DICOM files but this may be different to the experience of others.

The inventors have also noticed from examination of numerous DICOM slices that bone density appears to fall mostly within the range 1100 to 1300 and recognition of this factor is useful when bone-rendering calculations are preformed as part of the invention to be described later in this specification.

In this embodiment software may be used to initially analyse the series of DICOM formatted slices to determine which pixel's are representative of the different densities of material in the slice and in particular to automatically identify those pixel's which are bone.

For example, if the shape of a cross-section of bone/s is to be automatically determined in each slice, it will be necessary of the program to identify a pixel value or preferably a range of pixel values that represent the bone in the image.

Typically, lighter pixels are likely to be representative of the bone whereas darker pixels are likely to be representative of the lower density of the surrounding tissue but a range of pixel values will most likely be bone of slightly different density.

In the step of identifying pixels likely to be bone, it is preferable to select a range of pixel values say, between 1100 and 1200 that the computer program can use in an initial identification step. When those pixels are identified, as is done in FIG. **6** it will be noted that the bone boundary is clearly identifiable from its surrounding.

However, apart from any characteristics of the CAT or MRI scanning process for example lack of resolution, bones in the patient being scanned may have various densities so the DICOM format data will disclose this variation. There can also be calcification of non-bone tissue that may have similar densities to surrounding bone and other variations of bone densities caused by osteoporosis typically the result of the age of the patient. Such variants of bone and other tissue density can result in some mis-identification by the program of what is and is not bone.

FIG. **6** is a pictorial representation of a section A-A of FIG. **1**. FIG. **6** depicts a 2-dimensional top view of a slice through a wrist and a cross-section of the various bones of the carpus can be seen. In particular the distal end of the radius **12**, the scaphoid **18** and the lunate **14**.

The human eye is an excellent tool for performing an analysis of what particular grey scale value is representative of the bony portions of the slice and those of the surrounding tissue but more particularly for identifying what is likely to be bone and what is not. A computer however, deals with the values of every pixel and discrimination is a purely mathematical process. Thus, even though the speed and accuracy of the computer is of assistance in making an initial determination, the logical rules followed by the computer are not always useful in terms of their results.

It is therefore necessary to combine the effort of a computer with that of a skilled human in identifying in each slice the difference between bone and surrounding tissue. This is especially so when the computer generated representation of adjacent bones sometimes looks as if the bones are fused when indeed they should be separate from each other as is illustrated in FIG. **6** where the scaphoid **18** appears to be fused to the lunate **14**. A skilled human can assist the computer to separate bone from bone as well as surrounding tissues from bone, that would otherwise be considered by the computer to be one bone or a bone having an atypical shape.

As indicated previously, FIG. **6** pictorially depicts how a computer analysis indicates adjacent bones, the lunate **14** and the scaphoid **18** are co-joined. This is not the case in a typical patient and it is therefore necessary for this representation to be modified by the clinician to separate the bones.

Once the two bones are completely separated at the slice level it will be possible to depict them independently of each other and independent of other elements by using computer surface rendering tools to create a 3-dimensional representation. In particular the independent movement of each bone will be made possible once they have been separated.

The process of bone to bone separation can be best done with the input of a clinician or medical professional having appropriate anatomical knowledge. It anticipated that if the clinician can become involved at that stage of the process it will be beneficial to the utility of the method and ultimately beneficial to the patient. It is thus of some importance that the useability of the software at this stage of the process is preferably as simple and reliable as it can be.

FIGS. **6** and **7** show the same slice and it may be necessary for a person or persons to examine and if necessary modify every one of the tens or hundreds of slices that make up the basis for a 3-dimensional model of the body part being examined.

That is however unlikely as the slices which show co-joined bones are typically a small proportion of the total number created.

FIG. **3** indicates that a further step in this embodiment of the invention is for the clinician to varying the predetermined bone density range or upper or lower setting. The computer program will display the bone shape with greater or lesser degrees of merger with its adjacent bone until the bones appear separated.

