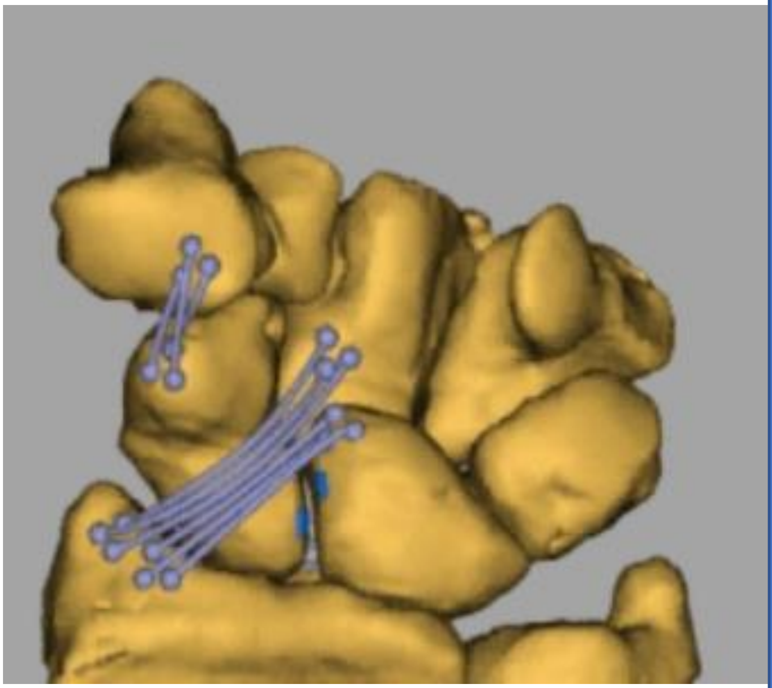
CAN THE WRIST BE EXPLAINED?

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



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

by

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Conflict of interest and terms of use

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

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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 expression 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 of the wrist, and regularly pressed me to carry this work through to a PhD.

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

Contents

Foreword

Michael Sandow's thesis is a unique endeavour towards an anatomical, biomechanical (kinematic and kinetic) concept of carpal motion through reciprocal action between the ligamentous-constrained bones. The concept is put into perspective with the evolutionary features (chimpanzee).

The seemingly simple concept of two single-axis cylinders with variable offset working as a rules-based motion (RBM) within a system such as the wrist is actually very clever: any individual component variation is offset or matched by changes in the other component. The product creates a consistent biomechanical outcome to achieve the required wrist function. This is a clever understanding of the reciprocal effect on one bone to the other within the proximal carpal row. This explains not only flexion-extension, but also radial-ulnar deviation of the wrist and suggests the dart-throwing motion. Such a 'two-gear four-bar' linkage is well described in other anatomical systems and creates a powerful connection between the rows.

Regarding kinetics, 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. Michael Sandow explains how the wrist resists translation in coronal, sagittal, transverse and longitudinal planes and how it uses oblique power grip to improve holding, thrusting and throwing while maintaining independent finger and wrist motion and providing a low-profile distal part of the upper limb. Applying the 3D-printed bones, and then adding the ligamentous constraints and tendon tension can re-create a stable yet mobile wrist. This is a major validation of Michael Sandow's original concept that includes reverse-to-forward engineering of the carpal bones.

The lunate has a balanced force couple with the long radiolunate ligament, which creates a volar proximal load to pull the lunate into flexion, thereby preventing its natural tendency to rotate into extension (DISI). This is balanced by the connection of the lunate dorsally to the DIC through the lunate-DIC ligamentous junction and creates a physiologically stable, well-aligned and reactive lunate intercalated segment—and central column.

Moreover, this in vitro/in vivo concept is studied and validated through a pathological scapho-lunate dissociation and includes the analysis of this disorder and a proposal for its treatment. Not only is the scapho-lunate pathology addressed but its conceptual and practical surgical treatment are also considered.

It is rare in the orthopaedic surgery literature to observe so many years' work integrating numerous aspects of the in vitro and in vivo functioning of a joint, including a strategy to solve one of our unsolved disorders. There is no doubt that this thesis and the many associate satellite publications are a keystone of the understanding of the wrist. Moreover, Michael Sandow's concept is open-ended, since it may be an incentive to go further and understand other dissociative (such as luno-triquetral dissociation) or non-dissociative (CIND) disorders of the wrist.

A thesis was the only way to put all the information together (this would have been impossible in a classic journal article format). An electronic book that any wrist surgeon would have available in its companion's files may be the next step!

Guillaume Herzberg, MD PhD

(PhD Thesis examiner)

Preface and contextual statement

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

However, as part of a larger study to define a kinetic model of the wrist, this project uses a conceptual approach to theory development, and then applies hypotheses and testing to refine, enrich or reject the proposed theory. It is important to recognise that this work was theory- and hypothesis-driven. On the basis of limited initial observations and assessments, isometric connections between various carpal bones were proposed. The ongoing work was performed to confirm or refute their existence as part of efforts to develop a wider theory of carpal mechanics.

This approach is fundamentally different from existing research, which is heavily based on cadaveric analysis. The approach of reverse engineering the dynamic system and then developing a Rules Based Motion concept to allow forward engineering, reanimation and 'what if'-type analysis has not been previously used—this claim is supported by the successful filing of patents on the subject.

The need to identify more effective solutions was created by the inability to offer patients reliable solutions to address their wrist dysfunction and while many proposed reconstructive procedures were available, none was able to provide consistent functional restoration. This was compounded by the variable success of recognised specialists in the field in presenting cogent and consistent arguments to explain carpal form and dysfunction.

The introduction of this monograph covers aspects that led to the genesis of the project. The relevant publications that developed from this work are summarised and recent presentations are also included, as they constitute ongoing work to apply the theory and expand the current understanding.

The pre-planned research journey that is covered in the thesis, and now condensed into this monograph, was to define carpal biomechanics, identify deficits that may lead to dysfunction and identify solutions to address such dysfunction. These aims were achieved using a conceptual theory development process rather than the typical empirical approach—and the publication of the successful results for the scapho-lunate reconstruction using a volar and dorsal surgical repair technique (Anatomical Front and Back - ANAFAB) completes the journey.

This approach (the ANAFAB reconstruction) can be considered a compilation of a range of existing approaches and may be viewed as adaptive rather than disruptive to traditional approaches. Although reconstructing the connections between the trapezium and scaphoid, the dorsal scaphoid and lunate, and the volar lunate and the radius has been previously described, the combination of all of these, as is part of the ANAFAB, is new.

The ultimate 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. Time and external scrutiny will show whether this approach has identified answers to explain and fix (when necessary), the perplexing, complex and critical part of our fundamental and humanly unique functional capabilities enabled by the wrist.

Abstract

The wrist remains a challenge with respect to its mechanical controls and biomechanics and has confounded researchers for many years. No standard wrist exists and previous attempts to characterise wrist motion or biomechanics have been unsuccessful. The work undertaken as in 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, particularly the wrist, can be defined and controlled by its four basic rules or factors, viz: morphology, constraint, interaction and load. Rather than utilising the standard empirical study design, this project implemented 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. The theory defines a stable central column and was applied to address the pathological disruptions within the carpus. Past repairs have been largely unsuccessful in predictably and reliably 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 2020)) 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 concept of the Stable Central Column Theory of carpal mechanics has challenged existing explanations of how the wrist works and how to fix a dysfunctional wrist. The concept received considerable opposition from certain sectors and was dismissed by several researchers and groups working in the same area of interest, who argued that it lacks consistency with current approaches. However, the barriers of understanding and treatment were resolved through an outcome-driven conceptual-based experimental approach, and while longer term, wider experience is required, this work represents a significant step forward in wrist disorder management.

The journey to identify the critical biomechanical restraints of the wrist using a reverse engineering technology and then identify a means to restore them in the pathologically injured wrist appears to have reached its destination, at least in one part of the wrist. In the case of scapho-lunate diastasis and collapse of the central column, the application of a logic-based reconstructive volar and dorsal surgical solution (ANAFAB; Sandow and Fisher 2020) has successfully restored carpal function 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 appears to be able to characterise carpal biomechanics and identify therapeutic solutions for wrist dysfunction—and to this extent, explain the wrist.

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-scapho-lunate septum
DIC	dorsal intercarpal ligament
DIC-L	dorsal intercarpal ligament-lunate connection
DICOM	Digital Imaging and Communications in Medicine
DISI	dorsal intercalated segmental instability
FEA	finite element analysis
IT	information technology
MRI	magnetic resonance Imaging
q.v.	*quod 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

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

Animation technology

This is a process that creates the 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 through the 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 organised 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 and 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 repeated measurements of an observed phenomena to identify patterns from which an explanation of that phenomena can be developed. This contrasts with Conceptual research which is based on hypothesis testing to assess the validity of a theory that is proposed from limited initial observations.

Proof of concept

The realisation of a certain method or idea 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 preliminary 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)

Defined components or elements 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 vary individually, but together create a consistent or generic outcome. RBM can be used to create one of three basic forms of animation: **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 phenomenon, 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 acting on and upon other rules or elements 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

A theory explaining the phenomenon of the stable, yet mobile wrist that is able to achieve a wide range of functional tasks. 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 attempting 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 must, 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 (Zhenying 2011).

Volume rendered

The construction or creation of an apparent 3D image using ray casting. The product is more like a projected shadow of the scanned object, and not an actual 3D object. It is not presented as a 3D object, but as projected and captured 2D screen views.

'What if'

This refers to the option to apply some variation to 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 test various operative interventions on a virtual model of the actual patient injury.

Introduction to Wrist Biomechanics

Preamble and project historical background

The wrist has been a challenging structure to analyse. Over many years, countless projects, departments and researchers have striven to understand and explain its complex mechanics (Garcia-Elias, 2013, Rainbow et al. 2016). Extensive reviews on the observation, explanation 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. A 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 scapho-lunate 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, p.1011).

When this project commenced, there were a number of proposed theories or concepts to explain how the wrist worked (Figure 1), including:

1. Row and column (Craigen and Stanley 1995, 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)

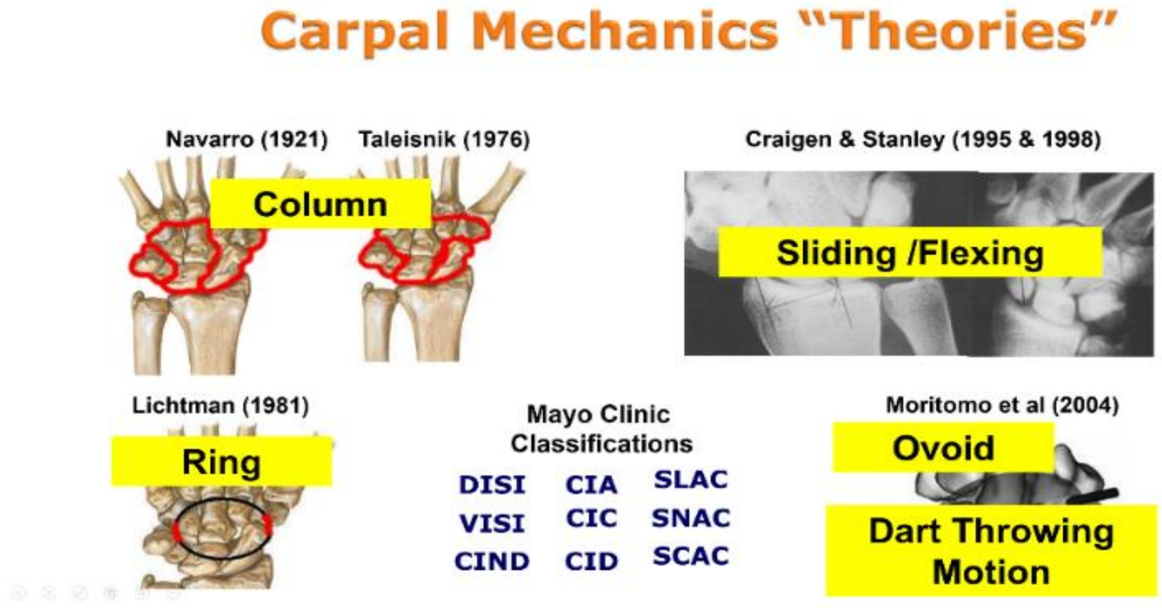


Figure 1. Diagrammatic summary of existing explanations for carpal biomechanics from the 1990s and early 2000s.

The problem with many of the proposed theories at that time was that they did not explain a number of the mechanical challenges facing 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.

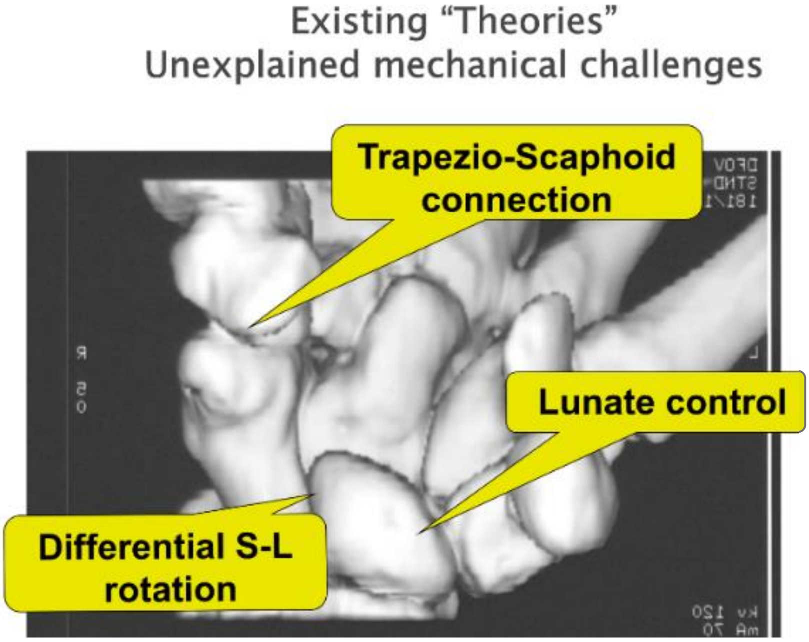


Figure 2. Unexplained mechanical demands on the wrist.

More specifically, many of the proposed theories lacked the features of a good theory. In his pivotal publication *A Brief History of Time*, Hawking 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 must, most importantly, be predictive (Hawking 1996). The current theories on carpal mechanics lack some or all of these features and thus, do not entirely qualify as theories. They are more in the nature of descriptions of observational data. The real question remains: why has the wrist been so difficult to understand despite extensive study?

One answer lies in the fact that wrists are all different and much of the previous work was based on large numbers of empirical observations in an attempt to identify a standard or 'normal' wrist. Such a standard wrist has eluded researchers (Crisco et al. 2005). The work of Linscheid et al. (1972) and the earlier 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 bones, without necessarily considering how this particular motion segment may relate to the wider biomechanics of the wrist. Further, the clinical results of various surgical procedures have been unpredictable, and subsequent researchers have typically been unable to replicate the outcome of the initial report of a particular repair or reconstruction.

The situation regarding carpal research in the late 1990s 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: '[c]urrent 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 [scapho-lunate] reconstruction' (Lee et al. 2014, p. 643).

Project initiator

The trigger for this particular project was Dr Sandow’s response to a question posed at a RACS conference in July 1998. The query was in regard to the dynamic spatial relationship of the lunate to the ulna, and sought to reconcile the claim that ulnar carpal impaction (pathological contact between the ulna and lunate bones) occurred on ulnar deviation of the wrist when, on a plain radiograph, the lunate is observed to move away from the ulna.

In an attempt to address this knowledge deficit, multipositional CT scans of Dr Sandow’s left wrist were created using a standard CT 3D imaging environment. The motion sequences of the wrist were then displayed by using screen captures 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 moved away from the ulna on ulnar deviation, but it moved in a flexion/extension motion arc despite the fact that there were no particular tendinous connections. Further, the scaphoid appeared to partly move with the lunate, while the trapezium pivoted 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.

Similarly, the motion of the scaphoid and the trapezium was 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 observed on plain x-rays would suggest that the scaphoid is not significantly connected to the trapezium. However, the initial cartoon-like step frame animation images suggested a definite connection between the scaphoid and lunate. With improved visualisation and the application of markers to certain parts of the carpal bone, connections between different carpal components became apparent. This initial work was performed in July 1998.

Initial observations and development of the Rules Based Motion concept

Even at this early stage, consistent motion patterns were identified and it became clear that there were 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 control of the motion of the proximal row of the carpus, which was poorly explained.

Screen captures of one of the early animations are shown in Figure 3. This animation was created from the original CT scan of Dr Sandow’s wrist using 3D Studio Max (Autodesk, CA, USA) as part of the True Life Creations Pty Ltd production environment. The importation of the scan data and creation of the model were extremely time-consuming and this method is not viable as a routine animation creation tool. Further, the resulting image sequences were limited with respect to quantitative analysis of motion and inter-bone interaction, particularly the creation of physics-based rigid body animation.

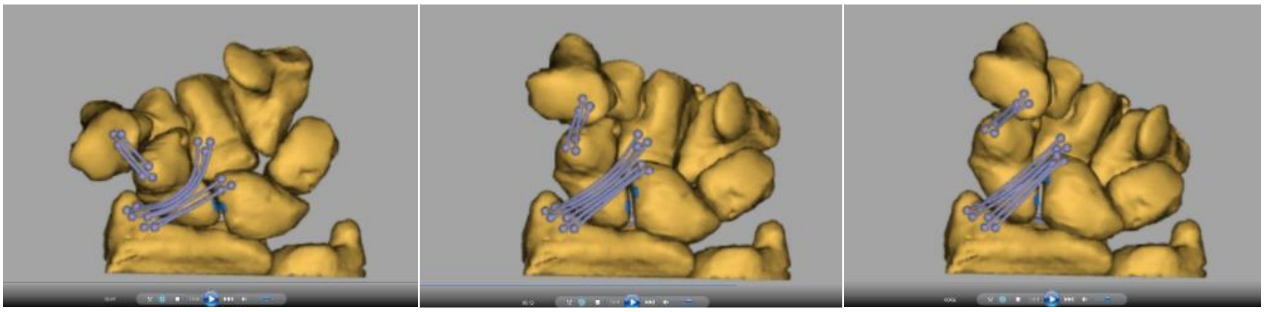


Figure 3. Screen captures of a wrist animation demonstrating the sequential motion of a single set of carpal bones moving from radial to ulnar deviation, with isometric regions joined by blue connectors. Also demonstrated is the differential motion of the volar aspect of the scaphoid and lunate. (see www.truelifeanatomy.com.au; screen captured from movie isofront.avi; 15 March 2001).

The animation depicted in Figure 3 was created by importing the CT Dicom scan data from each of the sequential CT scans captured as Dr Sandow's wrist moved from radial to ulnar deviation. Mr Sam Papas (as principal production animation specialist at True Life Creations Pty Ltd) has extensive skills in 3D animation and created seven 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. The bones of that single primary model, with its attached surface markers, were then copied and registered (aligned) with the same bone in each of the other positions.

As part of the initial work, multiple candidate points were defined and then measured. This created a massive computational task, but was assisted by the use of targeted but expanded regions of interest. While it is apparent that two bones may be linked, the actual location on the bones varies and even a minor change of a few millimetres in the tested point had a dramatic effect on the actual degree of isometricity.

As an important validation exercise, the degree of isometricty was also assessed between other bones. For example, the lunate-to-capitate link was examined and showed a clear lack of isometricity. This indicates a process to test for positive and negative isometricty.

The current diagnostic imaging using computed tomography 3D and 4D scanning creates animations that look like a single moving 3D model of the wrist. In reality, the images are simply a step frame presentation of a series of separate individual 3D volume rendered 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 images are then presented as a step frame animation to create the apparent motion sequence of the carpal bones. However, although they depict the same wrist, each image presented is unrelated to the others. Further, the images shown are volume-rendered representations; they are a 2D projection of the 3D data set and thus, no 3D object is actually created. This means that although the view direction and certain video presentation details can be modified, these 'moving' images cannot be manipulated in 3D, nor can they be measured accurately or exported in anything other than a 2D screen capture format. This technology conundrum is covered by Sandow (Sandow 2014).

The technique used in this project is different. By creating a 3D object comprising 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 contrasts with the process described above (step frame animation of seven scans where isometricity is more susceptible to errors). By using the single reference set of bones, we were able to accurately record the changes in the distance between the surface markers and document areas of isometricity, 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 wrist anatomy and the bones were given unrelated names (types of pasta!) to avoid any potential recall of connections from previous discussions.

The result was a quantitative identification of isometric connections between certain areas of the carpus by the computer program, which was independent of any prior anatomical knowledge or operator input. It is notable that the connections between the bones as depicted by the blue lines in Figure 3 are actually 3D objects in the form of ropes of connected spheres, or perhaps beads tightly packed on a string. This allows the connections to be correctly positioned over both convex and concave surfaces. The animation (shown as still screen captures in Figure 3) details the dorsal scapho-lunate ligament, the connection between the scaphoid and trapezium, and the radio-scapho-capitate ligament. It further identifies a connection between the volar lunate and the radius in a proximal radial-to-distal-ulnar direction. This structure, which appears to explain the control of lunate motion as indicated in Figure 2, had not been identified in previous scientific work or published in any anatomical papers at that time. Thus, the computer (and Sam Papas) identified a hitherto undescribed anatomical structure by performing a multipositional quantitative isometric analysis.

