The application of computer-based quantitative analysis to explain carpal biomechanics

In this article I outline my approach to investigate wrist kinematics that uses a conceptual or theory based research process. This is different to most wrist research, which is by empirical observation. This alternate methodology may provide explanations for the biomechanics of the carpus and, more importantly, techniques to address dysfunction.

Functional analysis of the wrist

The first step in my approach was to understand the specific requirements and then identify how those requirements can be achieved. Specifically, the wrist needs to: (1) position the fingers and palm to allow them to perform the functional requirements; (2) be based around the stable central second and third metacarpals on which the mobile thenar and hypothenar units act; and (3) deliver sufficient gripping and rotational power, controlled in the proximal forearm, to allow for a slim wrist (Sandow, 2020a, 2020b). On this basis, there appeared to be seven basic mechanical prerequisites that allow the wrist to perform its functional requirements (Sandow, 2020a, 2020b): (1) adequate flexion and extension for holding and pushing (flexion/extension); (2) adequate side-to-side rotation motion adjusting to holding in different angles (radial/ulnar deviation); (3) delivery of powerful rotational force by resisting rotation through the radiocarpal joint (resist rotation); (4) resisting translation in coronal, sagittal and transverse planes (resist translation/compression/distraction); (5) an oblique power grip to improve holding, thrusting and throwing (achieve co-linear palm and forearm during use); (6) independent finger and wrist motion; and (7) a low profile in the distal extremity to increase functionality.

Biomechanical analysis of the wrist

In my approach, analytical software (True Life Anatomy Pty Ltd, Adelaide, Australia) was used to identify the relationships between the various bones and perform a reverse engineering type analysis. By analysing the relationship of the bones of the proximal row in radial deviation and ulnar deviation, isometric connections were characterized between the dorsal scaphoid and lunate, the volar radius and lunate, the volar lunate and triquetrum, and the volar aspect of the scaphoid and trapezium (Figure 1(a)) (Sandow et al., 2014).

When a similar analysis was performed with the wrist in flexion and extension, the isometric connections were the same, indicating that the bones must move in the same direction in both flexion and extension and on sagittal deviation (Sandow, 2020b; 2020c). Therefore, the proximal row must move through a single uniaxial arc of motion with respect to the radius.

The distal row is firmly attached to the proximal row in the region of the scaphoid and trapezium. However, no isometric connections were identified between the ulnar aspect of the proximal and distal rows. Although the proximal row moves in a single axis with respect to the radius, and the distal row is strongly connected to the proximal row on its radial side, the variable pivot point on the ulnar side allows the axis of rotation of the distal row to shift (Sandow, 2020b).

While there was a clear pattern of isometric connections in specific regions within the carpus, the exact spatial locations on the various bones differed because there were considerable anatomical variations between the shapes of the bones (Sandow et al., 2014). To reconcile this consistent pattern but variable specific topographic distribution between individual wrists, an alternate conceptual explanation was required.

By using the concept of reverse engineering to define the components of the motion system, and then performing a theoretical forward synthetic kinematic biomechanical process, an algorithm denoted as rules-based motion (RBM) was developed. RBM is a form of animation where the resultant motion is due to the rigid body interaction of the various system components acting upon other components of that system. The resultant motion is an

interdependent product, which means that the components can vary; however, there is a compensatory variation in the other components to achieve the same net outcome (Sandow et al., 2014). In the wrist, these components are also denoted as rules: (1) the morphology or bone shape; (2) the connection between the components (such as isometric connections); (3) the interaction or friction/motion characteristic between the components; and (4) the load applied (both direction and point of application) (Sandow et al., 2014).

Together, these four rules create the net functional outcome; when there is a change in one (as occurs between individuals), there will need to be compensatory changes in the others to enable the same net functional outcome. RBM reconciles the variability within the wrist and, as an extension of the original concept presented by Sandow et al (2014), is a key element of the stable central column theory (Figure 1(b)) (Sandow et al., 2014).