The application of various filters to the DICOM data file can improve the computer's attempt to separate bones from one another. However, bones are not the only part of the body that can be identified and separated using such filters. Ligaments and tendons will have a different density to surrounding tissue and bones and thus appropriate choice of density (pixel value or range of values) will allow the computer to discriminate these other types of body parts for construction into specific 3-dimensional images relating to that chosen element.

These filters can be applied to the entire volume (all slices) or to a sub-volume (single slice, part of a slice or a part of more than one slice).

For example, a filter may only need to be applied to three or four slices in a series.

One preferred method of presenting the computer's separation effort for review by an appropriate medical professional is to display the individual slices as raster images. This is shown FIGS. **6** and **7** where a cross-section of the computer generated 2-dimensional surface of the bone is overlayed as a result of the choice by the clinician of the predetermined bone density or density range (ie. grey scale value or range) to be used.

The 2-dimensional cross-section described is a poly line that represents in the worst case, joined areas of two adjacent bones as illustrated in FIG. **6**. This representation is created because the source slice as examined by the computer, has areas of the same or similar density that are interpreted by he computer to be bone.

The user in this embodiment, and of course there are alternative methods, is able to vary the pixel value range that represents bone in the raster image. Areas between the two bones are likely to have values that will fall outside the predetermined range, such that when the computer reviews that slice again it will use the now adjusted bone density regions to construct its 2-dimensional representation of the now separate bones.

It helps and it is preferable that these modifications by the user are applied immediately to the 2-dimensional representation of the bone shape so that the result of the modification can then be viewed immediately by the medical professional. It is particularly useful for the before and after images such as FIGS. **6** and **7** to be displayed adjacent to each other.

When any filtering or density adjustment is done, it is preferable to continue to use the computer's rules to identify bone so as to maintain the characteristics of the 3-dimensional representation. This rule therefore acts as a check against totally incompatible modifications. Thus it is preferable for the user to vary a range of the pixel vales that represent non-bone rather than simply removing pixels. If pixels were merely removed from the rasterized slice the 2-dimensional representation of the bone wall may well be missing so much information that it may be difficult to generate an acceptable 3-dimensional representation when surface rendering tools are applied.

That is, a surface-rendering tool can be programmed to use the density variation of the outer wall of the bone to better define its outer surface. Say for example, the outer wall of bone has pixel values between 1150 and 1250 and that the density varies linearly with in that range. The surface-rendering tool will use these rules to create a more accurate representation of the surface of the bone because it can be determined with greater surety than otherwise would be the case. When a clinician merely eliminates/erases pixels that lie between bone it is likely that the surface-rendering tool will produce a less representative and likely jagged representation of the bone surface. This occurs because some of the erased pixels are actually bone and others were part of the transition of density values representative of the bone.

One further way of performing the process of separating bone, is to display the result of the computer's analysis in pictorial 3-dimensional form and allow the medical professional to adjust the shape of the displayed parts. This option however may allow the professional to dramatically stray from the information contained within the DICOM slices. Depending on how the software is set up such an approach may be possible within certain limits. Once a co-joined bone region is identified, the medical professional can designate with a pointing device the relevant area that needs to be modified. This process would be performed on the imperfect 3-dimensional surface mesh created by the computer until it was thought to more closely represent the patient's body part, which it would within the limits of the program's ability to take the DICOM data into account.

Once all the bones are isolated with either of the methods described above, it is possible for the program to surface render regions identified as and for the medical professional to select them and name them, refer to FIG. **3**.

It is also then possible for the medical professional, particularly clinicians, to manipulate the 3-dimensional image in ways that more readily identify the damage or disease affecting that particular body part. It will also be possible for the clinician or medical professional to remove one or more bones from the 3-dimensional representation, so that the shape of bones beside and behind a removed bone can be more readily observed.

It is also possible to use colour to identify the different bones and more readily examine the motion or immobility as the case may be of the injured or diseased portion of the body.

In this format it is possible to create a spatial reference point relevant to the body part being displayed. For example, in the wrist it could be a well-known point on the distal end of the radius **12**.