At that time, the long radiolunate ligament was not recognised as an important structural component of the wrist (based on previous work by Berger (1991 and 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 radiolunate ligament. However, until recently, this 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 technology was not yet 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 software system.

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 wrist movement. These rules could then be used in a forward kinematic fashion to re-create this motion using a mathematical or forward engineering model. The significant variation in the motion of individual components of the wrist was recognised and attempts to find a reliable and consistent pattern of motion had not yet been identified.

It was proposed that there are four specific rules or factors that, when combined, would potentially create a mathematical (kinetic) model that would explain the constant overall function of the wrist, but also 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 could address this specific requirement. The proposed reverse engineering and then forward engineering based on specifically identified ‘rules’ (with the option to modify any or all of the rules in ‘what if’ scenarios) appeared a novel concept.

As the initial observations potentially explained a number of unresolved issues and may be used to identify solutions for dysfunction, patents were filed in 2000. They were subsequently granted in both Australia (2002) and the United States (2006) to cover the animation technology model of reverse engineering the constraints followed by forward engineering. This novel concept remains central to the development of a solution to explain carpal instability and dysfunction. To be considered patentable IP, the proposal must have:

1. novelty (be a new idea)
2. inventiveness (be non-obvious to the trained observer)
3. utility (be useful for some purpose).

The 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 those components and the load applied to the system. With these four components, which can vary individually, a resultant motion can be created. The wrist appears to be a sound 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). Therefore, this project occurred in three main stages, each with a specific goal:

1. To develop the technology with which to study the motion of the wrist
2. To characterise the normal connections and factors that determine wrist morphology and motion
3. To apply the above technology and factors in an injury situation.

The hypothesis for the overall project was that by understanding the wrist and characterising the normal constraints that are missing from an abnormal wrist, one might restore wrist function by replacing the missing components based on an understanding of the mechanics that were disrupted. As discussed previously, the majority of wrist research has been empirical and comprised extensive examination and measurements of wrist motion in an attempt to explain the movement patterns observed. This project was based on a more conceptual approach where the rules that can vary are defined and then reapplied to simulate motion under a mathematical or kinetic environment.

Software development (True Life Anatomy)

To allow a quantitative analysis of the carpus and to better characterise the motion and relationships of wrist components, sophisticated 3D imaging and measurement was required and thus, 3D animation and manipulation software was developed: True Life Anatomy (Figure 4).

The True Life Anatomy software system was created as three separate programs and developed in a Virtual Studio development environment using Virtual Tool Kit libraries.

1. TLA Generator (www.rubamas.com/products/tla-generator)

   This allows the CT scan data to be parsed into the graphic environment and thresholded, and creates a 3D object. It allows primary segmentation of distinctly separate components but can also perform secondary segmentation on the 3D object using polygonal angle or touching iteration and selection. The created 3D object is saved as a .tla file that contains an STL file, spatially co-registered 2D axial slice images and patient demographic data.

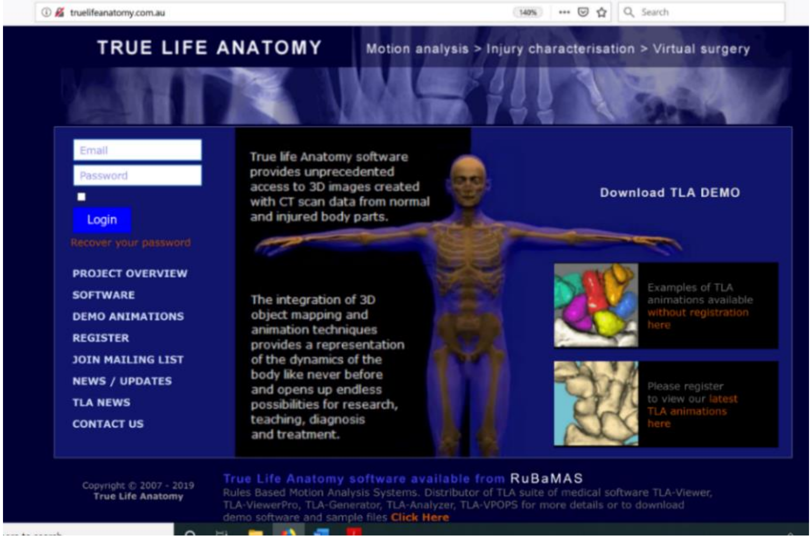
   The TLA Generator user manual is in Appendix 1.

2. TLA Animator

   This program imports the created 3D objects in a manipulative graphics environment to allow measurement and analysis.

3. TLA Viewer (www.rubamas.com/products/tla-viewer)

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



True life Anatomy software provides unprecedented access to 3D images created with CT scan data from normal and injured body parts.

The integration of 3D object mapping and animation techniques provides a representation of the dynamics of the body like never before and opens up endless possibilities for research, teaching, diagnosis and treatment.

Examples of TLA animations available without registration here

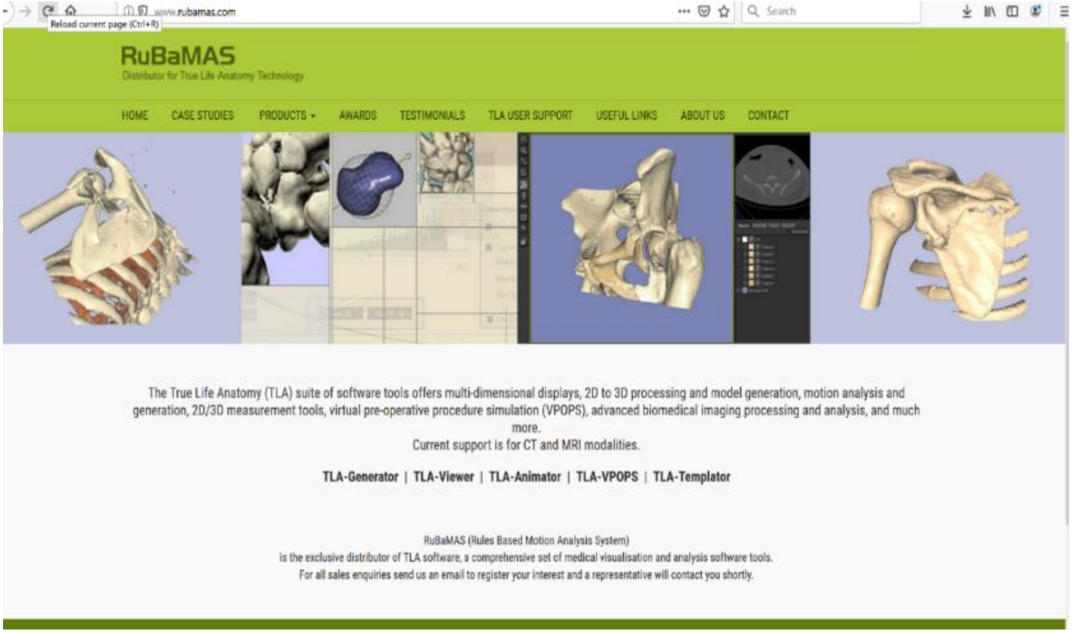
Please register to view our latest TLA animations here

Copyright © 2007 - 2019
True Life Anatomy

True Life Anatomy software available from RuBaMAS
Rules Based Motion Analysis Systems. Distributor of TLA suite of medical software TLA-Viewer, TLA-ViewerPro, TLA-Generator, TLA-Analyzer, TLA-VPOPS for more details or to download demo software and sample files Click Here

Figure 4. Screen capture of the True Life Anatomy website (http://truelifeanatomy.com.au)

A separate entity, RuBaMAS Pty Ltd (an acronym of Rules Based Motion Analysis System) with appropriate web content was created to support potential commercial and clinical access: http://www.rubamas.com (Figure 5).



The True Life Anatomy (TLA) suite of software tools offers multi-dimensional displays, 2D to 3D processing and model generation, motion analysis and generation, 2D/3D measurement tools, virtual pre-operative procedure simulation (VPOPS), advanced biomedical imaging processing and analysis, and much more.
Current support is for CT and MRI modalities.

TLA-Generator | TLA-Viewer | TLA-Animator | TLA-VPOPS | TLA-Templator

RuBaMAS (Rules Based Motion Analysis System)
is the exclusive distributor of TLA software, a comprehensive set of medical visualisation and analysis software tools.
For all sales enquiries send us an email to register your interest and a representative will contact you shortly.

Figure 5. Screen capture of the RuBaMAS website (http://www.rubamas.com)

Formal software development commenced in 1999. In contrast to many development projects, the end points were clearly and rigidly defined: the work aimed to solve the issues related to carpal dysfunction. The endpoints were divided 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 process, it was clear that the available technology was unable to deliver the desired functionality. Even at an early stage, the True Life Anatomy software appeared to offer a unique approach to the process of reverse engineering a mechanical system (the wrist) and also forward engineering reanimation capability with a ‘what if’ option to add additional mechanical factors. In view of this, patents applications were submitted in Australia, the US and Europe. The patents were granted in Australia (q.v., Paper Synopsis) and the US (q.v., Paper Synopsis).

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 wrists that are injured or not functioning correctly
4. Propose potential strategies to address the deficits 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. Implement the proposed reconstructive strategy with a target group of patients with a specific wrist dysfunction to validate the reverse engineering–forward engineering concept and approach

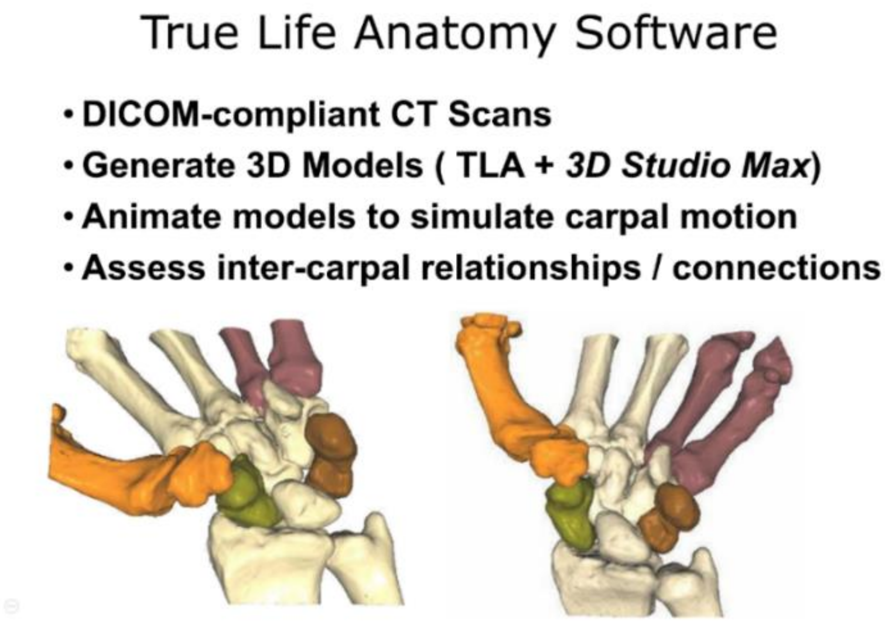
The first step to identify the rules or characteristics of wrist motion required division into various sub-stages. In the development of animation technology, they were:

1. Import volumetric data (CT) of first position multibody object (e.g., wrist)
2. Threshold volumetric data
3. Create 3D multibody object mesh
4. Perform first level segmentation of 3D Mesh (separate objects)
5. Perform second order segmentation of 3D Mesh (touching objects)
6. Import second position object into the same graphics environment
7. Identify points on pairs of bones that remain isometric throughout the motion range
8. Reapply isometric constraints on the primary segmented object
9. Reanimate the multibody object using isometric constraints, collision avoidance and load points with FE (Finite Element) analysis.
10. Add ‘what if’ conditions to the reanimated object and FE analysis

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.

The assumption that the distal row moved as one was tested early in the project. The distal row was segmented as a single 3D object in both radial and ulnar deviation. The two objects (distal row 3D models) were then registered (aligned) and there was no discernible variation between the shape or relationship of the components. On this basis, it was assumed that the original postulations of Taleisnik (1976) and others are valid.

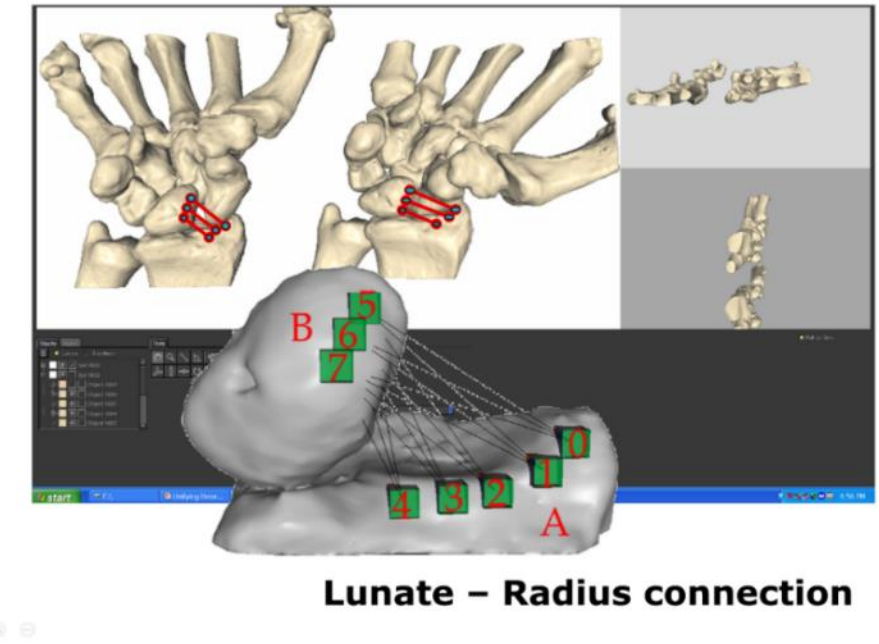
An example of the pathway for image creation and analysis is detailed in Figures 6–15. Additional details are available online (www.rubamas.com and www.truelifeanatomy.com.au) and in the published papers. For paper summaries, see pages 27 – 33. Further detailed step-by-step analysis of isometric connection is presented in Figures 10–15.



True Life Anatomy Software

- DICOM-compliant CT Scans
- Generate 3D Models (TLA + *3D Studio Max*)
- Animate models to simulate carpal motion
- Assess inter-carpal relationships / connections

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



Lunate – Radius connection

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

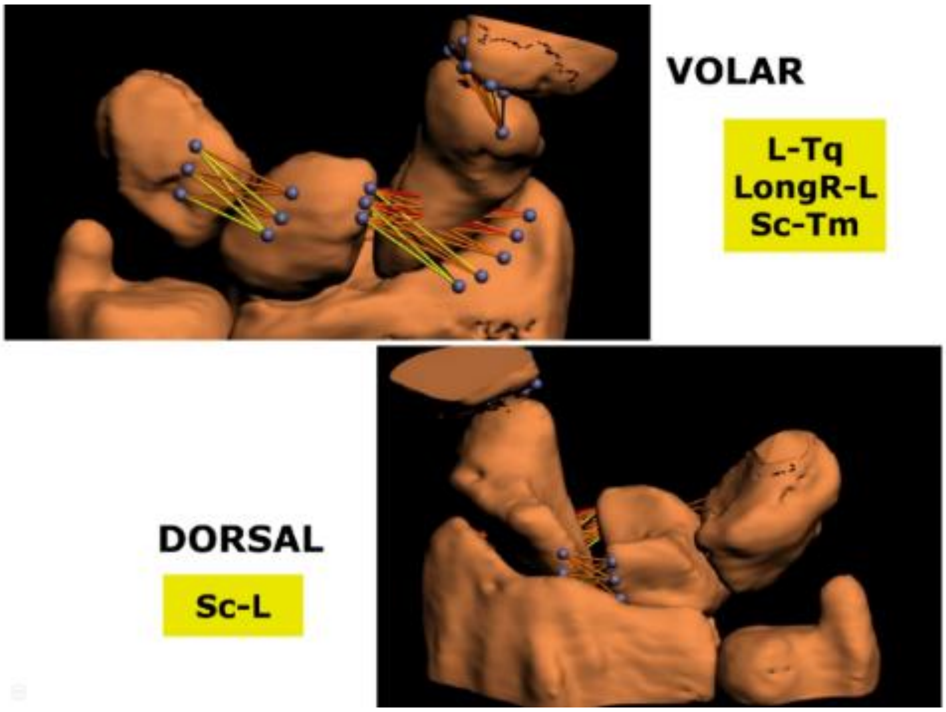


Figure 8. Specific isometric connection was identified in the scapho-trapezial (Sc-Tm), volar radiolunate (Long R-L), volar lunato-triquetral(L-Tq) and, dorsally, the scapho-lunate (Sc-L).

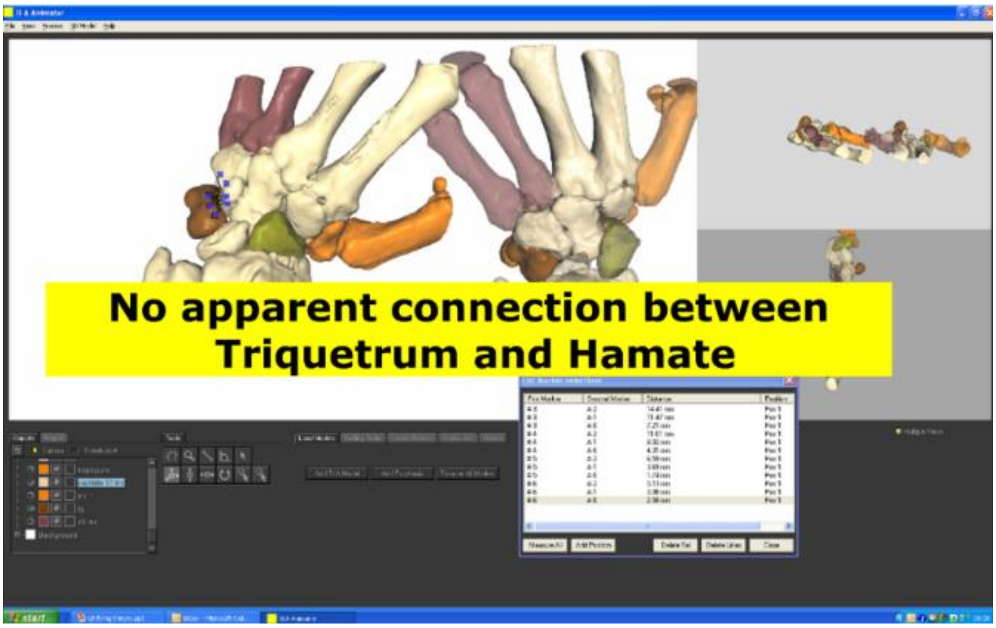


Figure 9. No isometric connection was identified in the region of the triquetrum and hamate.

Hide position 2 object, and mark the locations of interest on the corresponding bones.

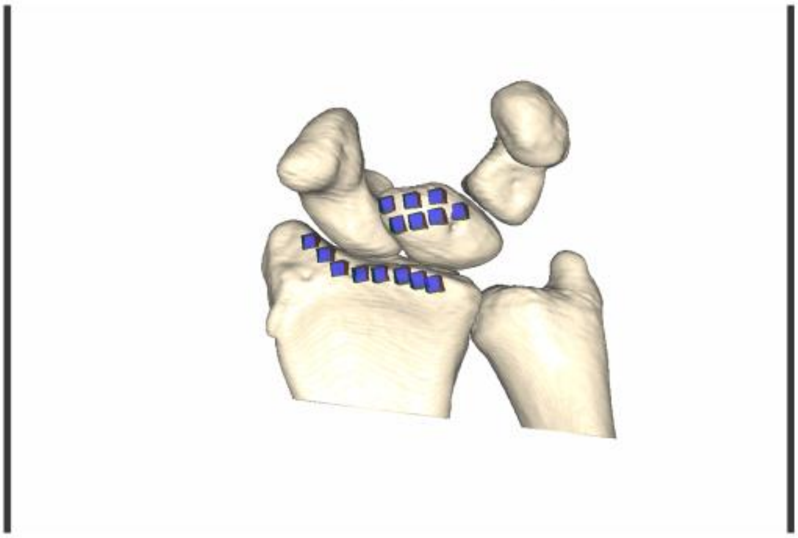
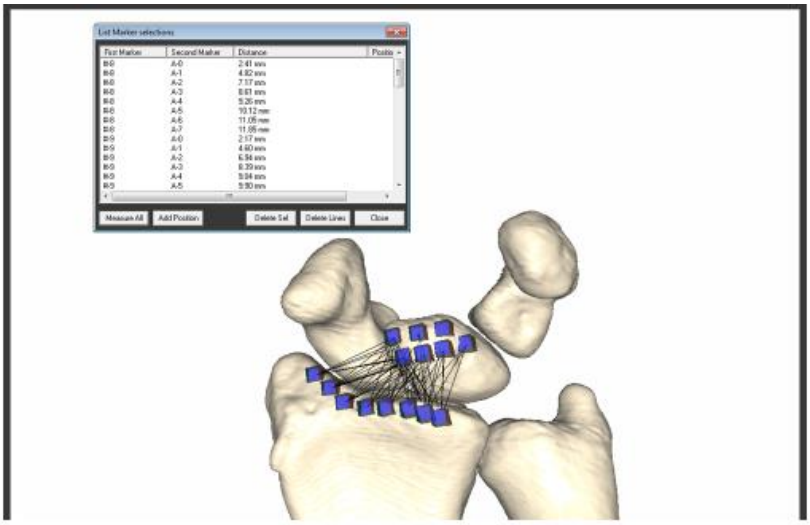


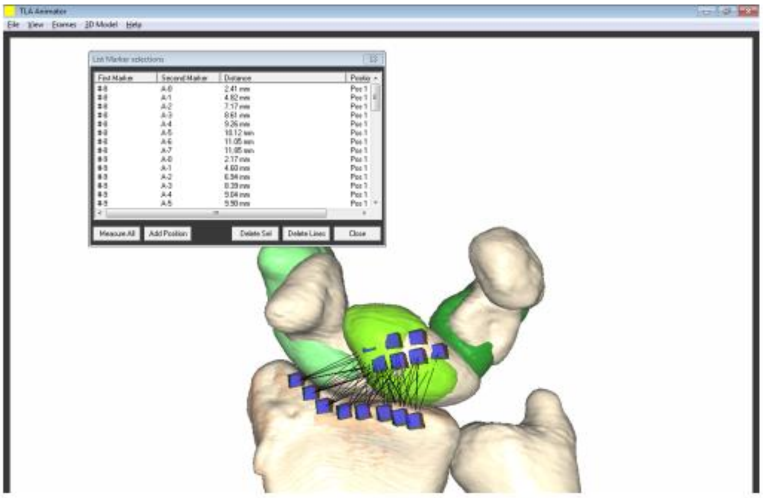
Figure 10. The 3D wrist model is imported and the non-target bones are hidden. Markers are applied to regions of interest on the bones of the position 1 model.



