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Can the wrist be explained? The application of computer-based quantitative analysis to explain carpal biomechanics.

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Editor's note:
This paper constitutes a summary of the body of work detailed in Sandow (2020a; 2020b). For expanded explanation and justification of the statements and claims, the reader is referred to the monograph (Sandow, 2020b), thesis (Sandow, 2020a) and relevant cited publications.

INTRODUCTION

The wrist is a complicated structure; a consistent characterisation of the biomechanics and a reliable means to address dysfunction have been elusive (Garcia-Elias, 2013; Rainbow et al., 2016). The predominant research approach to the wrist has been through empirical observation. This involves extensively measuring both static and dynamic aspects of the wrist and then attempting to identify patterns from which a theory of function can be developed. This has been problematic because it is evident that there is no standard or 'normal' wrist, and even basic relationships between components of the wrist can vary between individuals (Garcia-Elias, 2013; Kamal et al., 2016; Moojen et al., 2003; Rainbow et al., 2016). Therefore, a conceptual approach to theory development was taken as part of a more extensive kinematic study (Sandow et al., 2014) and hypotheses were applied to test and refine the postulations. This is a fundamentally different approach to most current wrist research and 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 analysing the wrist was to understand the specific requirements and then identify how those requirements can be achieved. Specifically, the wrist needs to: (i) position the fingers and palm to allow them to perform the functional requirements; (ii) be based around the stable central second and third metacarpals on which the mobile thenar and hypothenar units act; and (iii) deliver sufficient gripping and rotational power, controlled in the proximal forearm, to allow for a slim wrist (Sandow, 2020a; Sandow, 2020b). On this basis, there appeared to be seven basic mechanical prerequisites that allow the wrist to perform its functional requirements (Sandow, 2020a; Sandow, 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
7. a low profile in the distal extremity to increase functionality.

BIOMECHANICAL ANALYSIS OF THE WRIST

Due to vascular perfusion of the carpal bones, there is a limited area of bone surface to allow articulation, and there are no anatomical connections that would equate as axles; therefore, the bones can only be connected by external linkages. 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 characterised 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 (see Figure 1) (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; Sandow, 2019). Therefore, the proximal row must move through a single uniaxial arc of motion with respect to the radius.

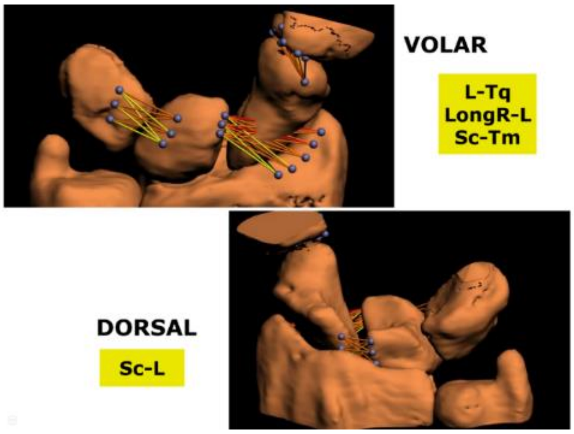

Figure 1. The specific isometric connections identified in the scapho-trapezial, volar radio-lunate, volar lunato-triquetral and dorsal scapho-lunate.

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: (i) the morphology or bone shape; (ii) the connection between the components (such as isometric connections); (iii) the interaction or friction/motion characteristic between the components; and (iv) 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 Taleisnik (1976), is a key element of the stable central column theory (see Figure 2) (Sandow et al., 2014).

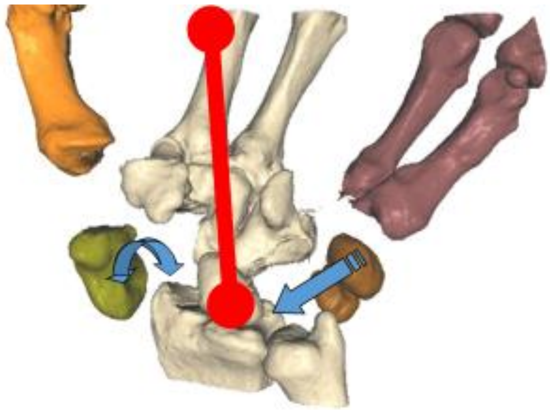

Figure 2. The stable central column of the carpus: radius - lunate - capitate = second/third metacarpals. Published with permission from the Journal of Hand Surgery (European Volume) (Sandow et al., 2014).