Once the fixed point is determined each 3-dimensional representation can be linked via that reference point to each other representation. This method of linking the individual representations is but one available to those skilled in the art of digital image display and manipulation, so that relative positions and in an advanced aspect of the invention, motion of bones can be referenced for an observer.

If the steps disclosed in FIG. **3** are repeated for the various CAT/CT and MRI scans of the body part in different positions it will be possible to place each 3-dimensional representation of the body part in a step frame animation sequence and replay the motion of the body part between the various positions recorded.

A total of seven positions should be adequate to provide the viewing clinician a much better understanding of the relevant movement of the bones of the wrist. The clinician will be able to observe the movement of a bone relative to others as they move and if necessary view those same motions from various points of observation.

Furthermore a digitally created image such as a 3-dimensional surface representation of various bones can be manipulated in many ways.

For example, since each bone is displayed as a group of pixels representative of a 3-dimensional surface, the bone represented by that surface may be manipulated as a whole.

In one example, a particular bone can be deleted from view, without interfering or changing the representation of other bones in the display. Thus by removing all the bones except the scaphoid **18**, the radius **12** and the ulnar **13** it is possible to view all of the distal and radial surfaces of the scaphoid, as it moves and interacts with adjacent bones including the bone/s deleted from view. Furthermore, once in the digital environment it is possible to remove all the surrounding bones so the clinician can obtain a 360° view of the scaphoid and thus be much better informed when providing a diagnosis of the problem and prognosis for its solution.

Clearly, the ability to manipulate the image in this and related ways can be useful to the clinician, but there are other features of the invention which will further assist clinicians and surgeons.

The inventors have identified that once the 3-dimensional surface representations have been created, it is also possible to accurately analyse the motion of each bone.

It has also been realised, that whereas the bones provide the skeletal anatomy of the human body, the ligaments determine the functional movements of the human body. Extrinsic loads on the bones are created by the action of muscles attached to specific bones wherein the various loads are counter balanced by ligaments in a non-obvious way. Thus to explain the reason certain bones or a collection of bones move in a certain way it is necessary to know how the many associated ligaments interact with those bones.

The location of various ligaments on a bone is known primarily from dissections during surgery and more particularly from studies of cadavers. Cadaver studies have revealed some of the functions of certain ligaments but those studies are not ideal due to an inability to adequately replicate the extrinsic loading of ligaments in the absence of live muscle tissue.

The inventors surmise however that ligaments provide the ability for bones to achieve their complex orientation and movement by tethering to and in most instances checking the motion of various points on the surface of the bone.

Ligaments remain under minimum tension and with oblique complex orientation along with the shape of the bone create a working environment that individualises the anatomy so as to achieve the final motion of the body part of that particular person.

Ligaments also provide positional feedback to allow for the control of the motion of the carpal bones via proprioception. That is, the reception by sensory nerve terminals within the muscles of the arm and the various receptors in the wrist, provide information to the body as to the position and relative motion of the wrist.

Thus the inventors have found that it is possible to infer the function of various ligaments by knowing the position of various isometric points that exist in any set of bones in a particular body part.

Typically ligaments will extend between carpal bones to and from points which remain a fixed distance from each other during motion of the bones of the carpal column. These points are isometric as they exist solely as result of the action of ligaments and bone shape. Thus such points could be considered the basis of isometric constraints on bone movement. In any event the identification of isometric points enables rules of motion for bones and groups of bones to be formulated, more about which will be described later in the specification.

Referring to FIG. **8** two points are shown, one on the scaphoid **18** and the other on the trapezium **20** with a line extending between them.

Referring to FIG. **9** the same two points as shown in FIG. **8** is shown one on the scaphoid **18** and the other on the trapezium **20** with a line extending between them.

A program set up specifically to choose such points identified this pair of points. The program is able to check many pairs of points on the representative surface of the bones and pairs of points that remain a fixed distance from each other during motion are identified. Clearly, there are many ways in which such a programming function could be performed to provide a collection of paired isometric points.