First Marker	Second Marker	Distance	Positio
B-8	A-0	2.41 mm	
B-8	A-1	4.82 mm	
B-8	A-2	7.17 mm	
B-8	A-3	8.61 mm	
B-8	A-4	9.26 mm	
B-8	A-5	10.12 mm	
B-8	A-6	11.05 mm	
B-8	A-7	11.85 mm	
B-9	A-0	2.17 mm	
B-9	A-1	4.60 mm	
B-9	A-2	6.94 mm	
B-9	A-3	8.39 mm	
B-9	A-4	9.04 mm	
B-9	A-5	9.90 mm	

Using the “Measure“ tool, we measure (in 3D – not just on the screen – very important point) between all the points on each bone.

Figure 11. The distances between all the markers on the regions of interest are measured.

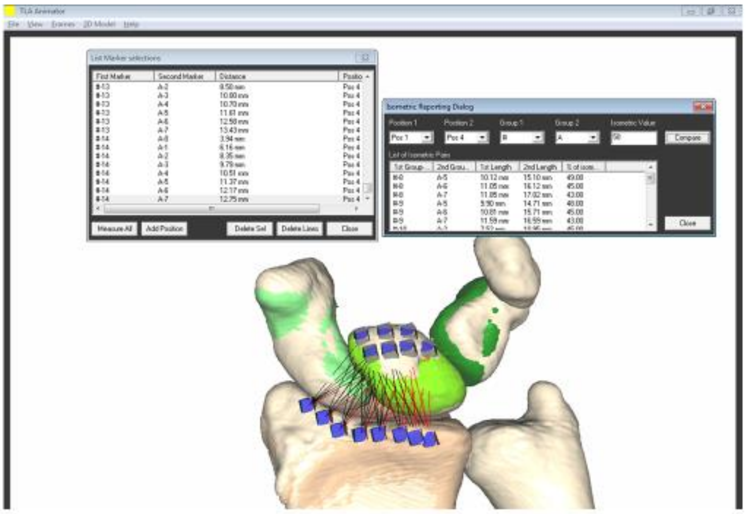


First Marker	Second Marker	Distance	Positio
B-8	A-0	2.41 mm	Pos 1
B-8	A-1	4.82 mm	Pos 1
B-8	A-2	7.17 mm	Pos 1
B-8	A-3	8.61 mm	Pos 1
B-8	A-4	9.26 mm	Pos 1
B-8	A-5	10.12 mm	Pos 1
B-8	A-6	11.05 mm	Pos 1
B-8	A-7	11.85 mm	Pos 1
B-9	A-0	2.17 mm	Pos 1
B-9	A-1	4.60 mm	Pos 1
B-9	A-2	6.34 mm	Pos 1
B-9	A-3	8.39 mm	Pos 1
B-9	A-4	9.04 mm	Pos 1
B-9	A-5	9.90 mm	Pos 1

Make the position 2 proximal row visible – green.

Manually align position 1 lunate (brown) with position 2 lunate (green).

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



First Marker	Second Marker	Distance	Positio
B-13	A-2	8.50 mm	Pos 4
B-13	A-3	10.00 mm	Pos 4
B-13	A-4	10.70 mm	Pos 4
B-13	A-5	11.61 mm	Pos 4
B-13	A-6	12.58 mm	Pos 4
B-13	A-7	13.43 mm	Pos 4
B-14	A-0	3.94 mm	Pos 4
B-14	A-1	6.16 mm	Pos 4
B-14	A-2	8.35 mm	Pos 4
B-14	A-3	9.79 mm	Pos 4
B-14	A-4	10.51 mm	Pos 4
B-14	A-5	11.37 mm	Pos 4
B-14	A-6	12.17 mm	Pos 4
B-14	A-7	12.75 mm	Pos 4

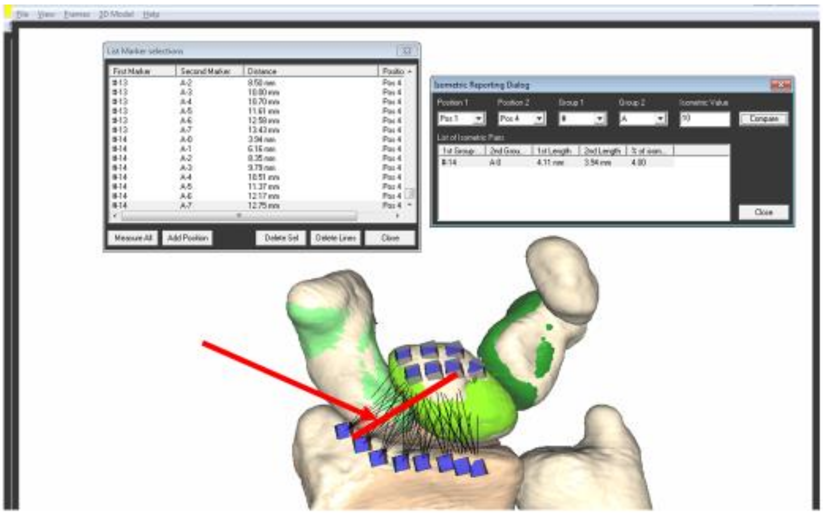
Position 1: Pos 1
Position 2: Pos 4
Group 1: B
Group 2: A
Isometric Value: 50

List of Isometric Pairs

1st Group ...	2nd Grou...	1st Length	2nd Length	% of isom...
B-8	A-5	10.12 mm	15.10 mm	49.00
B-8	A-6	11.05 mm	16.12 mm	45.00
B-8	A-7	11.85 mm	17.02 mm	43.00
B-9	A-5	9.90 mm	14.71 mm	48.00
B-9	A-6	10.81 mm	15.71 mm	45.00
B-9	A-7	11.59 mm	16.59 mm	43.00

If we look for those that vary by 50% we get a lot more – marked in red.

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



List Marker selections

First Marker	Second Marker	Distance	Positio
B-13	A-2	8.50 mm	Pos 4
B-13	A-3	10.00 mm	Pos 4
B-13	A-4	10.70 mm	Pos 4
B-13	A-5	11.61 mm	Pos 4
B-13	A-6	12.58 mm	Pos 4
B-13	A-7	13.43 mm	Pos 4
B-14	A-0	3.94 mm	Pos 4
B-14	A-1	6.16 mm	Pos 4
B-14	A-2	8.35 mm	Pos 4
B-14	A-3	9.79 mm	Pos 4
B-14	A-4	10.51 mm	Pos 4
B-14	A-5	11.37 mm	Pos 4
B-14	A-6	12.17 mm	Pos 4
B-14	A-7	12.75 mm	Pos 4

Isometric Reporting Dialog

Position 1: Pos 1
Position 2: Pos 4
Group 1: B
Group 2: A
Isometric Value: 10

List of Isometric Pairs

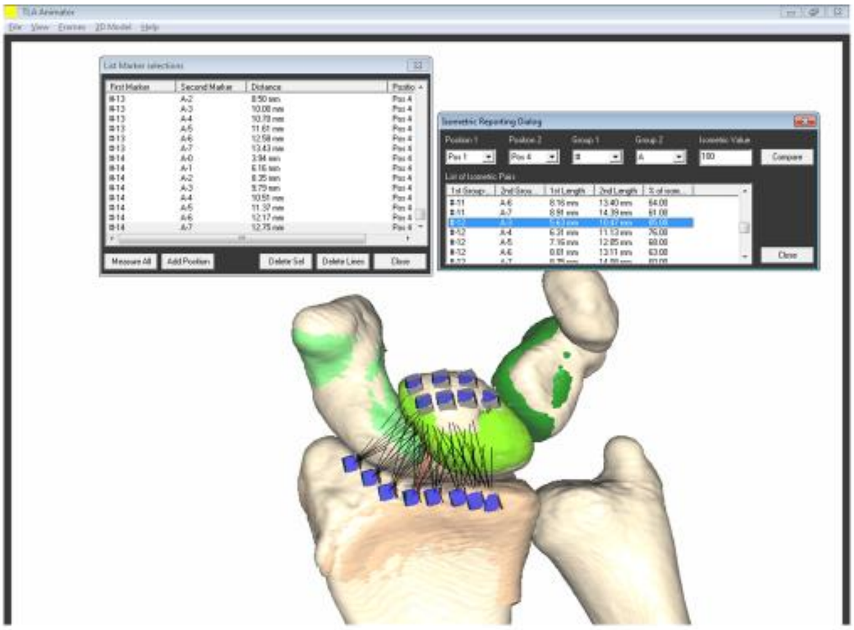
1st Group	2nd Grou...	1st Length	2nd Length	% of isom...
B-14	A-0	4.11 mm	3.94 mm	4.00

> Remeasure – same pairs, different lunate position

> Compare - looking for < 5% variation

Only one line (faint red line) – corresponding to the LRL!!

Figure 14. An isometric connection is one having less than 5% variation between the bone positions. This corresponds to the LRL (long Radio-lunate ligament).



List Marker selections

First Marker	Second Marker	Distance	Positio
B-13	A-2	8.50 mm	Pos 4
B-13	A-3	10.00 mm	Pos 4
B-13	A-4	10.70 mm	Pos 4
B-13	A-5	11.61 mm	Pos 4
B-13	A-6	12.58 mm	Pos 4
B-13	A-7	13.43 mm	Pos 4
B-14	A-0	3.94 mm	Pos 4
B-14	A-1	6.16 mm	Pos 4
B-14	A-2	8.35 mm	Pos 4
B-14	A-3	9.79 mm	Pos 4
B-14	A-4	10.51 mm	Pos 4
B-14	A-5	11.37 mm	Pos 4
B-14	A-6	12.17 mm	Pos 4
B-14	A-7	12.75 mm	Pos 4

Isometric Reporting Dialog

Position 1: Pos 1
Position 2: Pos 4
Group 1: B
Group 2: A
Isometric Value: 100

List of Isometric Pairs

1st Group	2nd Grou...	1st Length	2nd Length	% of isom...
B-11	A-6	8.16 mm	13.40 mm	64.00
B-11	A-7	8.91 mm	14.39 mm	61.00
B-12	A-3	5.63 mm	10.47 mm	85.00
B-12	A-4	6.31 mm	11.13 mm	76.00
B-12	A-5	7.16 mm	12.05 mm	68.00
B-12	A-6	8.01 mm	13.11 mm	63.00

The SRL would vary by 85%.

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

Mechanical challenges of the wrist

The question again arises: ‘Why has the wrist been so difficult to sort?’

The empirical approach has been flawed: no standard or average wrist has been characterised because 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 but perform basically the same functions and tasks.

This project adopted an alternate conceptual or theoretical approach. In this process, relatively general observations are made of the motion system and a basic theory is proposed for how they could be explained. This provides a clear hypothesis for testing and the theory is thereby validated, enriched or rejected. However, 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. These are detailed in Figure 16.

What are the requirements of the wrist?

1. **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 2nd/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 requirements 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 seven basic mechanical capabilities that are required for the wrist to perform its functions are that it:

1. provide 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. provide an oblique power grip to improve holding, thrusting and throwing (achieve CO-LINEAR PALM AND FOREARM DURING USE—so-called dart throwers motion)
6. support independent finger and wrist motion
7. ensure low-profile distal extremity.

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

Given these challenges, a more effective platform to analyse the anatomical capability of the carpus was required. The development of suitable technology (True Life Anatomy 3D animation software) enabled further analysis and allowed us to proceed on the journey of characterising the mechanics of the carpus, with the ultimate aim to identify solutions to address the dysfunctional wrist.

Summary

The wrist remains a challenge with respect to its 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). However, it expands this basic notion to incorporate the concept—or maybe 'law'—of Rules Based Motion, which states that a motion system, particularly the wrist, can be defined and controlled by its four 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 an approach that was different from how carpal research was typically being conducted and, rather than utilising the standard empirical study design, to use a conceptual research strategy. The experimental design involved making a limited number of observations of the mechanics of the wrist and then proposing 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 law, states that the performance of a mechanical system is the net interlay of its various components. While each could vary, such variation is offset by the compensatory adjustment of the other component to create the appropriate net outcome.

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

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. implement the reconstructive solution and follow the clinical outcomes for a minimum of two years.

The paper published by Drs Sandow and Fisher ('Anatomical Volar and Dorsal Reconstruction - ANAFAB) for Scapho-lunate dissociation') in the *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.

Prior Works included in the PhD Thesis

The following papers and presentation were included in the original PhD Thesis by Prior Publication. This research constitutes the investigational background upon which the claims and contents of the discussion were based.

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 19 September 2019)

2. United States Patent 7,236,817-B2 Granted: 26th June 2007
   https://patents.google.com/patent/US7236817 (accessed 19 September 2019)

3. 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. 2014, 39(4): 353–63.

4. Sandow M. The why, what, how and where of 3D imaging. J Hand Surg Eur. 2014, 39(4): 343–45.

5. Sandow MJ. 3D Dynamic Analysis of the Wrist. Hand Surg. 2015 Oct;20(3):366–68.

6. Sandow MJ. Computer modelling of wrist biomechanics – translation into specific tasks. Curr Rheumatol Rev. 2019, Jan 18. doi: 10.2174/1573397115666190119095311.

7. Sandow MJ, Fisher TJ. Anatomical volar and dorsal reconstruction (ANAFAB) for scapho-lunate dissociation. J Hand Surg Eur. 2020 May;45(4):389-395.
   doi: 10.1177/1753193419886536. Epub 2019 Nov 13.

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. J Wrist Surg. 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)

2. 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)

3. 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)

4. 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 11 March 2019)

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

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
(accessed 11 March 2019)

Synopses of Prior Publications and Presentations

The following publications are cited and summarised 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, identifying 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. implement such a reconstructive solution and follow the clinical outcomes for a minimum of two years.

The paper published by Drs 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 in wrist biomechanics and represents more a revolution rather than an evolution. Given the challenges to the existing reconstructive option, it is potentially disruptive rather than adaptive.

The conceptual research approach used in this project focuses on using limited observational data to develop the theory that attempts to explain or describe the phenomenon of wrist functioning. The concepts of reverse engineering, Rules Based Motion and 'what if' reanimation are outlined in the filed patents. Through a process of hypothesis testing, the stable central column theory was defined, enriched and validated.

By proposing and defining a possible explanation for how the wrist works at the start of the project, this work was able to follow an orderly and directed investigative pathway. 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 bear a remarkable resemblance to the figures in the original 2001 patent.

In lieu of presenting the papers themselves, this monograph includes summaries highlighting the key findings of each.

Patents: Development of animation technology to model bone movement

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 19 September 2019)

United States Patent 7,236,817-B2;
Granted: 26 June 2007
https://patents.google.com/patent/US7236817 (accessed 19 September 2019)

Animation technology simulates the 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, protection of the IP was required to mobilise the investment required to develop the software to spatially analyse the multipositional 3D objects. More importantly, the characterisation of proposed important isometric constraints, including the previously underappreciated long radiolunate ligament, could be time stamped.

This work describes a novel method for creating an animated image of the bones of a body part. The steps involve converting volumetric data (CT of MRI) into 3D objects, and then identifying isometric connections by comparing the relationship between various regions on pairs of bones in different motion positions (Figure 17). The next stage in the development of the technology was to reapply the various components or rules of the system to create motion based on its own biomechanical constraints and interactions, with the potential to perform a 'what if' modification. This allows the user to test possible surgical reconstructive solutions specifically configured to address the unique biomechanical characteristics of an individual injured wrist. This was one of the first examples of quantitative 3D analysis to define the controllers or rules of a motion system (reverse engineering/analysis kinematics) and to then reapply the identified rule (forward engineering/forward or synthesis kinematics) to create rules-based motion of the dynamic system.

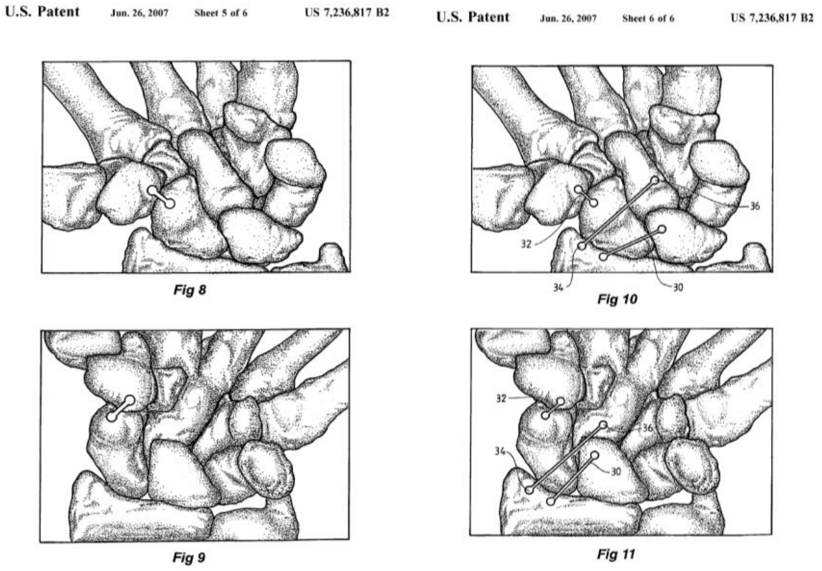


Figure 17. Connectivity between bone pairs predicted using animation technology (US Patent 7,236,817-B2) (Papas and Sandow 2007).

Paper: The Stable Central Column Theory

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): 353–63.

This study was the critical step to transition the theoretical concepts contained in the initial patent to a formalised theory that could 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 10 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 and controls lunate flexion. The trapezoid-shaped trapezoid bone 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.

Paper: Comparison and explanation of 3D imaging techniques

Sandow M. The why, what, how and where of 3D imaging. J Hand Surg Eur Vol. 2014, 39(4): 343–45.

Access to a 3D imaging environment offers considerable advantages in diagnosis, planning and treatment. However, it may be confusing due to misunderstandings of what 3D imaging is, what true 3D interactivity is and what a 3D object is: what may appear to be 3D is really more like a projected shadow. The capture of volumetric 3D data using computed tomography (CT) and magnetic resonance imaging (MRI) traditionally transforms these data into a 2D planar representation to allow a greater appreciation. However, to improve a clinician's 3D comprehension, they need an appreciation of the patho-anatomy in 3D and must be able to access and interact with image data within a 3D environment. Thus, there are a number of challenges in the successful utilisation of 3D technology. These can be explained and contextualised as the 'why, what, how and where' of 3D imaging.

The answer to '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. This paper presents the advantages of both 3D image creation modalities. It also places the strengths and weakness in context and is supported by comments 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.

Each way of presenting the 3D data set has advantages and disadvantages 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 its size, 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. However increasing requirements for interaction and planning in 3D will only be addressed by wider availability of such technology in the usual clinically relevant image delivery pathways.

Paper: Dynamic 3D analysis of the wrist

Sandow MJ. 3D Dynamic Analysis of the Wrist. Hand Surg. 2015, 20(3): 366–68.

New advances in imaging and computing technology continue to support greater capacity to diagnose, plan and deliver care to patients with hand and wrist disorders. This paper presented an update on our work to identify certain specific rules and factors that control wrist motion. The ability to extract the isometric constraints of a particular motion system substantially increases the long-term capability to provide quantitative diagnosis of (particularly) joint injuries. In combination with finite element analysis, this technology allows users to pre-test various operative solutions and then to assess whether the outcomes match the predictions.

Paper: Computer modelling of wrist biomechanics

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 challenging mechanical system and advancements in its 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 of Moritomo et al (2006) and others, but identifies that each row moves 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, by applying the Rules Based Motion concept to particular patient’s unique wrist anatomy, a forward synthesis mathematical model to reproduce the individual’s carpal motion in a virtual environment could be created.

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. 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 visualisation 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 to 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 lateral pivot joint (between the trapezium and scaphoid) and a medial saddle joint (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 positions required in wrist function. Upon 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 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 CT scan 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.