The relationship between the proximal and distal rows has been described as being consistent with a two-gear, four-bar linkage (Sandow et al., 2014). The stability of the proximal and distal rows is further enhanced by the connections of the lunate and scaphoid to the dorsal intercarpal ligaments (DIC) (Mathoulin, 2017; Sandow, 2020b). Thus, the lunate is controlled by a balanced force couple. The long

radio-lunate ligament (LRL) (creating a volar proximal load that pulls the lunate into flexion, thereby preventing its natural tendency to rotate into extension) is balanced by the connection of the lunate dorsally to the DIC (through the lunate–DIC ligamentous junction) and to the scaphoid – creating a physiologically stable, well-aligned and reactive lunate intercalated segment and a stable central column.

Wrist biomechanics

There are only two degrees of freedom in the wrist (Sandow, 2020b): pitch (flexion and extension) and yaw (radial and ulnar deviation). Directions of motions, such as translation, rotation and distraction or compression, are all resisted by the ligament constraints and structural components in the wrist. There is a variable degree of laxity within the wrist to allow some movement in these other directions. Therefore, the seven mechanical prerequisites can be reviewed in sequence.

Adequate flexion and extension for holding and pushing

The proximal and distal rows of the wrist can be envisioned as stylized cylinders, each of which moves through a single axis (Figure 2). The proximal and
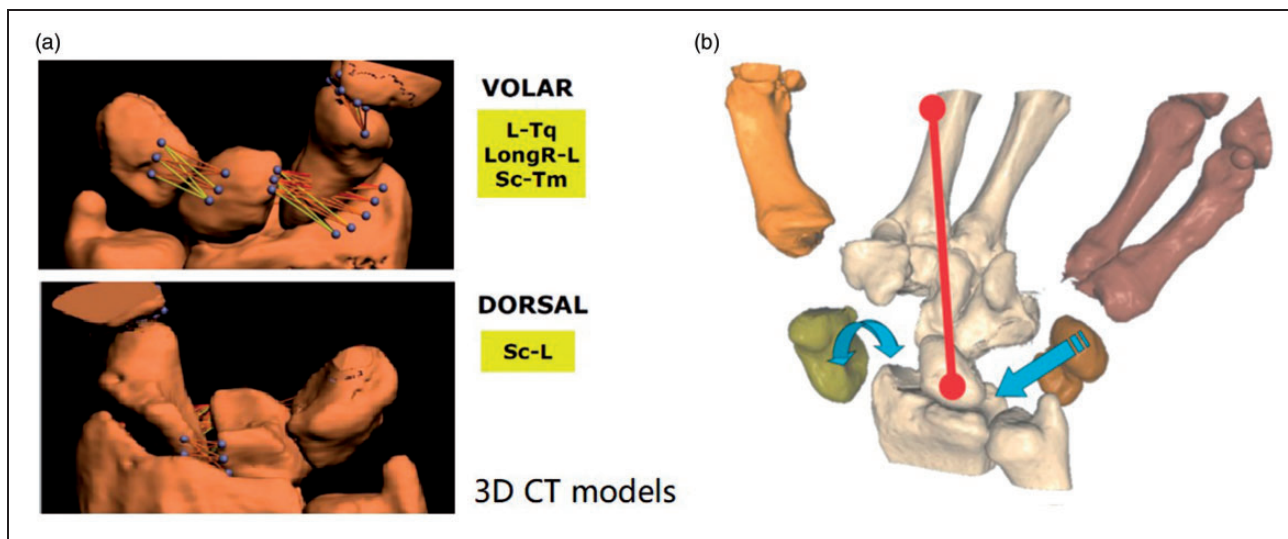