A preferable methodology is to identify a first point in 3-dimensional space that lies on the surface of a bone say the scaphoid **18** and calculate the distance to a plurality of points on the surface of another bone say the trapezium **20** while the bones are in one position, eg while the wrist is in a first position (the extreme radial deviation). It is then possible to recalculate the distances between those points at a second position (the extreme ulnar deviation). The distance between the chosen point on the trapezium and a point on the scaphoid that remains the same distance as the first measurement identifies an isometric pair of points. The distance measurement need not be exact to the mm and a range of variation would be acceptable. Thus isometric points will become isometric regions in one embodiment of the arrangement.

The same analysis can be carried out between a variety of points on different bones of the carpus. Clearly a computer program is best suited to such a task as there are many thousands of such points to be analysed.

Referring to FIGS. **10** and **11**, three pairs of points have been identified, and a line **30** between the first pair of points extends between the radius **12** and the lunate **14**, a line **32** extends between a second pair of points the first on the scaphoid **18** and the second on the trapezium **20**, and the third line **34** extends between the radius **12** and the capitate **36**.

As can be seen pictorially those same pairs of points are joined by paths that are the same length (isometric) with the change in position of the wrist from an extreme radial deviation to an extreme ulnar deviation (FIG. **10** to FIG. **11**).

Clearly such analysis need not be confined to the carpus as the skeletal anatomy other body parts is just as amenable to this type of analysis.

To recognise and be able to quantify the relationship between bones and ligaments provides real benefits to the clinician.

Firstly, it will be possible to scan a contra lateral limb of the same patient or use a model of a standard wrist and compare them with the damaged wrist. Isometric points as determined by the computer for the contra lateral limb can be compared with one or more isometric points identified on the damaged or diseased limb of the same patient. Comparison can also be made to a collection of reference wrists. If certain pairs of points are not identified it is possible to conclude that certain ligaments are damaged in certain ways or that certain ligaments are not being kept in tension when they should be.

More particularly, based on extensive analysis of a broad-section of the population the program can quickly narrow down isometric points by using a model to predict typical isometric points for certain body parts in which case the computer can more readily identify where to begin it search for isometric points.

Thus, if for example, an isometric point can not be identified on a damaged wrist because the lunate translates in a particular direction, it cannot only be deducted that there is ligament damage or disease, but the degree of translation can indicate the degree of the actual damage or disease of a particular ligament.

By way of further example, a tearing or stretching of a ligament may cause another ligament to be loose and by use of a virtual model it is possible to identify which of those ligaments are torn and which of those is caused to be loose.

To be able to quantify ligament damage, not only allows the clinician to suggest an appropriate repair mechanism it is also possible for the degree of healing after treatment to be readily determined.

Yet furthermore it is possible for a surgeon to conduct a "what if" analysis on the 3-dimensional surface model of a particular patient's bone structure. Thus, if a particular ligament is damaged, it is possible to experiment in the virtual domain, with the effects of virtual surgery so as to test the results of that virtual surgery.

For example, if the surgeon thought a reconstruction of a ligament by partial tendon transfer was in order they could ensure that they have correctly identified the optimal fixing point of the tendon to a particular bone.

In a further example, the surgeon may experiment by virtually fusing two or more bones together at a particular point or points to regulate bone movement in a way different to that which is normal but which may restore acceptable function to the movement of other bones.

In such a circumstance, it is also possible by performing isometric point analysis again on the wrist that has had virtual surgery, to provide predictions as to the outcome of that intended surgery. Certain types of surgery can be performed in the digital environment and a realistic understanding of the result can be provided to not only the surgeon but also the patient about the expected functionality of the repaired body part following surgery.

Indeed, as a result of this approach, there may be choices and preferences for the surgeon and patient, which can be made, based solely on the predicted outcome of surgery, using the method of the invention.

It is also possible to create a model of the expected motion of one or more of the bones being examined. Such a model can be based on various rules developed from careful analysis of the 3-dimensional representations created by the method(s) described above.

For example, once the 3-dimensional representation of a particular bone is created certain points in or on its surface can be identified either by judicious choice or repeated experimentation, such that it is possible to determine certain rules of movement associated with those points. For example, a point on the lunate may only move linearly or within a small but defined deviation from a line. Such a rule defines by way of limitation a characteristic of the motion of that bone. There exist many other points in or on certain bones that will have certain quantifiable limits of movement and that therefore can be defined by a rule of motion.