Paper: Anatomical volar and dorsal reconstruction (ANAFAB)

Sandow MJ, Fisher TJ. Anatomical Volar and Dorsal Reconstruction (ANAFAB) For Scapho-lunate dissociation. J Hand Surg Eur. In press October 2019, published May 2020.

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. Now, based on a better understanding of the mechanics of the wrist and the SCCT, this work reports 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 that is also based on published kinematic evidence. It aims to restore the anatomical mechanical constraints on both anterior and posterior aspects of the carpus. Patients were immobilised in a cast for 6 weeks, but no stabilising wires were used. A total of 10 patients underwent the reconstruction and were assessed at a minimum 24-month follow-up. They achieved excellent realignment of the carpus, a post-operative median scapho-lunate gap of 3 mm and the recovery of more than 75% of grip strength and range of motion. No patient required secondary surgery or treatment related to the carpal stabilisation.

The ANAFAB procedure appears to be able to reverse the scapho-lunate diastasis and proximal scaphoid subluxation while still retaining 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 to the carpus without a significant loss of motion and indicates the successful restoration of functional carpal biomechanics.

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, measuring the motion of various wrist components in both in vitro and in vivo situations, then attempting to sort the motion into patterns of movement – given the variation in wrist anatomy between individual.. An alternative strategy to resolve this dilemma is to abandon the exhaustive measurement of bone movement and forlorn attempts to identify patterns and instead, follow an approach that assesses what the wrist actually does and, conceptually, how. This migration from largely empirical to conceptual research was key to the success of this project.

The human wrist function is unique and places us at a distinct advantage when interacting with the environment. The wrist can be characterised as having three principal functional requirements to (Figure 16):

1. stably position the fingers and palm for holding, grasping and throwing
2. support the second and third metacarpals as a stable central functional axis that is acted on by mobile thenar and hypothenar metacarpal anatomical units
3. provide rotational and oblique gripping power that 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 18). 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).

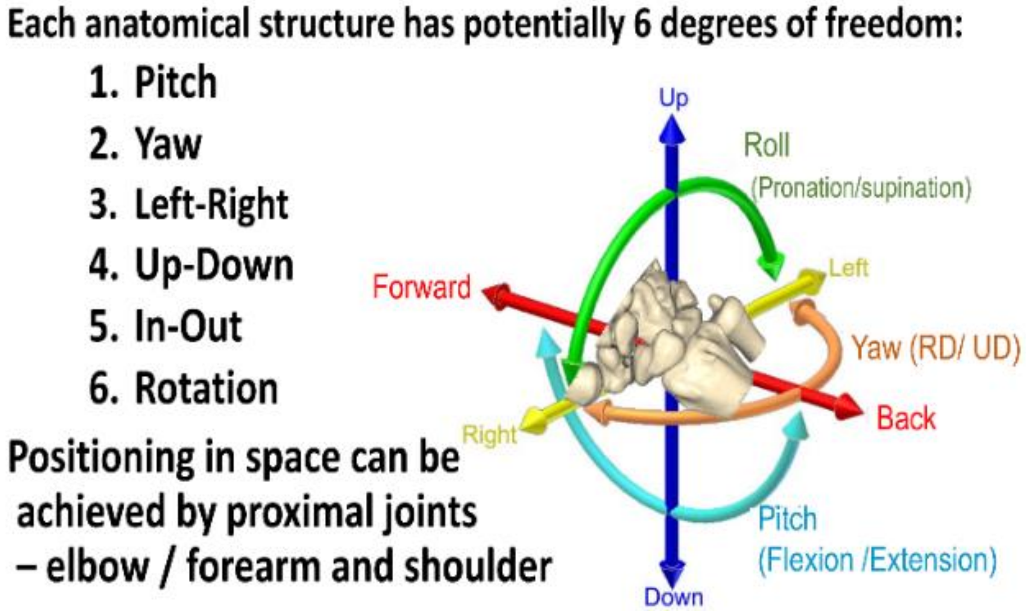
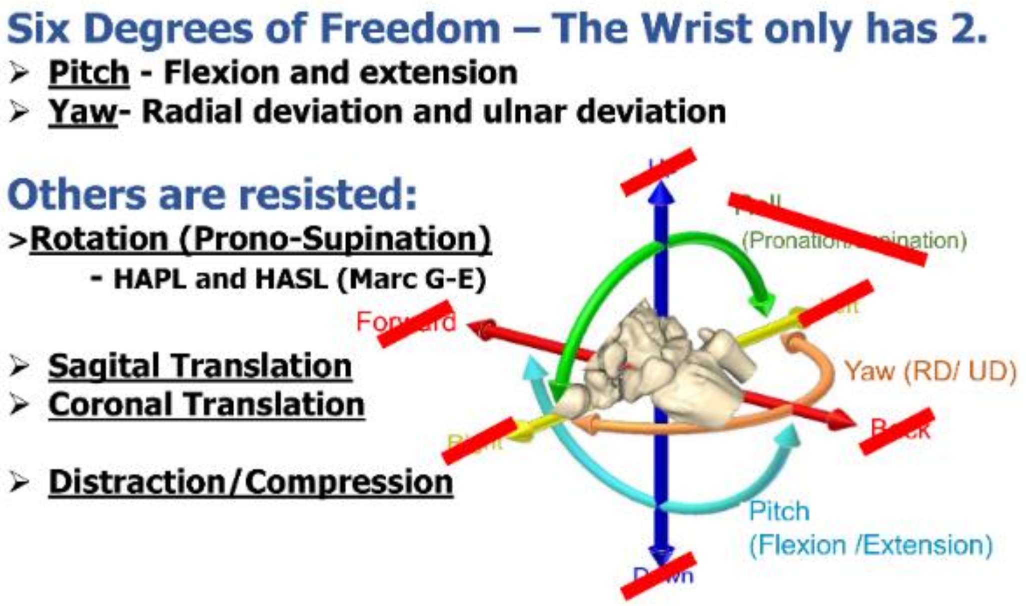


Figure 18. Potential degrees of freedom in the wrist.

The actual degrees of freedom in the wrist are not uniformly accepted and Garcia-Elias (2008) strongly contends that the wrist has actively controlled and resisted pronation and supination. However, Sandow et al. (2014) argue that active control of carpal rotation is unlikely, 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 to deliver the rotational power generated by powerful muscles in the proximal forearm to the metacarpals.

The wrist has two degrees of freedom: pitch (flexion/extension) and yaw (radial and ulnar deviation). All other movements are resisted, including rotation (prono-supination) (Figure 19). 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.



Six Degrees of Freedom – The Wrist only has 2.

- **Pitch - Flexion and extension**
- **Yaw- Radial deviation and ulnar deviation**

Others are resisted:

>Rotation (Prono-Supination)
  - HAPL and HASL (Marc G-E)

- **Sagital Translation**
- **Coronal Translation**

- **Distraction/Compression**

Figure 19. Two degrees of freedom in the wrist. Of the six potential degrees of freedom, the wrist has only two: pitch (flexion and extension) and yaw (radial and ulnar deviation). All other degrees are resisted by a combination of bone shape and ligament attachments. HAPL – helical anti-pronation ligament; HASL – helical anti-supination ligament (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 a reduced wrist profile to increase its function but still provides sufficient power. This will be discussed further in subsequent sections.

It has been stated that ‘form follows function’; however, it certainly appears that form enables function in the wrist. While each wrist is different, the function itself is generally consistent.

Basic functional requirements

There are seven mechanical prerequisites that the wrist must fulfil to achieve its function:

1. provide adequate flexion and extension for holding and pushing (FLEXION/EXTENSION)
2. allow adequate side-to-side rotation motion for holding different angles (RADIAL/ULNAR DEVIATION)
3. provide powerful rotational force delivery by resisting rotation through the radio-carpal joint (RESIST ROTATION)
4. resist translation in coronal, sagittal and transverse planes (RESIST TRANSLATION/COMPRESSION/DISTRACTION)
5. provide oblique power grip to improve holding, thrusting and throwing (ACHIEVE CO-LINEAR PALM AND FOREARM DURING USE)
6. enable independent finger and wrist motion
7. ensure low wrist profile in the distal extremity to increase functionality.

These mechanical prerequisites 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 bone, limiting the extent of surface articulation. Further, there are no true axles in the human body and certainly no central pivot points, so bones must only be connected by some form of external linkage. Further to this, there is substantial anatomical variation between the various bones.

Current carpal motion theories fail to generate consensus among researchers, are largely observational (and thus, poorly predictive) and are generally unable to test the effect of an 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'. This is also supported by the work of 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 no average or 'typical' wrist. A way forward may be to identify a generic wrist that includes the various bones, which have 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 basis 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 (Sandow et al. 2014). Therefore, wrist biomechanics are 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 change will be matched by corresponding adjustments in the other components to create the same net outcome (Figure 20).

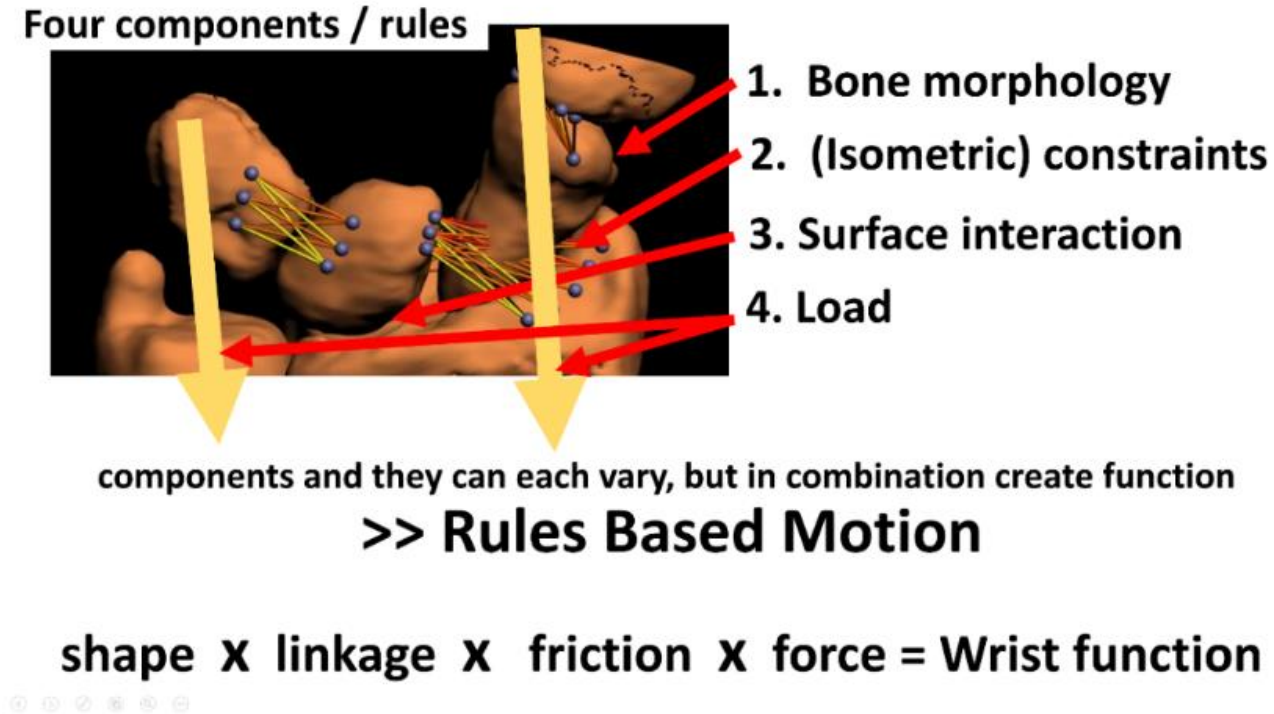


Figure 20. Rules Based Motion. There are four components or rules within a motion system (e.g., the wrist) and each can vary. This individual component variation is offset or matched by changes in the other rules, which creates a consistent net biomechanical outcome to achieve the required wrist function.

Considering this background, the defined seven mechanical prerequisites of the wrist can be explained in sequence.

1. Provide adequate flexion and extension for holding and pushing

Given the biological constraints (e.g., vascular input), a single linkage within the wrist could probably only achieve approximately 45 degrees of movement in each direction or an approximate 90-degree motion arc. The wrist requires 180 degrees of motion; therefore, a single linkage is inadequate and a double linkage is likely required to achieve 90 degrees of both flexion and extension.

This will produce a potentially unstable proximal row but also requires a smooth transition between flexion and extension. Mechanically, this could be achieved using a series of cylinders that each have a single axle (Figure 21). 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. The assumption that the distal row moves as one was tested early in the project, around 1999. The distal row was segmented as a single 3D object in both radial and ulnar deviation. The two objects (distal row 3D models) were then registered (i.e., aligned) and there was no discernible variation between the shape or relationship of the components. On this basis, it was assumed that the original postulations of Taleisnik (1976) are valid.

Figure 21. The Wakefield Carpal 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 22). However, the substantial biological constraints noted previously mean that this is not possible through non-biological axles.

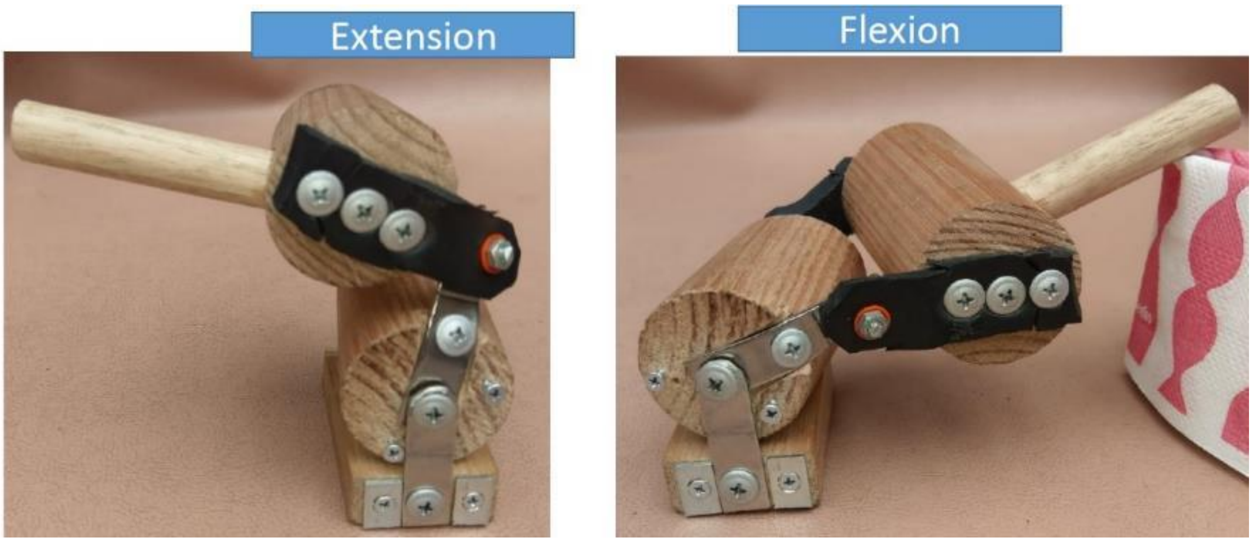


Figure 22. Wakefield Dowel Model showing both dowels moving in the same direction to achieve an adequate flexion and extension range.

Sandow et al. (2014) demonstrated a clear pattern of connections between the various bones of the carpus. Thus, 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 are controlled by external linkages in the form of ligaments (Figures 23–24), 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 (Figure 24).

This implies that the bones of the proximal row can only move in a single direction which is the same for both sagittal or coronal motion.

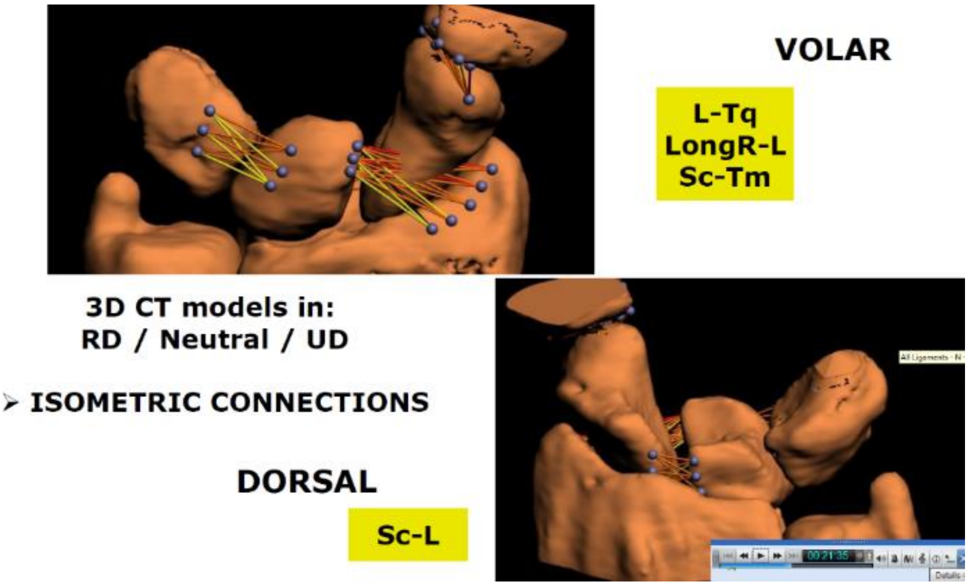


Figure 23. Isometric connections between and within the proximal carpal row and the radius. RD (Radial deviation), UD (Ulnar deviation).

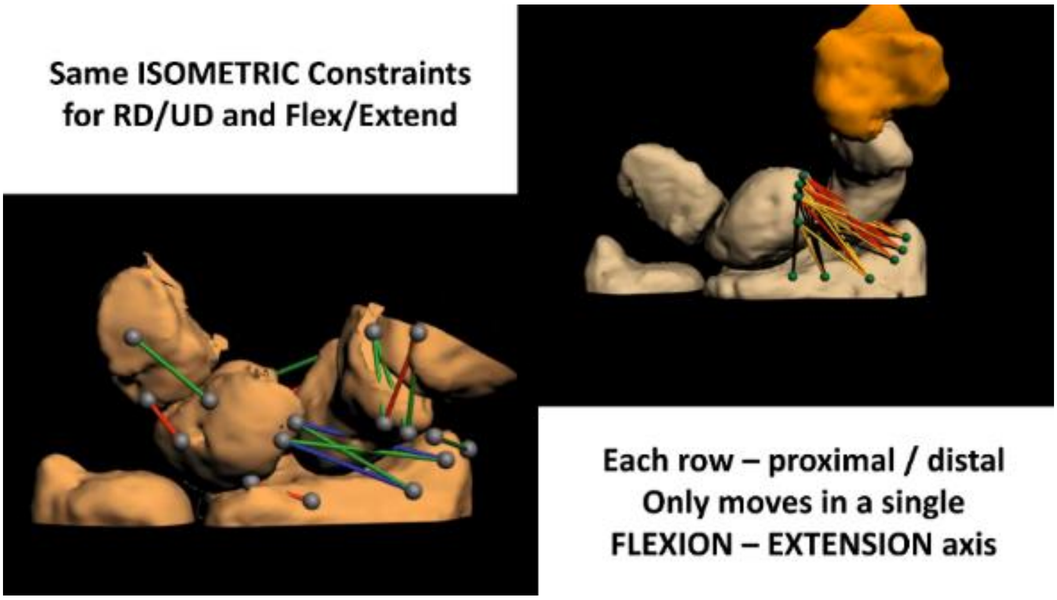


Figure 24. Clear connections between proximal carpal bones and the radius were demonstrated by Sandow et al. (2014) and allow notional flexion and extension of the proximal row without a central axle. Green and Yellow lines indicate the most isomeric connections. Isometric connections are the same for 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 proximal and distal rows can therefore be stylized as consisting of cylinders, having a single axis of rotation, but controlled by external linkages (Figures 25). Flexion is achieved by both rows moving into flexion, and extension is achieved by both rows moving into extension. The axis of rotation of each row is relatively in line or parallel.

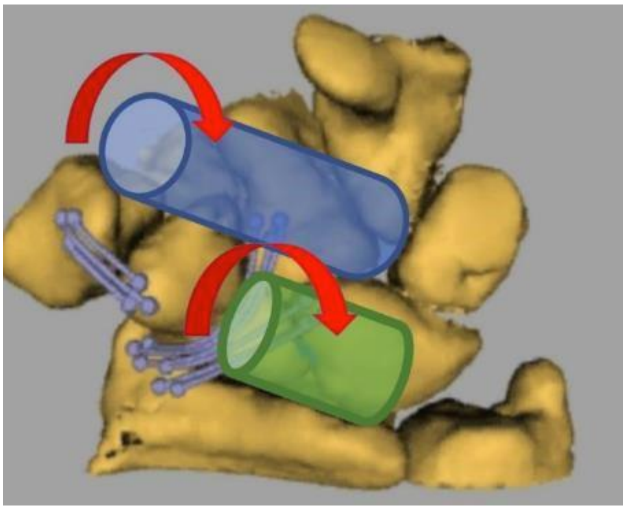


Figure 25. Proximal and distal carpal rows stylised as single-axis cylinders. Each cylinder moves in the same direction to achieve flexion or extension.