Figure 1. (a) A three-dimensional model of a representative wrist showing extent of isometricity between various regions on carpal bones during sagittal motion using quantitative spatial analysis with True Life Anatomy software. Yellow lines indicate that the distance between the blue spheres varied by less than 5% through the motion range. These largely corresponded to described intercarpal ligaments: L-Tq: lunatotriquetral, LongR-L: long radiolunate, Sc-Tm: scaphotrapezium and Sc-L: scapholunate dorsal interosseous. Orange lines indicated isometricity of 5–10% and red lines indicated motion between the corresponding blue spheres varied by more than 10% during sagittal motion. (b) The stable central column of the carpus is the radius-lunate-capitate-second/third metacarpals. Modified from *Journal of Hand Surgery (European Volume)* with permission (Sandow et al., 2014).
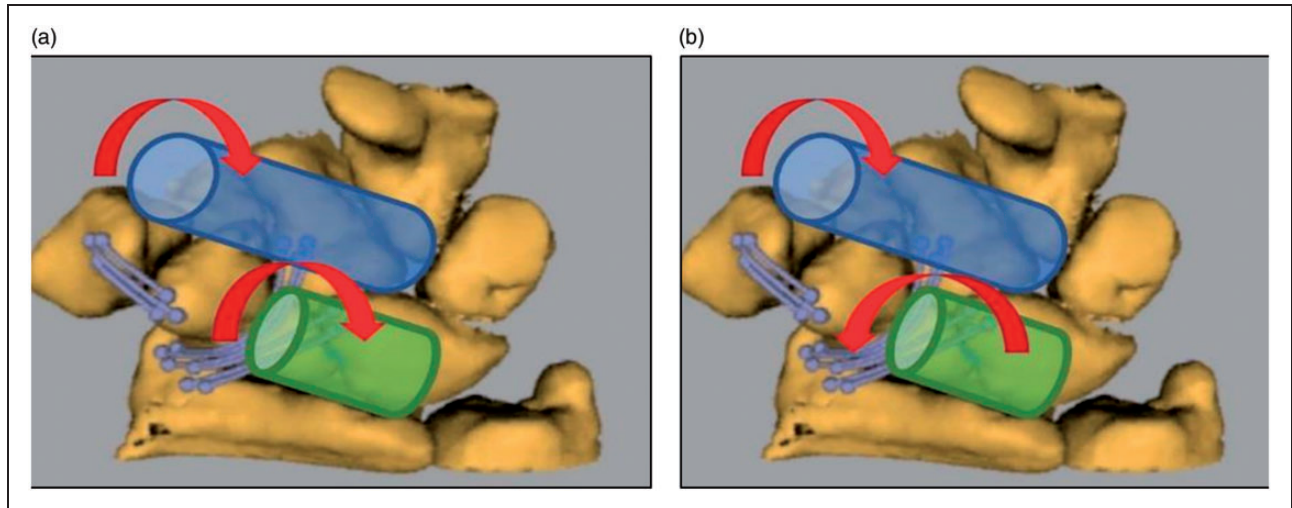
Figure 2. (a) Proximal and distal carpal rows stylized as single-axis cylinders. (b) The proximal and distal rows stylized as offset single-axis cylinders moving in opposite directions to achieve radial and ulnar deviation.

distal rows both move in a flexion and extension arc. Force is generally applied to the base of the meta-carpals by the volar and dorsal wrist flexors and extensors, and the proximal row acts as an interca-lated segment to allow for the increasing arc of motion. Both cylinders roll into flexion to achieve a flexion arc of motion, and when both cylinders rotate into extension, an extension arc of motion is achieved (Figure 2). An expanded summary is contained in the monograph (Sandow, 2020b). Figure 3 demonstrates the stylized sequential motion of the wrist in flexion; the mobile carpal bones are segmented and artifi-cially moved sequentially (proximal row then distal row) to simulate the flexion motion.

Adequate side-to-side rotation motion adjusting to holding in different angles

Fixed cylinders acting around a single rotation axis however would not achieve the offset motion required for radial and ulnar deviation. The wrist cannot act as a universal joint because it would become rotationally unstable and would require active muscular control to be delivered perpendicular to the resultant motion, as is the case in the hip. This is clearly inappropriate for the wrist. However, the required motion can be achieved by varying the offset between the two notional uniaxial motion cylin-ders of the wrist, with each cylinder moving in oppos-ite directions.