This approach is commonly referred to as Rules Based Modelling and it is a matter of judicious selection which rules should be created and how they are applied.

The mass of the component bones as well as their characteristic shape, size and orientation can be included in the rules.

The extent to which bones can interact with adjacent bones in regards to proximity and collision avoidance and inter-bone compression tolerance given the particular (typically modest) deformity characteristics of the surface of the bones in question can be included.

Fixed distance constraints (isometric constraints) between points or regions on adjacent and non-adjacent bones can form the basis of one or more rules. These constraints most likely represent the action of various ligaments working with various bones. Knowledge of the variance of an expected isometric relationship is indicative of, for example, the physiological elasticity of one or more of the related ligamentous constraint elements.

Load points at which force can be applied to move various objects in a specific and thus predicable way can be used as part on the model. Indeed the expected deviation of certain points on bones can be quantified, even from patient to patient and a model of the typical patient created.

The complexity of any model has a direct correlation to the quantity of rules and the acceptable accuracy of the model will determine how complex the model needs to be. Thus certain models will, although not as accurate as others still provide results in circumstances that are still clinically acceptable.

Thus, in the context of this invention, it will be appreciated that once a suitable typical model or selection of models is available, it will be possible to further enhance the method(s) of clinical analysis disclosed previously.

The model of a typical wrist can be used in several ways.

One way is to create a model which is representative of a typical wrist and compare it with the 3-dimensional representations obtained of a patient's wrist.

Abnormalities may be readily identified if the typical wrist model is not the same as the performance of the patient's and the parameters of the model that are different (under or over value) can help to identify the abnormality and may also quantify the abnormality.

Another way is to create the 3-dimensional representations of a patient's wrist in accord with the method(s) described and apply the parameters of the model to the representation and create a free flowing representation of that patient's wrist. A single scanned image of the patient's wrist may suffice, but preferably at least two scanned images in extreme positions can be used as the basis for the application of the model. This approach can not only speed up diagnosis but also dramatically reduce costs while delivering clinically acceptable and useable results.

Thus, beyond analysis and "what if" manipulation of the multiply scanned wrist previously described, it is possible to manipulate a patient's modelled wrist in a virtual environment upon which virtual surgery can be performed as previously described.

Clearly, if the wrist of the patient is damaged or diseased such that it falls outside the parameters of an existing model the simple process of comparison will enable the development of a custom model for that patient. Once a unique virtual model of the wrist of that patient is created virtual surgery can be performed on that particular wrist and its working tested and virtual modifications conducted using pre and post surgery models.

Rules Based Modelling is but one convenient way of creating a further tool to assist the clinician and surgeon repairing or ameliorating the particular ailment of a patient.

Yet further, such a display and structural analysis of bone structure is most useful for teaching purposes thus opening a greater understanding of what heretofore has been a very specialist and not totally understood field.

It will be appreciated by those skilled in the art, that the invention is not restricted in its use to the particular application described and neither is the present invention restricted in this preferred embodiment with regard to the particular elements and/or features described and depicted herein. It will be appreciated that various modifications can be made without departing from the principle of the invention, therefore, the invention should be understood to include all such modifications within its scope.

The claims defining the invention are as follows:

1. A method of producing 3-dimensional visualisations of digital representations of cross-sectional slices of a vertebrate animal or human body part includes the steps of:

a) obtaining a first ordered series of slices of a portion of said body part in a first position;

b) applying one or more filters to each of said digital representations of said first ordered series of slices to identify the skeletal portions of said body part;

c) converting said first filtered series into a 3-dimensional representation of the skeleton of said body part in said first position;

d) obtaining a second ordered series of slices of said portion of said body part in a second position different to said first position wherein said first and said second position of said portion of said body part is representative of extremes of the achievable movement of said portion of said body part;

e) applying one or more filters to each of said digital representations of said second ordered series of slices to identify the skeletal portions of said body part;

f) converting said second filtered series into a 3-dimensional representation of the skeleton of said body part in said second position;

g) combining said 3-dimensional representations to form a step frame animation having as many steps as there are ordered series of slices.