This process readily explains the process that achieves an adequate range of flexion and extension. The flexor and extensor tendons act on the distal row and the proximal acts as an intercalated segment that is controlled by external linkages. Motion is achieved through 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 for holding different angles

The fixed-position single-axis cylinders discussed above would achieve an adequate range of flexion and extension, but would not provide the offset motion required for radial and ulnar deviation. The wrist cannot be a universal joint, as this would be rotationally unstable. Pronation and supination motion only occur through the radio-ulnar joints, not the radio-carpal. The carpus uses the radius as the fixed reference and rotation is excluded as a degree of freedom—although it is used in some situations to describe the position of one part of the carpus with another. In this context, the terms pronation and supination are used to describe axial alignment, not a dynamic degree of freedom.

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 rotational axis of the distal row. The mechanical arrangement that would allow this motion would require the proximal dowel to retain its single arc of motion in the same axis and that 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, but the ‘ulnar’ side can move to change the offset of the two dowels. Thus, each dowel still only moves in a single arc, but their axes can be variably offset.

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 24). 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.

The lines depicted in Figures 23 and 24 show degrees of isometricity, with green and yellow indicating a 5% length variation during motion. The software measurement is only ‘line of sight’. Some of the initial work did create 3D models of ‘rope’ to represent 3D ligaments as objects that could adopt a convex path. This process is currently under development but is beyond the capabilities of the current TLA program. In virtually all situations, the occasional convex shape of the ligament as it passed over the carpal bones had relatively little effect on the ultimate length, given the minimal degree of non-linearity, although it is reflected in an isometry acceptance of around 10% rather than 5%.

By then changing the offset, and having each dowel move in an opposite direction, side-to-side motion can be achieved (Figure 26-28 and, later, Figure 29). 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 26-28).

Figure 26. Wakefield Carpal Model showing radial (RD) and ulnar (UD) deviation. Offset of the axes of each 'row' is achieved through the variable pivot point on the ulnar side with the cylinders/dowels moving in opposite directions.

Again, as noted previously, this mechanical modelling using the linked dowels is not valid. This movement is not possible in the biological world because there are no axles and the bones are constrained by external ligaments. This has been demonstrated in the computational isometric connections. This more realistic motion sequence is stylised as the single axis cylinders moving in opposite direction, and with offset axes (Figure 26 and 27). The anterior and posterior shift of the triquetrum changes the medial pivot point of the distal row to change the interrow axis offset.

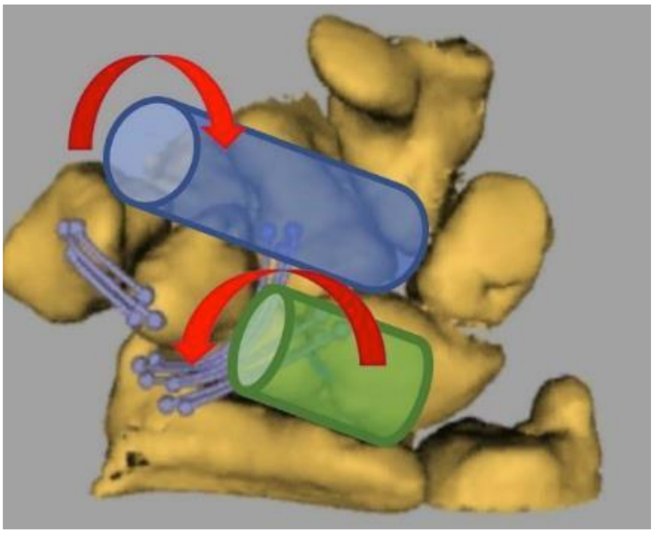


Figure 27. Proximal and distal carpal rows stylised as single-axis cylinders. The cylinders move in opposite directions to achieve radial and ulnar deviation. Isometric connections are the same for radial and ulnar deviation and for flexion and extension, indicating that each row has a unitary arc of motion with respect to its caudal neighbour.

Although wrist could be stylised as a series of proximal and distal cylinders (Figure 27), with the dynamic modelling capabilities of the TLA software, the motion of the wrist can be more realistically analysed by moving a 3D model of each row sequentially. This is artificial, as each row would move concurrently, making it difficult to appreciate the specific relationship of the rows in motion. Figures 28A–I demonstrate the stylised sequential motion of the wrist in flexion and radial and ulnar deviation. Here, the mobile carpal bones are segmented and graphically manipulated to move sequentially, first proximal row then distal row, to simulate the motion that occurs during coronal and sagittal movement.

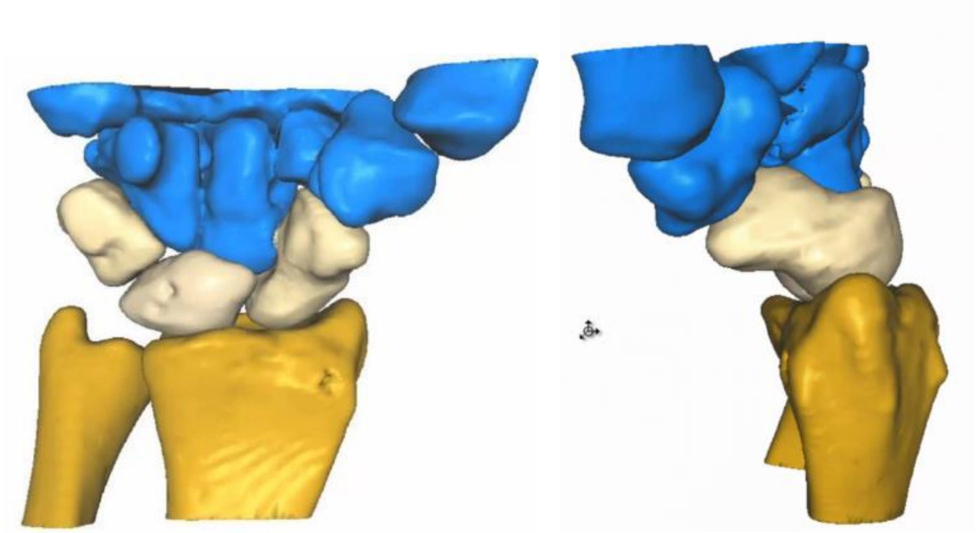


Figure 28A. 'Generic' wrist 3D model in neutral position, separated into radius and ulnar (tan), proximal row (brown) and distal row (blue).

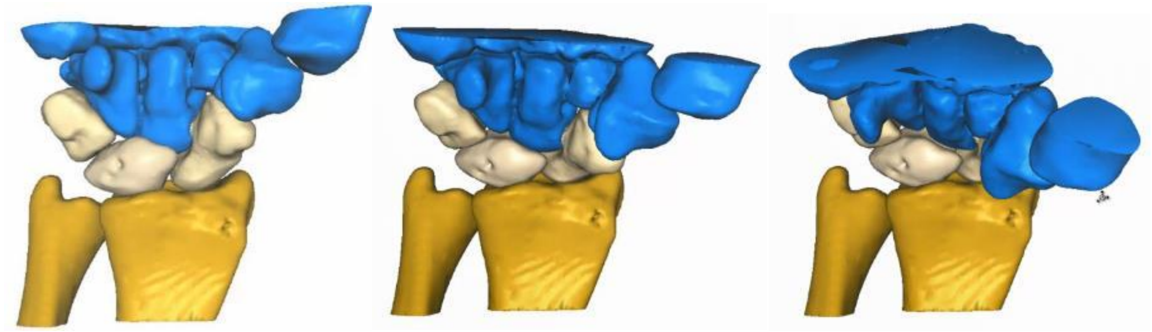


Figure 28B. Wrist flexion, anterior view, showing the (left) neutral position, (middle) proximal row flexed and then (right) distal row flexed.

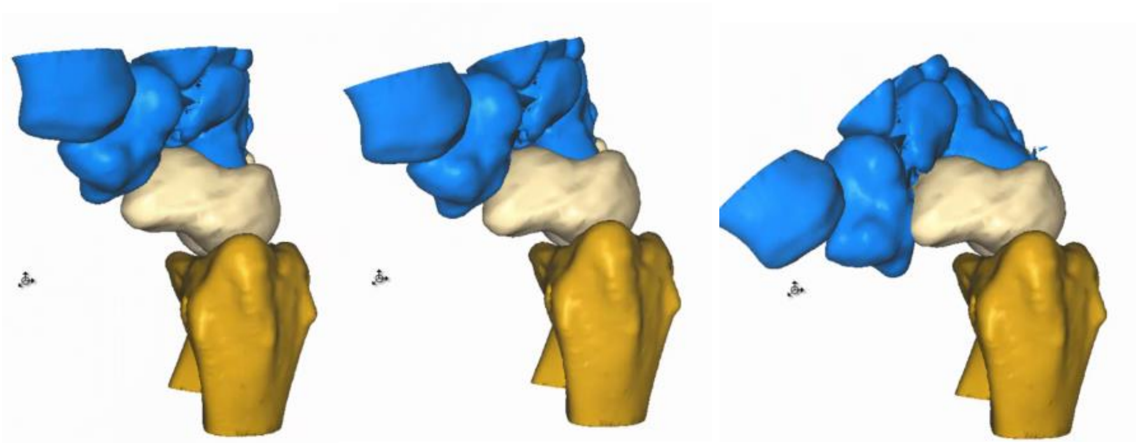


Figure 28C. Wrist flexion, lateral view, showing the (left) neutral position, (middle) proximal row flexed and then (right) distal row flexed.

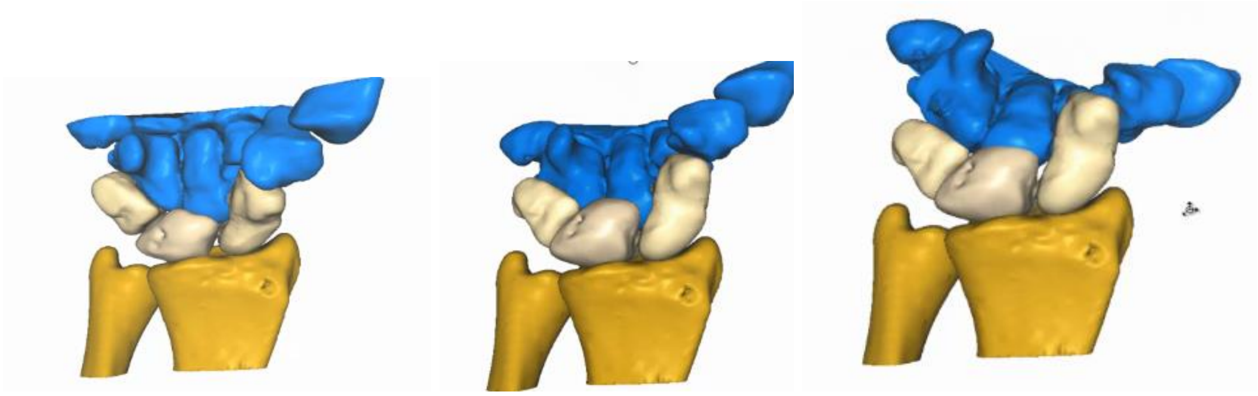


Figure 28D. Wrist extension, anterior view, showing the (left) neutral position, (middle) proximal row extended and then (right) distal row extended.

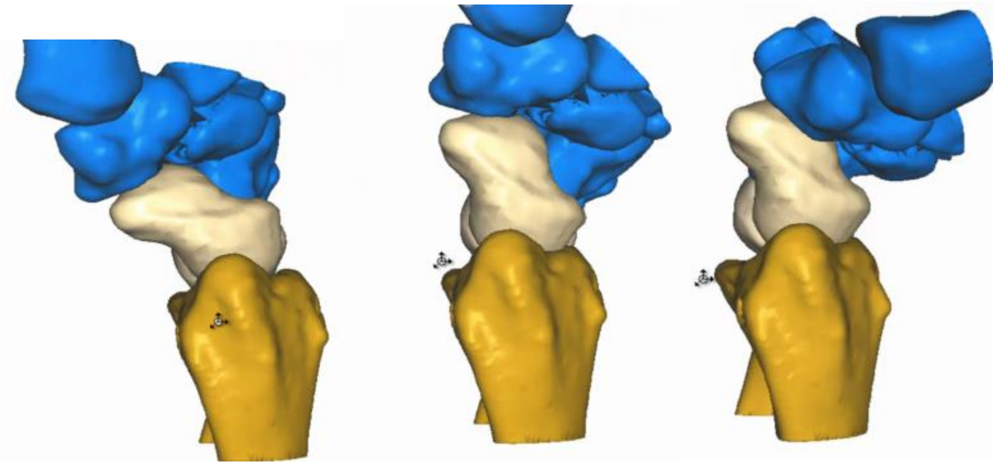


Figure 28E. Wrist extension, lateral view, showing the (left) neutral position, (middle) proximal row extended and then (right) distal row extended.

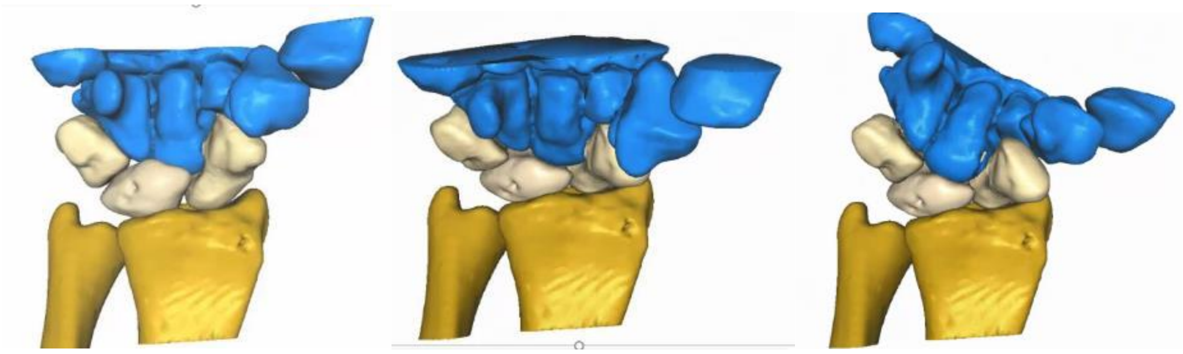


Figure 28F. Wrist radial deviation, anterior view, showing the (left) neutral position, (middle) proximal row flexed and then (right) distal row extended.

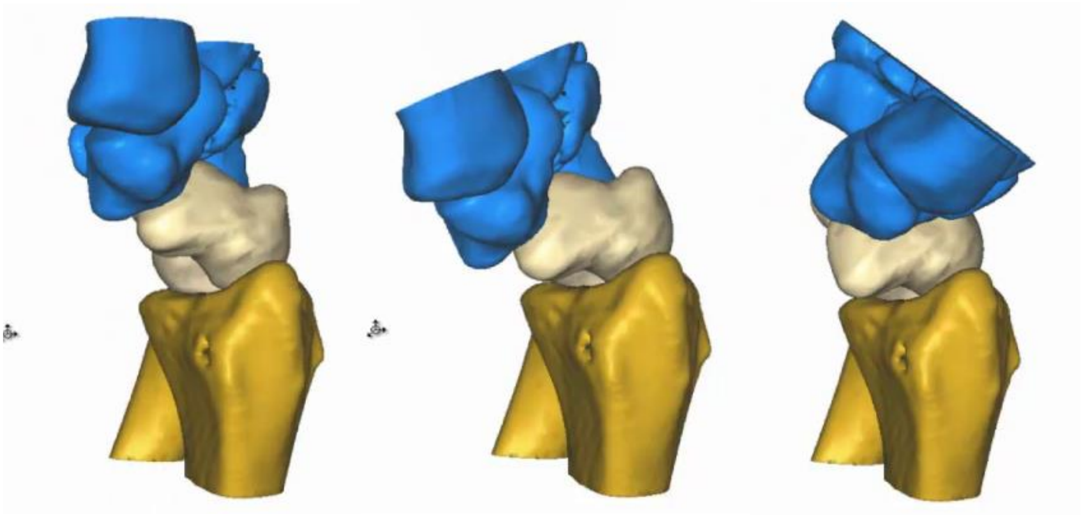


Figure 28G. Wrist radial deviation, lateral view, showing the (left) neutral position, (middle) proximal row flexed and then (right) distal row extended.

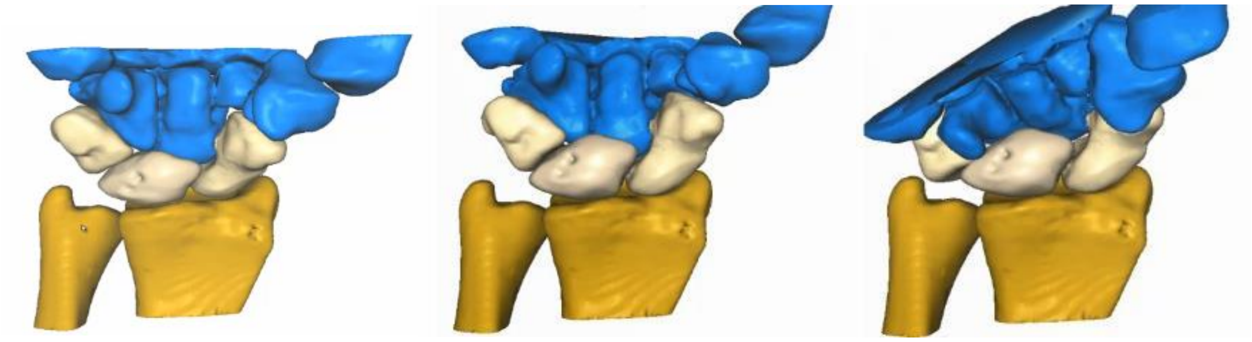


Figure 28H. Wrist ulnar deviation, anterior view, showing the (left) neutral position, (middle) proximal row extending and then (right) the distal row flexing.

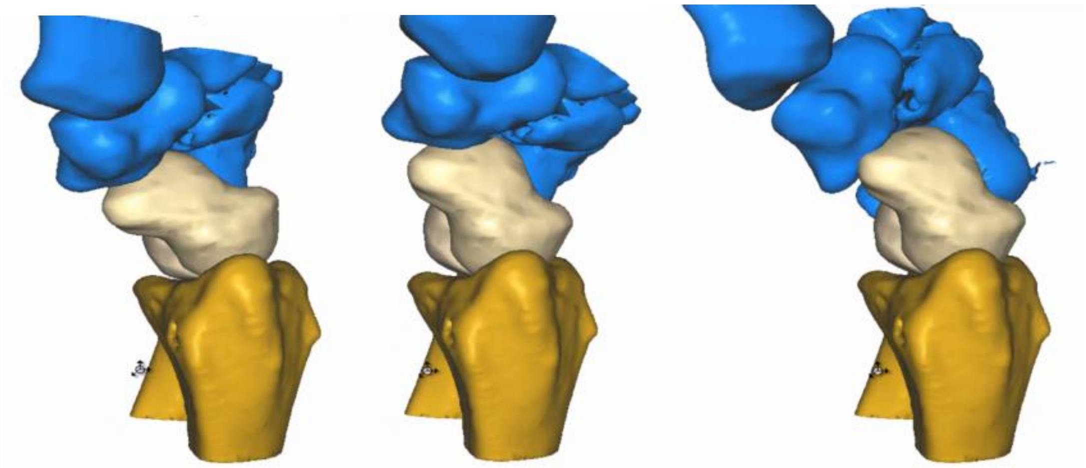


Figure 28I. Wrist ulnar deviation, lateral view, showing the (left) neutral position, (middle) proximal row extending and then (right) the distal row flexing.

In summary, the wrist notionally consists 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 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 29).

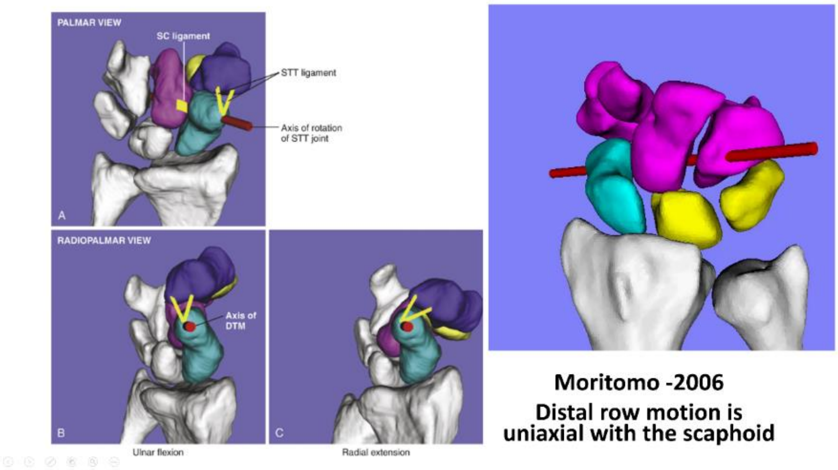


Figure 29. The distal row is linked to the proximal row (Moritomo et al. 2006).

Thus, the carpus can be seen as two carpal rows that are linked, but variably offset. Each only moves through a single arc of motion, but the combined binary output of the variable offset alignment creates the required two degrees of freedom (Figure 30).