While the proximal row remains fixed in its rota-tional axis with respect to the radius, because there is no firm isometric constraint on the medial aspect of the proximal and distal rows (coupled with the mobil-ity of the triquetrum), the axial alignment of the distal

row can change. The dorsal translation of the trique-trum pronates the distal row out of the plane of the proximal row, thus, changing the alignment of the axis of the distal row rotation. This is consistent with the previous work by Moritomo et al. (2006). Therefore, the two uniaxial cylinders can create radial and ulnar deviation (now with an offset axis) by moving in opposite directions. When the wrist moves into radial deviation, the proximal row flexes and the offset (pro-nated) distal row extends. Similarly, in ulnar deviation, the proximal row extends and the offset (pronated) distal row flexes (Figure 2(b)) (Sandow, 2020b).

The concept of the proximal row controlling mid-carpal alignment and motion explains not only the general carpal biomechanics but, as part of the RBM concept, the many normal carpal functional and mor-phological variants. The ligamentous stabilizers of the intercalated segment (principally the lunate) are the key to carpal biomechanics (Sandow et al., 2014). Although this is a simplistic explanation for the motion, it does provide a conceptual basis for explain-ing the well-controlled, two-dimensional wrist motion that is powered by the proximal forearm muscles. The carpus can be understood as two carpal rows that are linked but variably offset. Each row only moves through a single arc of motion; however, the combined binary output of the variable offset alignment creates the required two degrees of freedom (Figures 2 and 3). A detailed diagrammatic explanation is provided in the monograph (Sandow, 2020b).

Deliver powerful rotational force

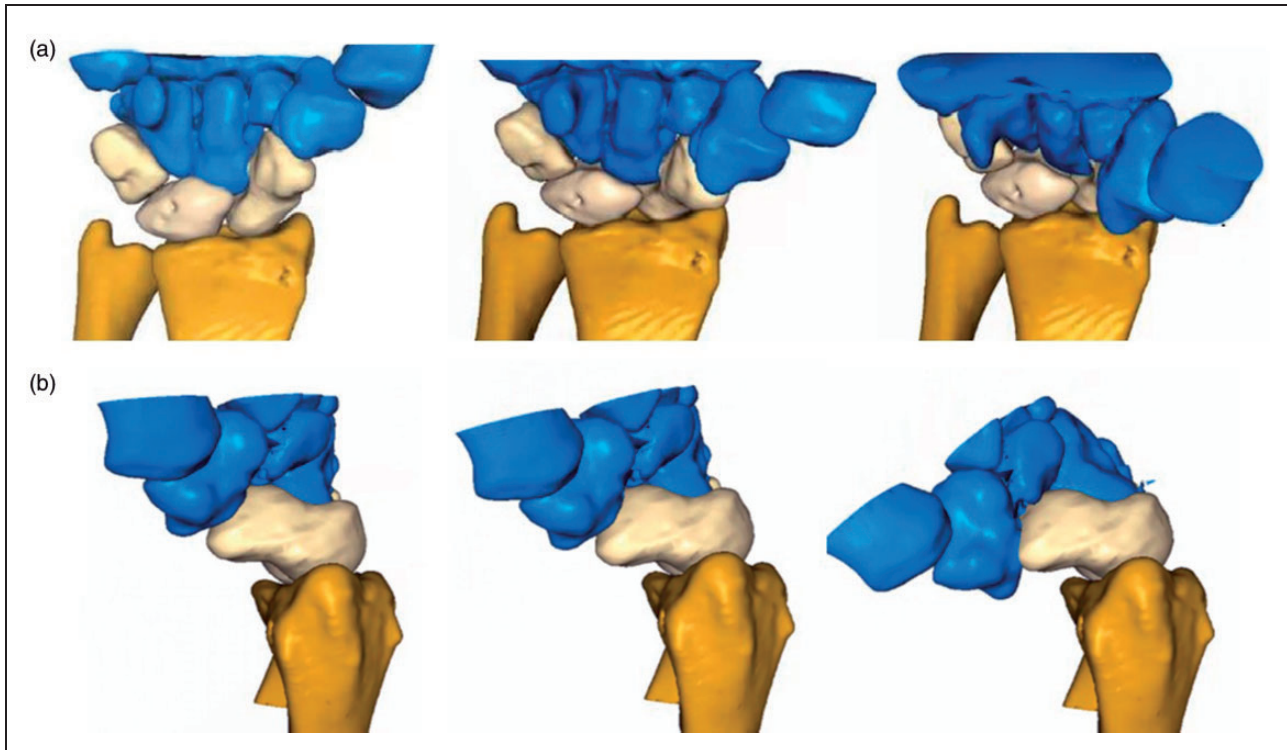One of the functional requirements of the forearm and wrist is that it has a slim distal aspect that can