2. A method according to claim **1** further includes the further steps of:

h) obtaining a one or more further ordered series of slices of said portion of said body part in a one or more further positions between the extremes of the achievable movement;

i) converting said further filtered series into a 3-dimensional representation of the skeleton of said body part in said further positions;

j) combining said 3-dimensional representations to form a step frame animation having as many steps as there are ordered series of slices.

3. A method according to claim **1** further includes the steps of:

k) selecting a plurality of points on two or more skeletal object s in each said 3-dimensional representation; and

l) analysing whether the distance between pairs of said points on different skeletal objects are isometric, if the distance between pairs of points remain the same or within a predetermined variance of distance during said step frame animation.

4. A method according to claim **3** further includes the step of:

m) comparing the changes, if any, of the distances between predetermined pairs of points with expected changes, wherein the result of said comparison provides assistance to a cliniclan to form a diagnosis regarding the body part.

5. A method according to claim **3** wherein isometric points determined equate substantially to the fixation location of the ends of ligaments associated with said portion of said body part and the further step of:

n) comparing the isometric points determined in step **3** to predetermined isometric points of a typical or contralateral body part and if said isometric points vary a greater than a predetermined amount a problem or abnormality or a degree of problem or abnormality associated with one or more ligaments associated with said portion of said body part exists.

6. A method according to claim **1** wherein step b and/or e includes a filter that allows an anatomically knowledgeable medical professional to adjust the bone selection criteria of said filter until a representation of adjacent bones shows that said adjacent bones are separate from one another.

7. A method according to claim **6** wherein said filter that allows an anatomically knowledgeable medical professional to adjust the density range criteria of said filter until a representation of adjacent bones shows that said adjacent bones are separate from one another.

8. A method according to claim **1** wherein said digital representation of slices of a vertebrate animal or human body part is provided by CAT/CT or MRI apparatus.

9. A method of producing 3-dimensional visualisations of digital representations of cross-sectional slices of a vertebrate animal or human body part includes the steps of:

a) obtaining a first ordered series of slices of a portion of said body part in a first position;

b) applying one or more filters to each of said digital representations of said first ordered series of slices to identify the skeletal portions of said body part;

c) converting said first filtered series into a 3-dimensional representation of the skeleton of said body part in said first position;

d) obtaining a second ordered series of slices of said portion of said body part in a second position wherein said first and said second position of said portion of said body part is representative of extremes of the achievable movement of said portion of said body part;

e) applying one or more filters to each of said digital representations of said second ordered series of slices to identify the skeletal portions of said body part;

f) converting said second filtered series into a 3-dimensional representation of the skeleton of said body part in said second position;

g) applying to one or more points on the skeleton of said body part of each said 3-dimensional representation, one or more rules based animation constraints;

h) creating a 3-dimensional animation of the movement of said body part according to said constraints.

10. A method according to claim **9** further includes the further steps of:

i) obtaining a one or more further ordered series of slices of said portion of said body part in a one or more further positions between the extremes of the achievable movement;

j) converting said further filtered series into a 3-dimensional representation of the skeleton of said body part in said further positions;

k) combining said 3-dimensional representations to form a step frame animation having as many steps as there are ordered series of slices according to said rules based animation constraints.

11. A method according to claim **9**, wherein step b and/or e of claim **10** includes a filter that allows an anatomically knowledgeable medical professional to adjust the bone selection criteria of said filter until a representation of adjacent bones shows that said adjacent bones are separate from one another.

12. A method according to claim **9**, wherein said digital representation of slices of a vertebrate animal or human body part is provided by CAT/CT or MRI apparatus.

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Appendix 3: True Life Anatomy Software

Web site – www.truelifeanatomy.com.au

Distribution agent – RuBaMAS Pty Ltd, Adelaide, Australia – www.rubamas.com

TLA Generator manual - on line - http://www.rubamas.com/products/tla-generator/

TLA Viewer manual – on line - http://www.rubamas.com/products/tla-viewer/