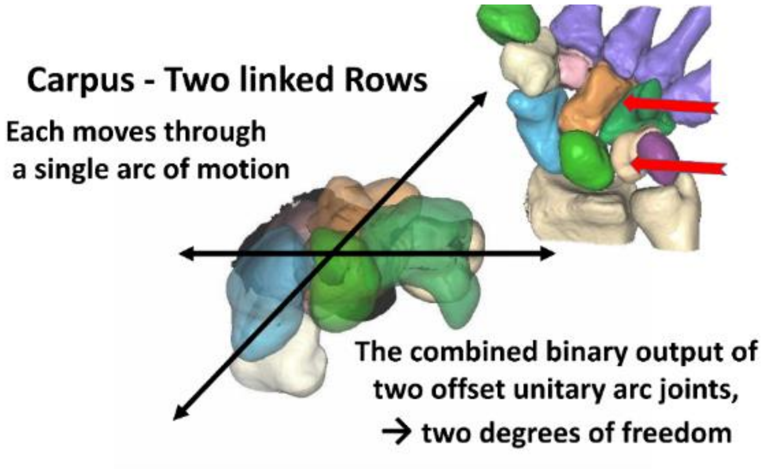


Figure 30. The wrist can be viewed as two linked rows. Each row moves in a single arc of motion. The binary output of the two offset joints creates the required two degrees of freedom (Sandow et al. 2014).

The pivot points between the proximal and distal rows are the key to understanding the wrist's ability to create 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 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 and thus, supports the offset binary motion of the two rows (Figures 31A and B)

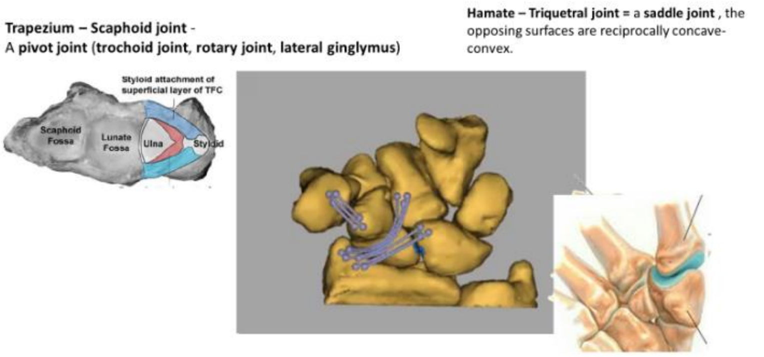


Figure 31A. The connection between the distal and proximal rows on the radial side. Here, the connection forms a pivot point similar to the distal radio-ulnar joint—a trochoid, rotatory or ginglymoid joint.

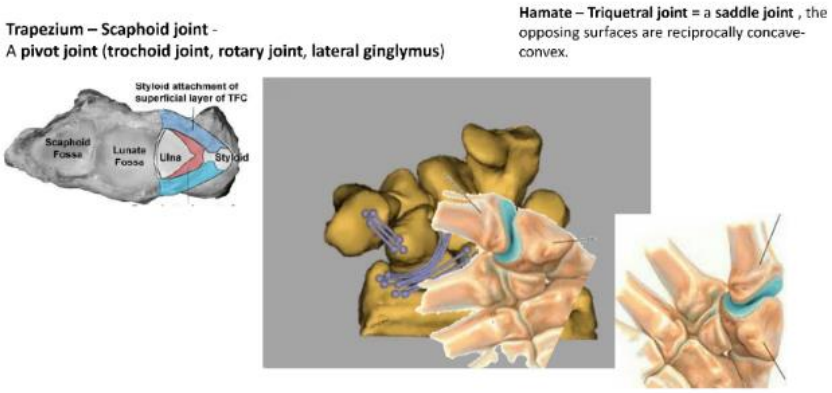


Figure 31B. The connection between the proximal and rows on the medial aspect. Here, the rows are connected by a saddle joint, much like the basal joint of the thumb.

The proximal and distal rows are joined in the form of two-gear four-bar linkage. These connections are well described in other anatomical systems and create a powerful link between the rows (Figure 32). The gear in one of the bars can reconcile the change in the distance between the centroids of the proximal and distal rows. The carpal rows, wide stable and rigid under load do not form a simple four-bar linkage.

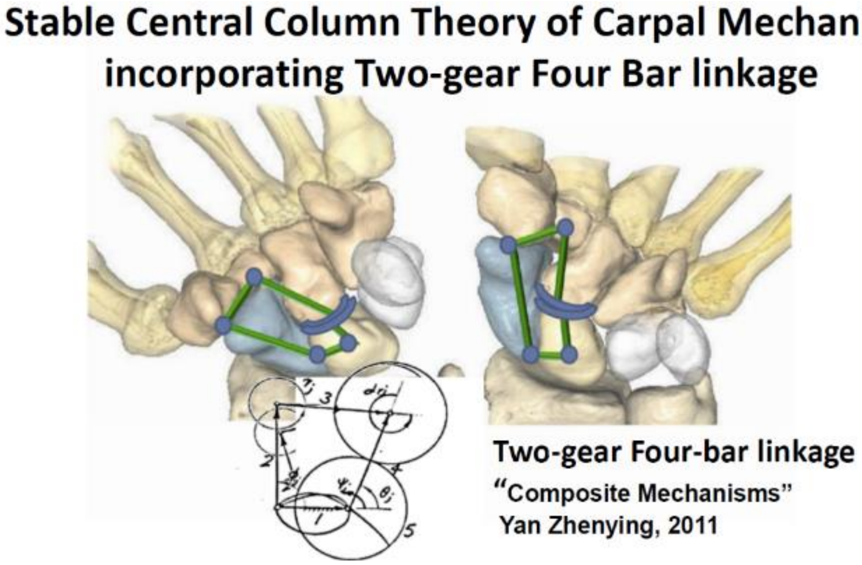


Figure 32. Two-gear four-bar linkage (Sandow et al. 2014).

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 agree 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 of Sandow et al. (2014), they (Akhbari et al. 2019) demonstrated that the bones of the distal row move largely as a single unit during wrist motion. They further identified greater differential motion between bones of the proximal row in different wrist arcs of motion; however, when moving in a specific anatomical axis, the differential intra-row intercarpal 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 across each of the two degrees of freedom. This allows the axis 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 SCCT, the lunate is placed between the scaphoid and triquetrum. It is attached firmly to only one side of the adjacent bone—to the scaphoid dorsally and the triquetrum volarly. This alternating attachment of the inter-row intercarpal ligament (presented later in Figures 42 and 43) 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. However, what must be stressed is that while these articulations can be described as a notionally consistent linkage, there is considerable variation in terms of the actual angles of displacement and the specific axes of rotation. Nevertheless, the concept of Rules Based Motion provides the justification for acceptance and, perhaps, the means to explain how there can be such variation in the actual individual carpal bone motion and yet the 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, particularly wrist, is generally perpendicular to the motion vector. To avoid extremity bulk, the location of such rotational loading via strong muscles cannot be at the level of the wrist. A joint such as the hip, which is largely a universal joint, has large muscles to control its rotation; however, these would make the wrist dysfunctionally bulky and therefore, the delivery of rotational power must be more proximal. This is achieved by the arrangement of the carpal ligaments to prevent rotation. As the forearm rotates—and the radius rotates around the ulna—the carpus is rigidly constrained in a rotational manner to the distal radius but is still able to perform flexion and extension, as well radial and ulnar deviation in the two other degrees of freedom (Figure 33).

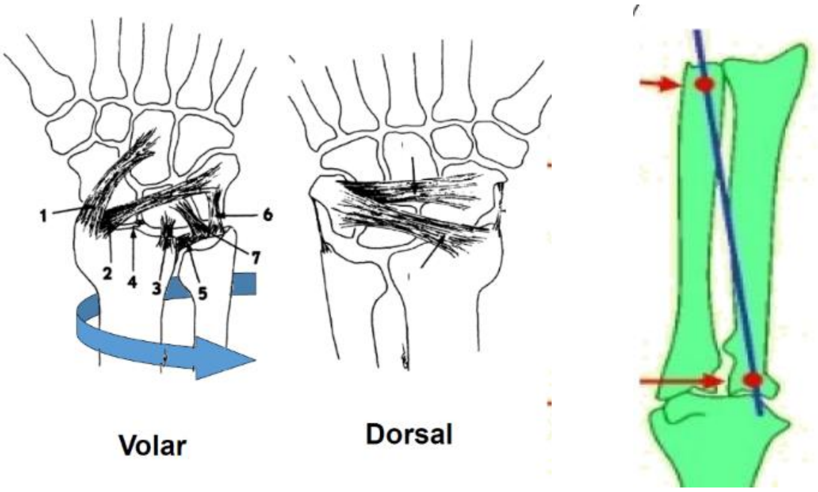


Figure 33. Pronation/supination is restrained by obliquely positioned ligaments to resist rotational force. Red arrows indicate the pivot points of the radius and ulna which pass through the head of the radius (proximally) and the head of the ulna (distally).

This concept is not fully consistent with the more dynamic rotational control proposed by Garcia-Elias (2008). The biological constraints require external linkages that create 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 metacarpals, and to resist all translation but pitch and yaw. Strong obliquely oriented ligaments 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 34) is critical to prevent ulnar translation of the carpus on the radius.

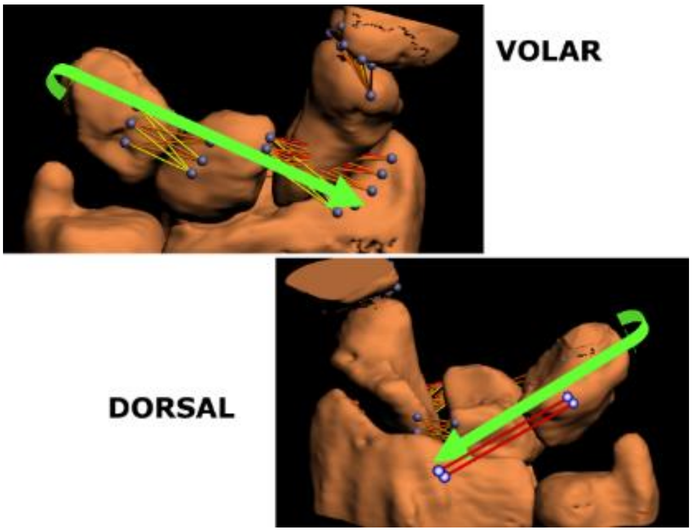


Figure 34. Resistance to ulnar translation due to volar and dorsal oblique ligaments (Sandow et al. 2014).

While the short radiolunate ligament has been previously considered limited to lunate extension (Garcia-Elias 1997), it is more appropriately positioned as a restraint of distraction (Figure 35).

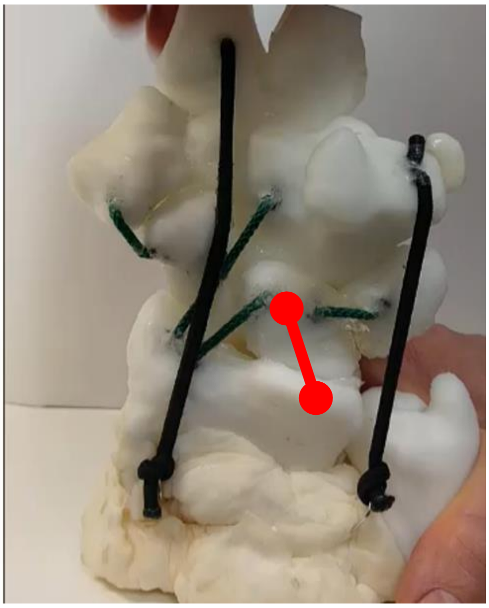


Figure 35. The short radiolunate ligament (red line) becomes taut with the wrist in slight ulnar deviation, thus resisting distraction.

5. Provide 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 is present in the primate. This requires flexion and ulnar deviation of the wrist and places the palm co-linear with the forearm. It is achieved by pronation and flexion of the distal row on a stable proximal row to produce the so-called ‘dart thrower’s motion’.

This is achieved by the pronation of the distal row on the proximal row so that the distal row has a resting position at approximately 45 degrees to the coronal access of the radius and ulna. This is facilitated by through the shape of the trapezoid, as detailed in the paper on the SCCT (Sandow et al. 2014); this movement 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, which substantially increases improved function overall (Marzke, 2009).

In contrast, the chimpanzee 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 aligned in a coronal plane and the primate lacks the oblique power grip that is characteristic of the human wrist. This difference is well described (Figures 36–37).

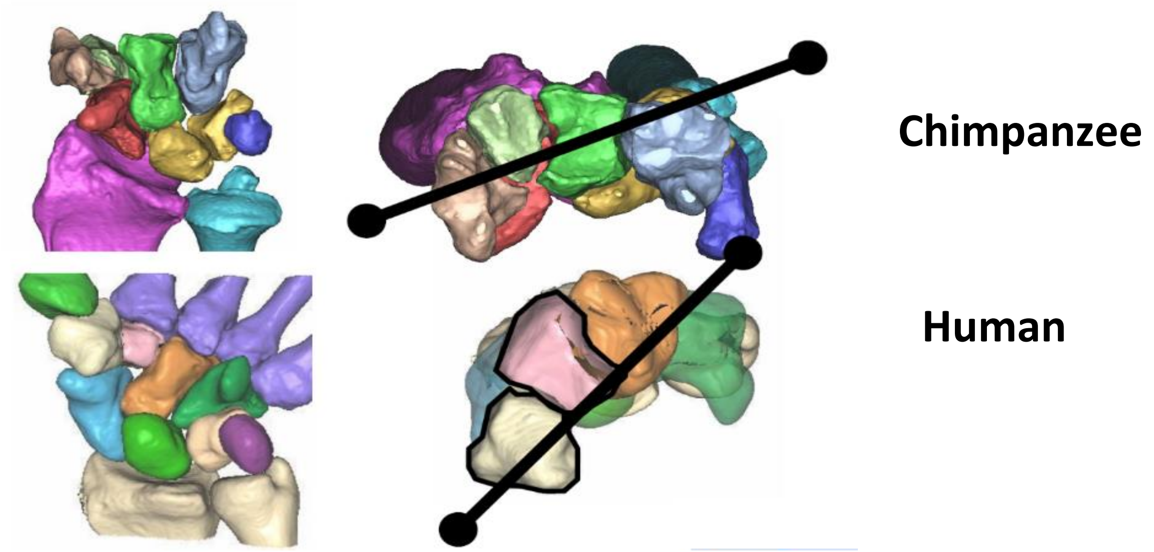
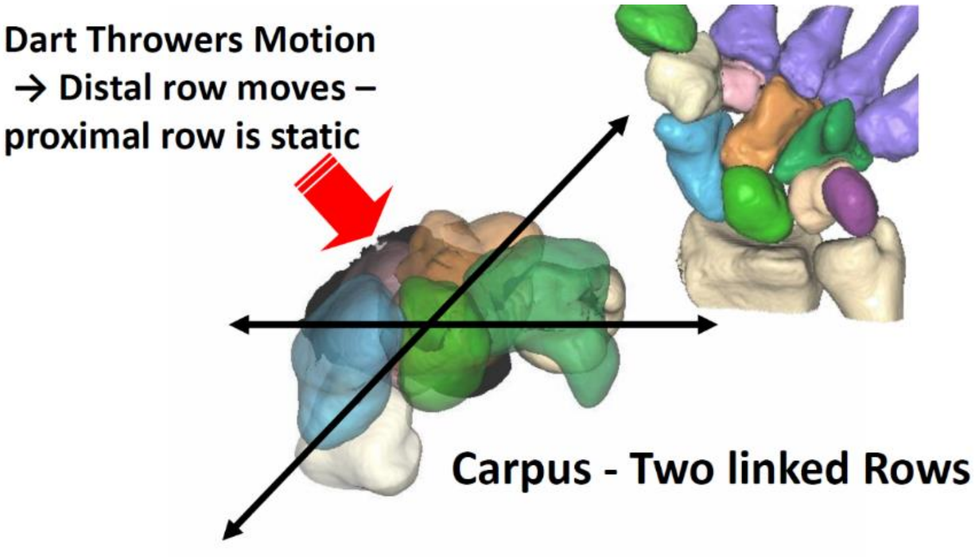


Figure 36. The chimpanzee trapezoid (lime green) is triangular and does not translate the trapezoid (tan) as far forward and out of the coronal plane as the human trapezoid (with its more trapezoid-shaped trapezoid bone (pink)) does. Due to the different shape of the trapezoid, the distal row of the human is pronated by approximately 45 degrees compared the chimpanzee, thus allowing oblique power grip.



Future 37. The structures underlying the human ability to perform the dart thrower's motion.

6. Enable independent finger and wrist motion

The functioning of the wrist requires the fingers be positioned in space and allowed to move independently. This is achieved by the positioning of flexor and extensor tendons 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 38).

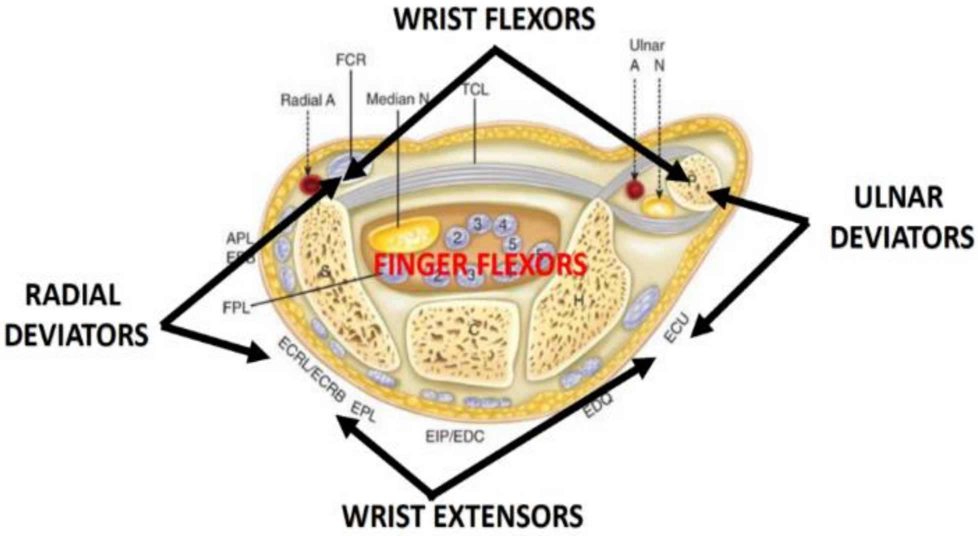


Figure 38. The wrist and finger muscles are arranged optimally to achieve controlled motion and power.
FPL – flexor pollicis longus; APL – abductor pollicis longus; EPB – Extensor pollicis brevis; ECRL – extensor carpi radialis longus; ECRB – extensor carpi radialis brevis; EIP – extensor indicis proprius; EDC – extensor digitorum communis; EDC – extensor digit quinti; ECU – extensor carpi ulnaris; Ulnae A/N – ulnar artery and nerve; TCL – transverse 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 extensors (extensor carpi radialis longus/brevis and extensor carpi ulnaris muscles), the wrist will flex or extend, respectively. Conversely, by contracting the radial- or ulnar-sided wrist muscles, the wrist will deviate radially or ulnarly, 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 largely function to lift the fingers from the palm and are 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 their 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. Maintain low wrist profile in the 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 near perpendicular to the direction of motion. 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, 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 39).

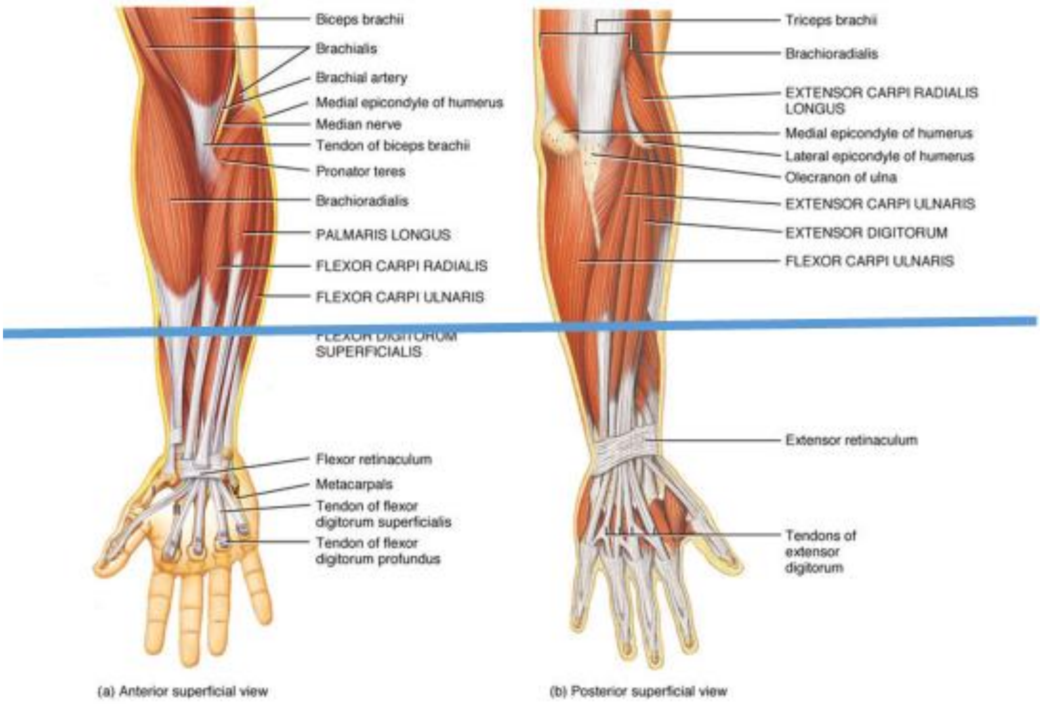


Figure 39. Muscles acting on the wrist to create finger and wrist motion are mostly positioned in the proximal half of the forearm to create a slim distal extremity that remains capable of powerful motion control.