Figure 3. (a) Anterior view of wrist flexion (from left to right): neutral, proximal row flexed and distal row flexed. (b) Lateral view of wrist flexion (from left to right): neutral, proximal row flexed and distal row flexed.

deliver strong rotational forces. This is achieved by the active pronation and supination of the radius around the ulna by strong forearm muscles (including the supinator, pronator quadratus, pronator teres and the biceps) acting on a radiocarpal joint that resists rotation. This rotational stability at the radiocarpal joint is achieved through the obliquely orientated rotation resisting ligamentous constraints (Garcia-Elias, 2008).

Resist translation in coronal, sagittal, transverse and longitudinal planes

As detailed previously, the function of the wrist is to deliver the load to the second and third metacarpals and resist all motion apart from pitch (flexion/extension) and yaw (radial and ulnar deviation). Strong obliquely orientated ligaments, combined with the enveloping capsule, prevent coronal and sagittal translation. In particular, the ligament connections between the radius, via the lunate to the triquetrum on the volar side, and the direct connection between the radius and the triquetrum on the dorsal aspect creates a restraint to ulnar translation (Sandow et al., 2014). The short radiolunate ligament serves as a longitudinal restraint to resist distraction of the

wrist when the wrist is in slight ulnar deviation (Sandow, 2020a; 2020b).

Oblique power grip to improve holding, thrusting and throwing

The human wrist has the ability to perform an oblique power grip, which allows alignment of the palm with the forearm. This is distinct from the oblique grip achievable by primates, which utilizes a neutrally orientated wrist but with variable flexion of the fingers (Sandow, 2020b). In humans, the oblique power grip is enabled by the articulation between the trapezium and the scaphoid being anatomically positioned anterior to the coronal plane of the distal radius, the effect of which is to place the thumb in increased opposition to allow for better thumb function and increase the offset variability of the proximal and distal rows; which further facilitates radial and ulna deviation.

This volar positioning of the trapezium and scaphoid connection is achieved through the trapezoidal shape of the trapezoid, translating the trapezium anteriorly or in a volar direction (Sandow et al., 2014). This allows the distal row of the wrist to assume a 45° offset, which enables the wrist to

accomplish the oblique power grip and the dart thrower's motion (Moritomo et al., 2007). In primates, the trapezoid is a relatively triangular shape; consequently, the trapezium is more in the coronal plane of the distal radius, thus, limiting the oblique power grip and dart thrower's motion (Sandow, 2020b; Sandow et al., 2014).

Independent finger and wrist motion

A cross-sectional analysis of the wrist demonstrates that the flexor tendons of the fingers are positioned in a central axis within the carpus. Wrist position, both in flexion and extension, thus has little effect on the moment of inertia on the flexor muscle tension (Sandow, 2020b). However, the wrist muscle tendons (flexor and extensor carpi ulnaris and flexor and extensor carpi radialis) are positioned to allow optimal control of wrist motion. The finger long extensors principally act to produce extension of the metacarpophalangeal joints, and interphalangeal joint extension is controlled by the intrinsic muscles within the carpus. The spatial arrangement of muscles within the forearm and hand achieve independent finger and wrist motion.

Low profile in the distal extremity

The wrist must have a narrow profile to optimize the independence and function of the fingers. Therefore, the strong muscles acting on the wrist to create finger and wrist motion are largely positioned in the proximal half of the forearm, which creates a slim distal extremity with powerful motion control.