Functionality Summary

The complexities of wrist function are enabled by the presence of a stable central column that delivers load from the radius to the lunate to the capitate and to the second and third metacarpals. This is largely stabilised by the scaphoid, as detailed in the SCCT, 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 40).

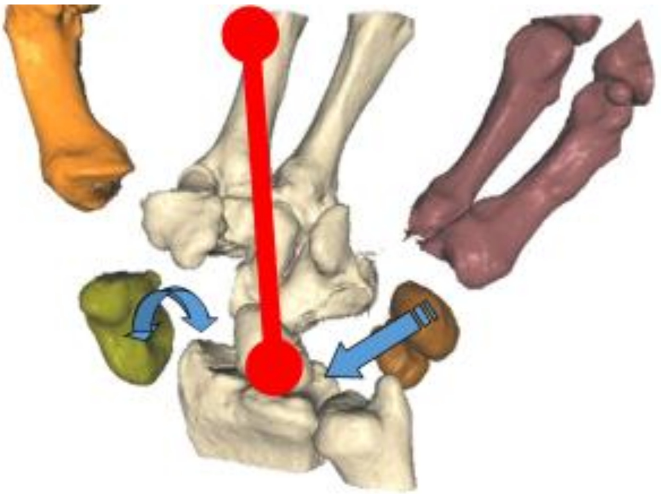


Figure 40. Stable central column of the carpus creates a stable functional axis extending from the Radius > lunate > capitate > 2/3 metacarpal. (Published with *permission JHS-Eu, Sandow et al. 2014).*

Therefore, the seven basic functional requirements (Figure 41) are enabled Rules Based Motion driving a stable central column, with variable offset of the proximal and distal rows.

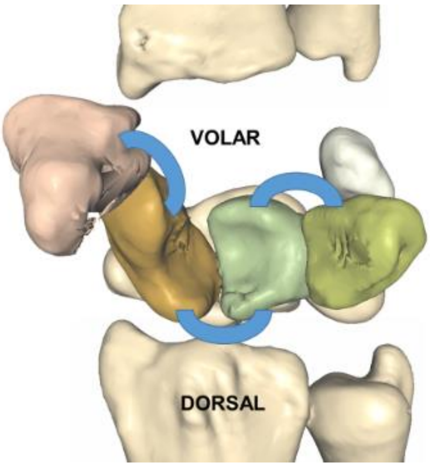
1. **Provide adequate flexion and extension for holding and pushing (FLEXION/EXTENSION)**
2. **Allow side-to-side rotation motion for adjusting to holding different angles (RADIAL/ULNAR DEVIATION)**
3. **Deliver powerful rotational force by resisting rotation through the radio-carpal joint (RESIST ROTATION)**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

Figure 41. The seven basic requirements of the wrist are enabled by the stable central column.

However, the key in this situation is that the proximal row must remain stable, while the lunate remains a critical intercalated segment. The lunate tends to extend but is pulled volarly by the long radiolunate ligament and distally at the dorsum by its connection to the dorsal capsular ligamentous scapho-lunate septum, which is connected to the dorsal intercarpal ligament (DIC).

Recent work by Mathoulin 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) - q, v. page 33.

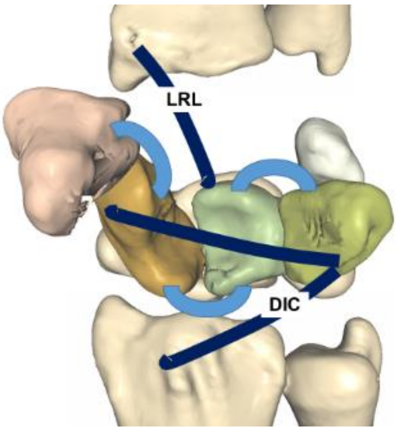
Reviewing the arrangement of the ligamentous constraints identifies an emerging pattern. The apparent volar and dorsal alternating intra-row connection arrangement provides stability and yet allows for a change in the shape of the rows. This is matched by a complimentary connection on the opposite side where there is the inter-row connection to either the distal or caudal row, which creates matching inter-row connections (Figures 43A and B).



There is a pattern emerging of volar and dorsal connections.

No bone is directly connected on the dorsal AND volar side to its row neighbour

Figure 42. The connections between the carpal bones create an alternating <u>intra-row</u> connection that provides stability and yet allows the rows to change shape.



There is a pattern emerging of volar and dorsal connections.

No bone is directly connected on the dorsal AND volar side to its row neighbour

Figure 43. The intra-row linkages are matched by complimentary connections on the opposite side, where there is the <u>inter-row</u> connection to either the distal or caudal row. The anterior and dorsal regions of the carpal bones are never both connected to the same row.

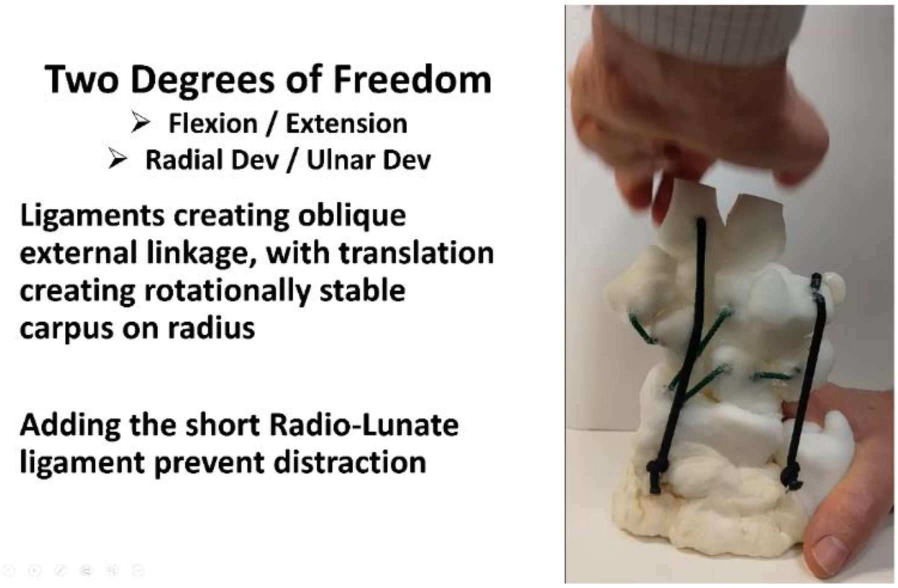
Thus, emerges a pattern between the connections between the proximal and distal rows. The critical factor of the wrist is that the proximal row must remain stable to facilitate the positioning of the distal row. No bone in the proximal row is strongly connected at both its volar and dorsal aspects; rather, each forms an alternating pattern between volar ligament constraints on the trapezium scaphoid, then dorsally between the scaphoid and lunate, and then volarly again between the lunate and triquetrum. This is matched by further ligamentous constraints that extend either to the opposite joint or further across the carpus, but not to the adjacent carpal bone. This allows the specific shape of the distal articulating surface of the proximal row to change; it is able to flex and extend under the control of the distally loaded distal row via the various wrist flexor and extensor muscles. Therefore, the lunate is an intercalated segment that is not attached to tendons; rather, it 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 that 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 the palm and fingers are engaged in gripping. The variable offset of the stable distal row allows the two degrees of freedom, but a variable offset is provided as the axis between the two rows changes.

The 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, it allows two degrees of freedom. The oblique power grip is achieved by flexing and extending 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 its function. This is facilitated by the offset axis between the distal and proximal rows, as detailed above, and occurs largely as a result of the trapezoid pushing the lateral pivot volar to the coronal access of the carpus, radius and ulna, and the mobility of the triquetrum that allows for a variable offset.

The dart throwing motion is typically an isolated midcarpal movement on a stable proximal row, where the proximal row sets the starting point of the distal row, which then moves from radial extension to volar flexion in the characteristic dart thrower or oblique power grip position. Therefore, the carpus can be conceptualised as having two degrees of freedom, pitch and yaw, which are achieved through a stable central column. The lunate is the intercalated segment that connects the radius to the capitate to the second and third 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).



Two Degrees of Freedom

- **Flexion / Extension**
- **Radial Dev / Ulnar Dev**

Ligaments creating oblique external linkage, with translation creating rotationally stable carpus on radius

Adding the short Radio-Lunate ligament prevent distraction

Figure 44. A combination of the 3D-printed bones, 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 (Figures 45 and 46). This creates a stabilising force couple for the central column that allows motion coupled with stability.

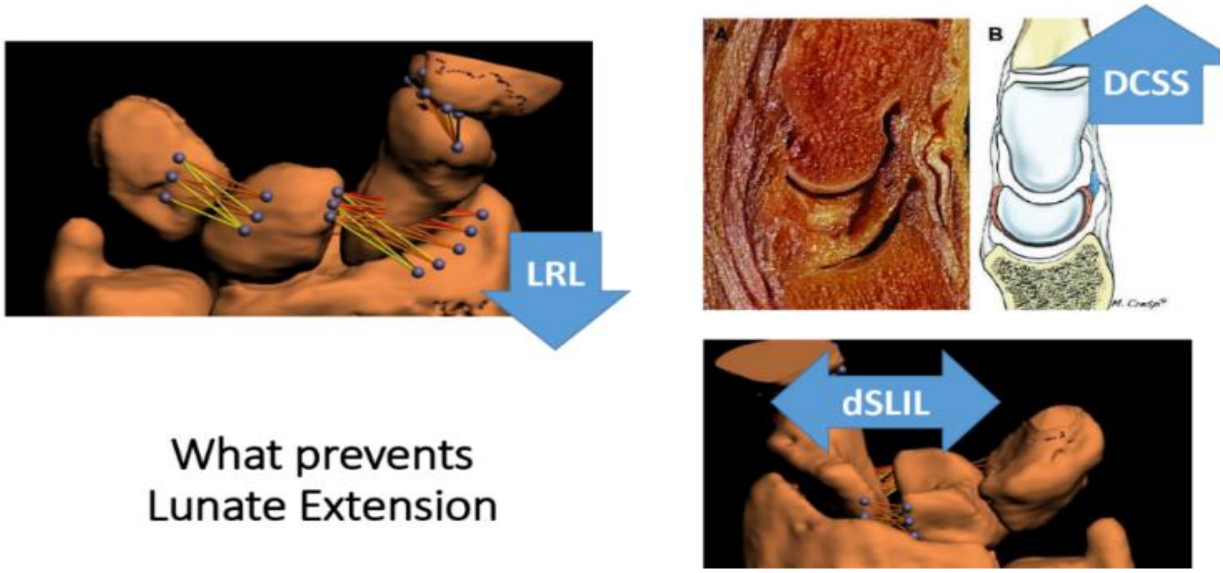


Figure 45. The lunate has a balanced force couple with the long radiolunate ligament (LRL). This creates a volar proximal load to pull the lunate into flexion and thereby, prevent the natural tendency of the lunate to rotate into extension. It is balanced by the connection of the lunate dorsally to the scaphoid via the dSLIL (dorsal scapho-lunate interosseous ligament) and dorsal capsulo-scapho-lunate septum (DCSS), creating a stable well-aligned and reactive intercalated segment: the lunate. (DCSS images reprinted with permission, Mathoulin et al. 2017)

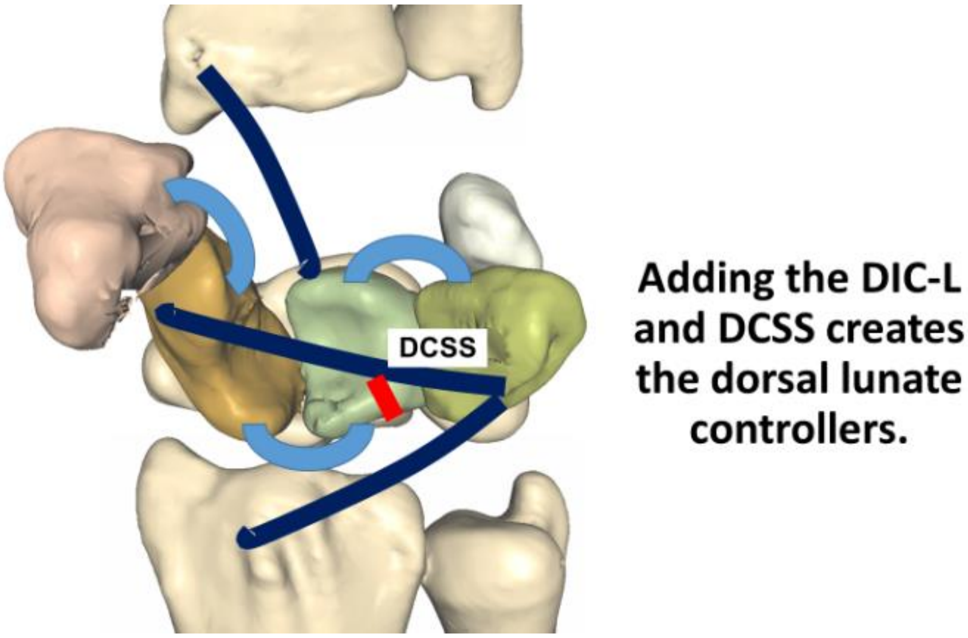


Figure 46. Adding the dorsal lunate connection to the DIC creates an additional constraint in the control of the central column via the lunate.

Forward animation theory validation

In developing the concept, the main goal was to identify the rules and then reapply them to re-create motion. The true test of this concept is embodied in challenge to import the rules and re-created the original motion. In this process, the bones were 3D printed (Figure 47A and B), the computationally derived constraints were applied (Figure 48) and the simulated tendon was attached (Figure 49).

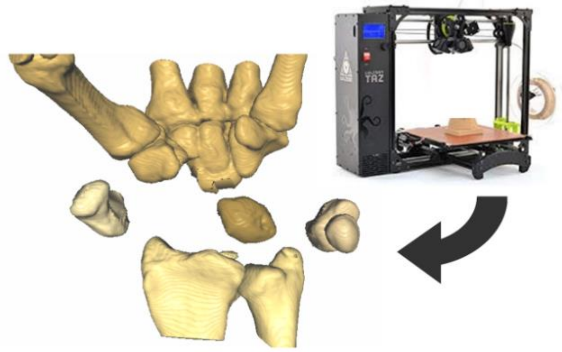


Figure 47A. Following identification of the bone morphology and isometric connections, the selected wrist can be printed using existing 3D printing technology.

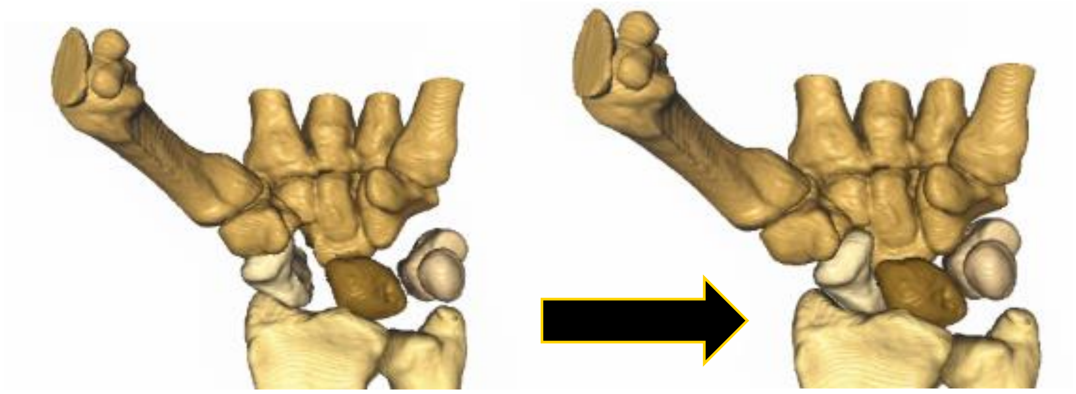


Figure 47B. Bone printed and then realigned into their usual neutral anatomical position.

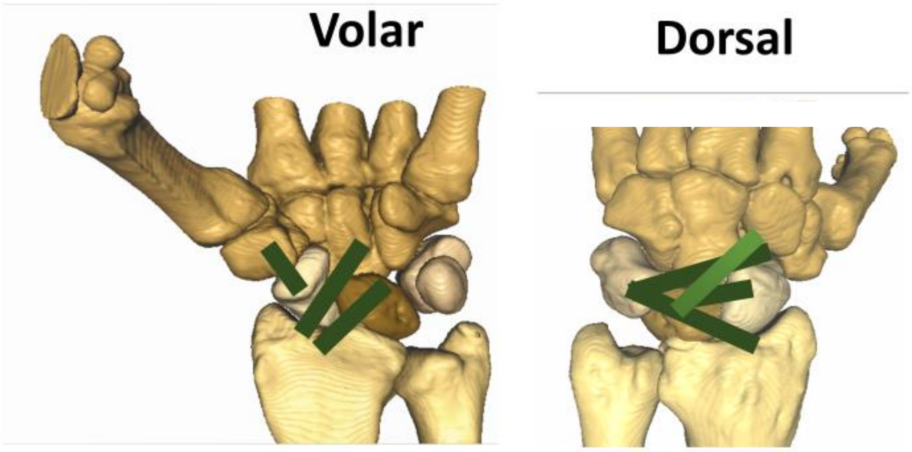


Figure 48. Computationally derived isometric linkages were identified and reapplied.

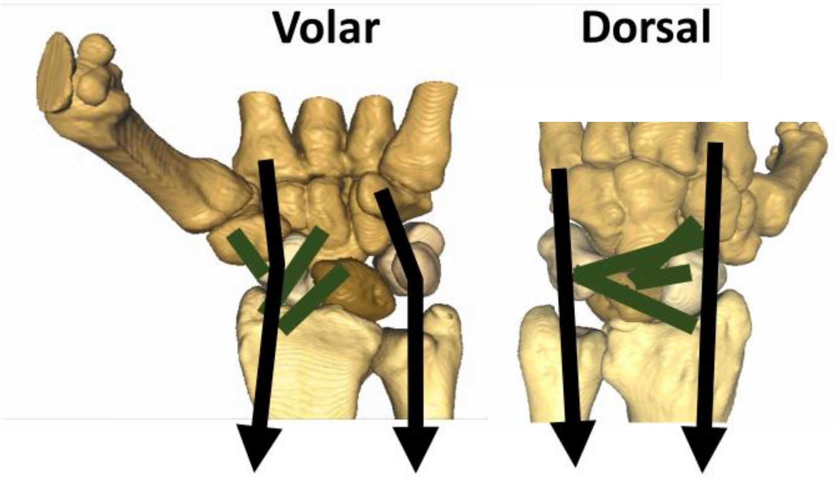
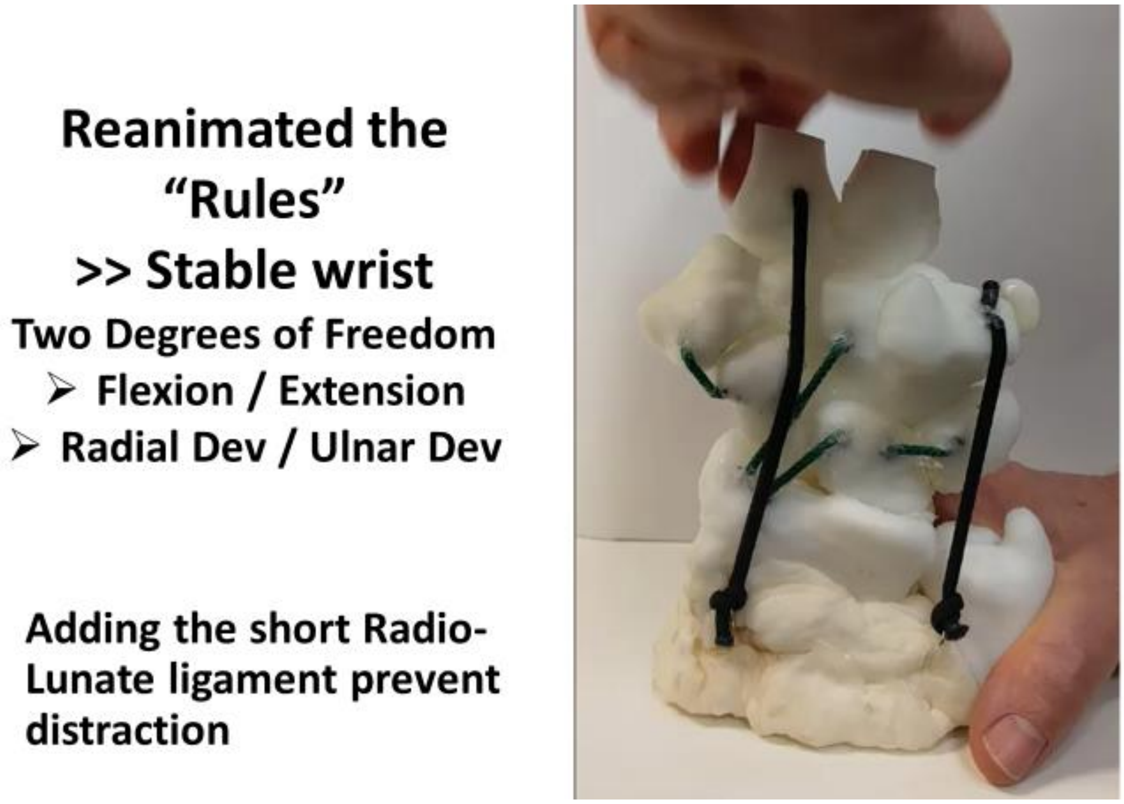


Figure 49. Notional tendon load points are added.