Summary

The complexities of the wrist are enabled by the presence of a stable central column that delivers axial load from the radius to the lunate, then to the capitate and, finally, to the second and third metacarpals. This double row articulation is primarily stabilized by the spanning scaphoid. The identified connections between the proximal and distal rows can be characterized as a notional two-gear, four-bar linkage (Sandow et al., 2014). The alternating interconnections, both intra- and inter-row, between the carpal bones and the forearm bones follow an intricate pattern to allow flexibility and stability and, therefore, function (Sandow, 2020b). The stable central column theory of carpal biomechanics provides a unified concept for explaining carpal mechanics and understanding ways to address pathological disruptions of the carpus.

By using three-dimensional spatial quantitative analysis to assess disruptions, such as scapholunate instability, the various defects within the wrist can be identified. These include scapholunate diastasis, scaphoid dorsal subluxation, scaphoid flexion and lunate extension and ulnar translation. The specific defects can be characterized by a variable loss of the scaphoid trapezium ligaments, the LRL, the dorsal scapholunate connection and the connection of the
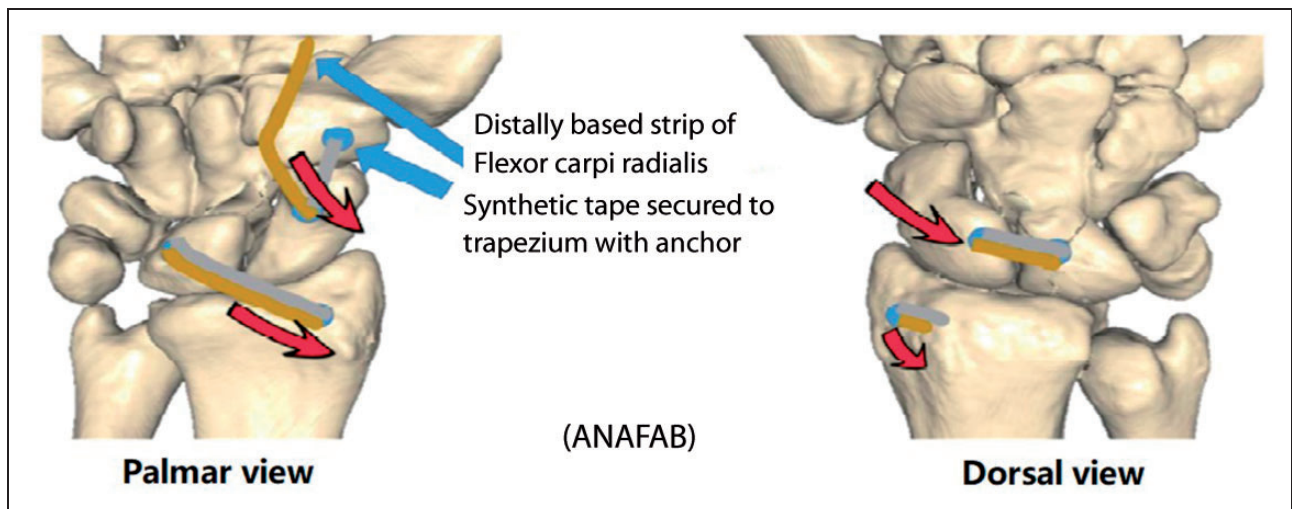

Figure 4. The anatomical front and back reconstruction (ANAFAB) addressing scapholunate dissociation: a hybrid of synthetic tape was secured to the trapezium with a bone anchor, and a distally based strip of flexor carpi radialis tendon was passed transosseously through the scaphoid, then the lunate and the radius. The tendon strip is secured with a further anchor to the bone. K wires were not used, but the wrist was immobilized in a cast for 6 weeks. Modified from illustration in Sandow and Fisher (2020) with permission from the *Journal of Hand Surgery (European Volume)*.

lunate to the DIC. Recent studies have provided additional support for the important role of the LRL and dorsal ligamentous connections (Pérez et al., 2019). A detailed explanation is beyond the summary in this article and is covered by other publications (Sandow, 2020b; Sandow and Fisher, 2020).

In cases of scapholunate diastasis and collapse of the central column, the application of a logic-based reconstructive volar and dorsal – anatomical front and back (ANAFAB) – surgical solution (Figure 4) has restored carpal function in a series of patients (Sandow and Fisher, 2020). This constitutes an initial proof of concept.

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