When load is applied to the re-configured carpus, motion can be created under its own rules (Figure 50). This represents a validation of the reverse engineering and then forward re-engineering animation of the wrist, base on quantitative extraction of isometric constraint and bony morphology.



Reanimated the
"Rules"
>> Stable wrist
Two Degrees of Freedom
- Flexion / Extension
- Radial Dev / Ulnar Dev

Adding the short Radio-Lunate ligament prevent distraction

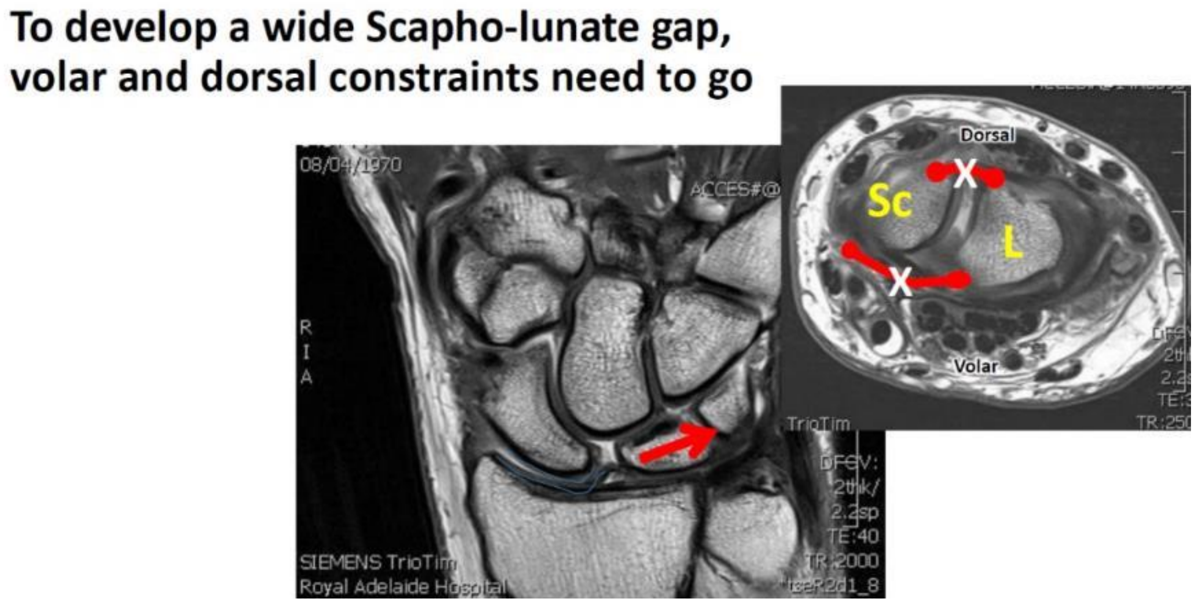
Figure 50. Combining the 3D-printed bones, computationally derived isometric constraints and notional tendon load creates a stable mobile wrist. The final model is remarkable and validates the concept of reverse engineering, forward engineering and reanimation. Both support the notion of a stable central column, a relative biomechanical correlation to Kock's postulate.

Carpal disruption: What happens when things go wrong?

The question is now: ‘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 that is the critically intercalated segment. The lunate has a tendency to collapse into extension but can, on occasion, rotate into flexion. It is normally firmly attached to the scaphoid on the dorsal aspect and thus, various instability patterns can be categorised by whether or not it is separated from the scaphoid. There are two broad patterns: dissociated (separated from the scaphoid; carpal instability dissociative (CID)) or non-dissociated (connected to the scaphoid; carpal instability non-dissociative (CIND)). As part of an instability pattern, the lunate can collapse into flexion (volar intercalated segmental instability (VISI)) or extension (dorsal intercalated segmental instability (DISI)). Therefore, the four instability patterns of the central column are 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 firmly attached to the scaphoid dorsally but is also volarly attached to the radius by the long radiolunate ligament. The lunate is also pulled dorsally by the dorsal capsule ligamentous scapho-lunate septum (DCSS) (Figure 45). As the proximal row is usually stable in its transverse aspect, for a scapho–lunate gap to develop, both the volar and dorsal constraints must be disrupted (Figure 51).



To develop a wide Scapho-lunate gap, volar and dorsal constraints need to go

Figure 51. For scaphoid- lunate dissociation, the lunate must move away from the scaphoid (red arrow), or, alternatively, the scaphoid must move in a radial direction. Both the dorsal and volar stabilising ligaments must fail for the lunate to be displaced.

As detailed above, the longitudinal stability of the proximal row is critical and thus, separation of the lunate from the scaphoid produces a dissociative pattern (CID) and frees the lunate to then move into flexion or extension. When the volar long radiolunate ligament is disrupted and there is a loss of the stabilising effect of the DCSS, the lunate will go into extension and the scaphoid will flex. This creates a CID/DISI collapsed deformity (Figure 52).

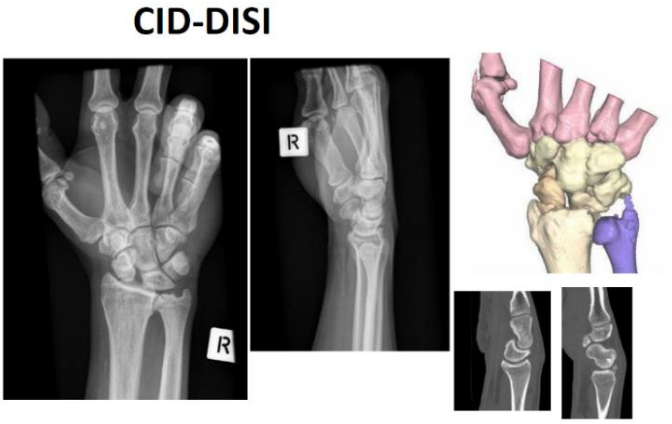


Figure 52. A fall on outstretched hand created an injury that includes a scaphoid flexion, scaphoid-lunate diastasis and lunate extension.

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. On the basis of the SCCT, three critical ligaments appear important to control this motion. These include the scaphoid–trapezium ligament, the dorsal scapho-lunate ligament and the long radiolunate ligament (Figure 53).

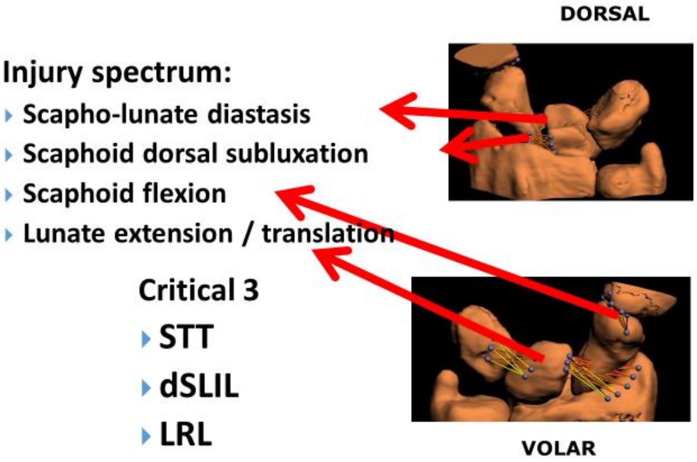


Figure 53. Although scapho-lunate dissociation can occur as a spectrum, the key elements are scapho-lunate diastasis, scaphoid dorsal subluxation, scaphoid flexion, and lunate extension and ulnar translation.

As detailed in Figure 53, an important observation is that the carpal bones can move or be displaced in a 3D direction. This means that a 2D planar image may not completely identify the changes in carpal bone relationships. Figures 52 and 54 demonstrates a clinical case of a disruption of the dorsal scapho-lunate ligament where the scaphoid is abnormally pronated and proximal pole dorsally displaced – without significant separation of the lunate and scaphoid on the coronal planar image. The virtual reduction of the carpal malalignment as part of the pre-operative planning (using True Life Anatomy software) identified a 10mm pathological separation of the attachments of the dSLIL, not the 2mm shift that would have been indicated by the planar measurements.

It is the correction of this dorsal displacement of the proximal pole of the scaphoid that is a critical structural deficit that needs to be controlled to achieve a satisfactory outcome in the various reported reconstruction options for scapho-lunate dissociation (Lee et al, 2017 and Chan et al 2019).

The anatomical front and back reconstruction (ANAFAB) described by Sandow and Fisher (2019) addresses the scapho-lunate dissociation of the classic CID/DISI pattern (Figures 55–57).

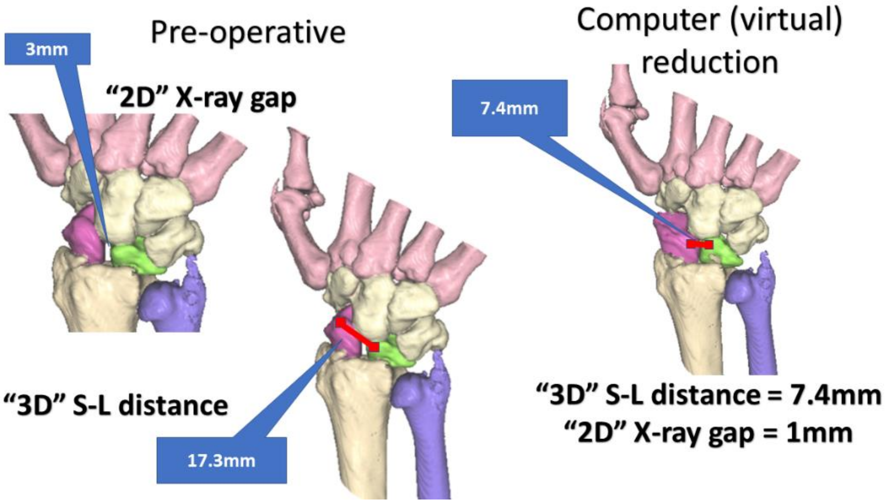


Figure 54. Case example of scapho-lunate dissociation with the scaphoid pathologically pronated and the proximal pole displaced dorsally. The coronal planar separation as would be identified on a plain radiograph was approximately 3mm. However, the distance between the attachments of the dSLIL was 17.3mm. Using 3D manipulation software to preform a virtual reduction of the scaphoid as part of preoperative planning the distance between the attachments of the dSLIL was reduced to 7.4mm, and the planar scapho-lunate gap was 1mm. This suggested that the true scapho-lunate separation was 10mm, not 2mm.

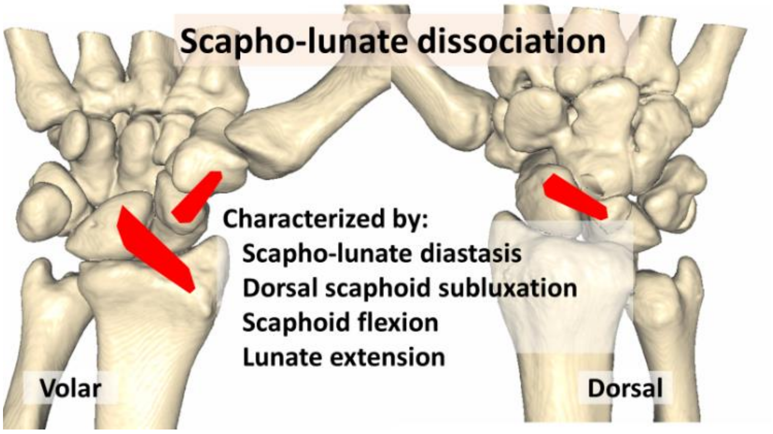


Figure 55. The deficits in scapho-lunate instability include scapho-lunate diastasis, scaphoid dorsal subluxation, scaphoid flexion, and lunate extension and ulnar translation.

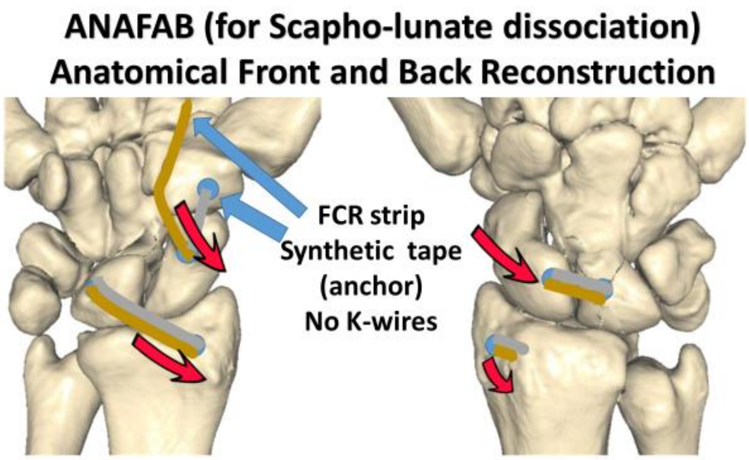
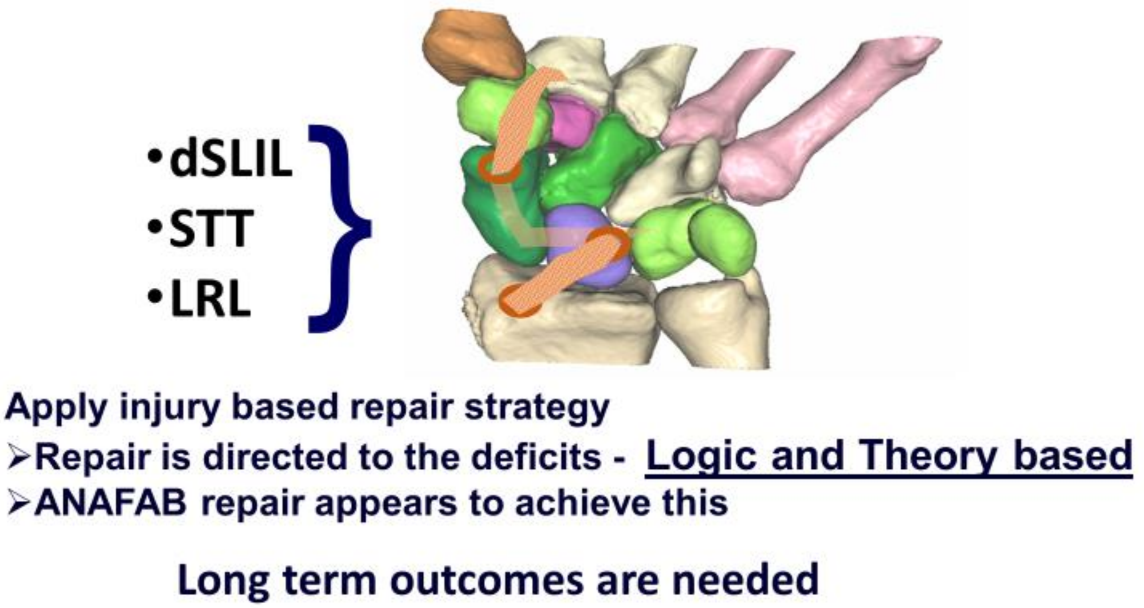


Figure 56. The ANAFAB procedure aims to address the identified deficit.

The ANAFAB procedure appears to be able to reverse the scapho-lunate 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 success in restoring longitudinal stability to the carpus without a significant loss of motion, which indicates successful restoration of functional carpal biomechanics (Sandow and Fisher, 2019).



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

Apply injury based repair strategy

- **Repair is directed to the deficits - <u>Logic and Theory based</u>**
- **ANAFAB repair appears to achieve this**

Long term outcomes are needed

Figure 57. The ANAFAB provides a logic- and theory-based solution to scapho-lunate dissociation.

The ANAFAB reconstruction addresses the major recognised deficit in wrist injuries. Based on carpal mechanics and deficits, this reconstruction delivers a solution that was not previously possible. Thus, 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. Therefore, the final approach is to use a quantitative analysis of the constraints in an injured wrist, to compare the findings to the expected pattern and to then use the differences 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 the volar long radiolunate ligament, the dorsal DCSS and 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. If both scaphoid and lunate move into extension, the scapho-lunate has become non-dissociated, which creates a CIND/DISI. The question is then: How does this reconcile with the SCCT, as the long radiolunate ligament is known to be critical?

On further examination, it is evident that the scaphoid moves radially as it goes into extension (as part of a CIND/DISI collapsed deformity), as does the lunate. This translates the lunate radially, creating a physiological lengthening in the long radiolunate ligament and allowing the lunate to go into extension while the long radiolunate ligament remains intact. Therefore, pathological lunate extension can occur with an intact long radiolunate ligament but only if the scaphoid moves radially to allow increased radial translation of the lunate. This, therefore, creates the CIND/DISI deformity, which implies the disruption of the DCSS. The question then arises as to what normally prevents pathological scaphoid extension.

Based on the author’s operative experience, removal of the trapezium (as part of a reconstruction for an arthritic first carpo-metacarpal joint) does not create excessive scaphoid extension or flexion. Therefore, it would be likely that the scaphoid–trapezium ligaments are not the primary restraints of scaphoid extension. A review of previous literature (Berger 1997) identifies a strong ligament between the capitate and the scaphoid and this is most likely the primary restraint of scaphoid extension. However, further work is required to validate this proposal.

A recent clinical case demonstrated 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 and thereby, allow excessive and pathological scaphoid extension. Therefore, it appears that the distal scaphoid is certainly bound by the 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 initially aimed to identify a solution to the classic instability pattern of scapho-lunate dissociation. By developing a theory to explain how the stable central column of the carpus is maintained, this work allowed observed deviation from the typical anatomical arrangement to 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 consistent with the SCCT 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, through application of the SCCT and characterisation of the particular structures that may have been disrupted, it is possible to develop an appropriate and successful management plan.

Thus, this work completes the first part of the journey to the understand 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 outcomes 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 area of wrist instability that requires separate attention. However, the stable central column provides a basis on which to expand the understanding of the wider carpal biomechanics, assess the deficit and, thereby, propose and test potential solutions.

As detailed in the introduction, this project was part of a larger study to develop a kinetic model to explain the carpus. The work also aimed 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 Rules that control the carpal biomechanics have been characterised, their application has only been possible through laborious 3D printing of each of the individual carpal bones of a specific patient or subject, follow by the application the static and dynamic constraints. As a proof of concept, this was superb. However, the next major advance will be the development of technology to allow the application of the individual rules in an interactive and interconnected virtual multibody animation environment to complete the full process from reverse and forward engineering to final ‘what if’ conclusions.

Conclusion

The wrist explained

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

As noted previously, theories cannot be proven but can be validated, justified or replaced and they must be predictive and testable. This work potentially represents a major advance, in both the understanding of what constitutes a theory that can be applied to the carpus and how such a theory can be applied to characterise a mechanical disruption and determine a logical 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, then to the capitate and, ultimately, to the second and third metacarpals. The components of the wrist, particularly the bone morphology, ligaments and tendon attachments, can each vary but together create the required wrist function and represent possibly the first described example of Rules Based Motion.

Marc Garcia-Elias (2013) has famously described attempts to understand the carpus as a ‘long and winding road’, given the vagaries of progress that have frustrated multiple attempts to understand and address carpal mechanics and their deficiencies. His analogy suggests that the journey to understand the wrist does not have a clear end point; the journeymen travels the pathway of exploration seeking the next most likely productive opportunity—but without a clear vison of the final destination. A more logical approach would be to address the challenge of the wrist as a planned journey to the desired location. A journey is best planned by starting from where one wishes to finish; although the destination is somewhat imprecise, it is still conceptually evident. The termination point is defined, even if not in great clarity, and the journey is then planned in reverse. This analogy is perhaps akin to climbing a tropical mountain. The traveller may know roughly where they wish to finish but cannot see it directly. This is distinct from heading down a ‘long and winding road’. If the traveller knows approximately where they are heading and has anticipated potential obstacles, they are more likely to select the correct path when encountering a fork in the research trail. Thus, the scientific journeyman will likely be more successful if they have planned their journey with an end point in mind.

The journey to identify the critical biomechanical restraints of the wrist using reverse engineering technology and then planning a means to restore them to the pathologically injured wrist appears to have reached its goal destination, at least in one part of the wrist. In cases of scapho-lunate diastasis and collapse of the central column, carpal function has been successfully restored in the majority of this group of patients through the application of a logic-based reconstructive volar and dorsal surgical solution (ANAFAB) (Sandow and Fisher, 2019).

Further work is now required to address other areas of wrist pathology, but the SCCT and the arrangement of isometric constraints provide a useful basis for further study of the complex biomechanics of the wrist. However, the SCCT is still just a theory and, as is the case, the best thing that can happen to a theory is for it to be replaced by a better one. For now, wrist researchers and surgeons have a true theory to guide their approach to the dysfunctional wrist. This work has provided a shift from the aimless measurement that is typical of the empirical research approach to a more logic-based conceptual methodology. Thus, this 20-year journey may well have answered the opening question: ‘Can the wrist be explained?’. Indeed, the application of computer-based quantitative analysis appears able to explain carpal biomechanics and identify therapeutic solutions for wrist dysfunction.

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Appendix 1: True Life Anatomy Software

Web site: www.truelifeanatomy.com.au

Distribution agent: RuBaMAS Pty Ltd, Adelaide, Australia, www.rubamas.com

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