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;

Zhenying, 2011). 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.

DISCUSSION

Each anatomical or other motion system has the potential for 6 degrees of freedom. However, there are only two 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. While there is a variable degree of laxity within the wrist to allow some movement in these other directions (Garcia-Elias, 2008), the wrist is under active control in only 2 degrees of freedom (Sandow, 2020b). Therefore, the seven mechanical prerequisites can be reviewed in sequence.

1. **Adequate flexion and extension for holding and pushing**

Given the vascular and articulation constraints, a single row of wrist bones could only achieve approximately 45° of motion in each direction. A double articulation is required to achieve an arch of motion approaching 90° in both flexion and extension. However, this would create an inherently unstable linkage.

The proximal and distal rows of the wrist can be envisioned as stylised cylinders, each of which moves through a single axis (see Figure 3). The proximal and distal rows both move in a flexion and extension arc. Force is generally applied to the base of the metacarpals by the volar and dorsal wrist flexors and extensors, and the proximal row acts as an intercalated 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 (see Figures 3, 4A and 4B). An expanded summary is contained in the monograph (Sandow, 2020b).

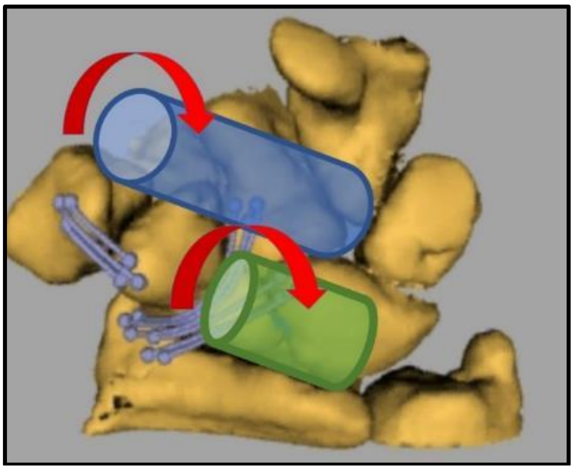

Figure 3. Proximal and distal carpal rows stylised as single-axis cylinders.

Figures 4A and 4B demonstrate the stylised sequential motion of the wrist in flexion; the mobile carpal bones are segmented and artificially moved sequentially (proximal row then distal row) to simulate the flexion motion.

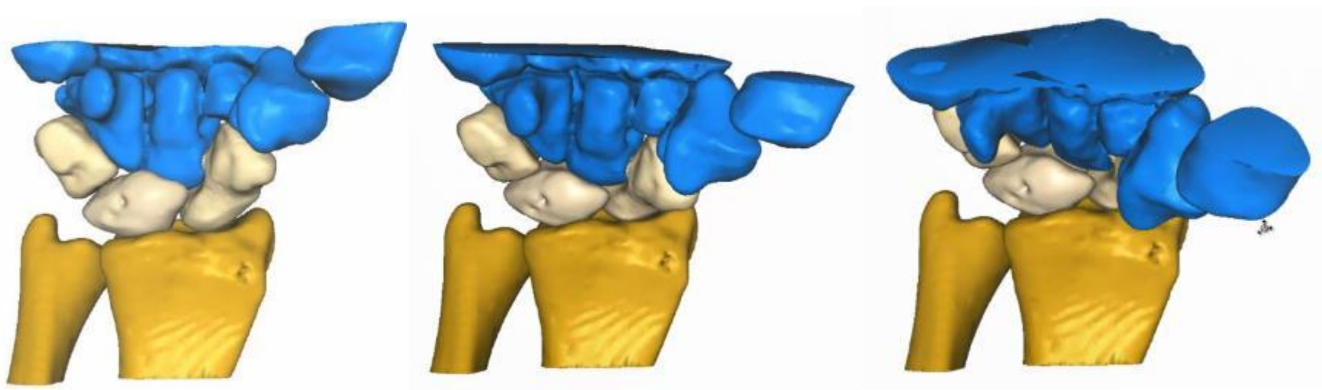

Figure 4A. Anterior view of wrist flexion (from left to right): (i) neutral, (ii) proximal row flexed, and (iii) distal row flexed.

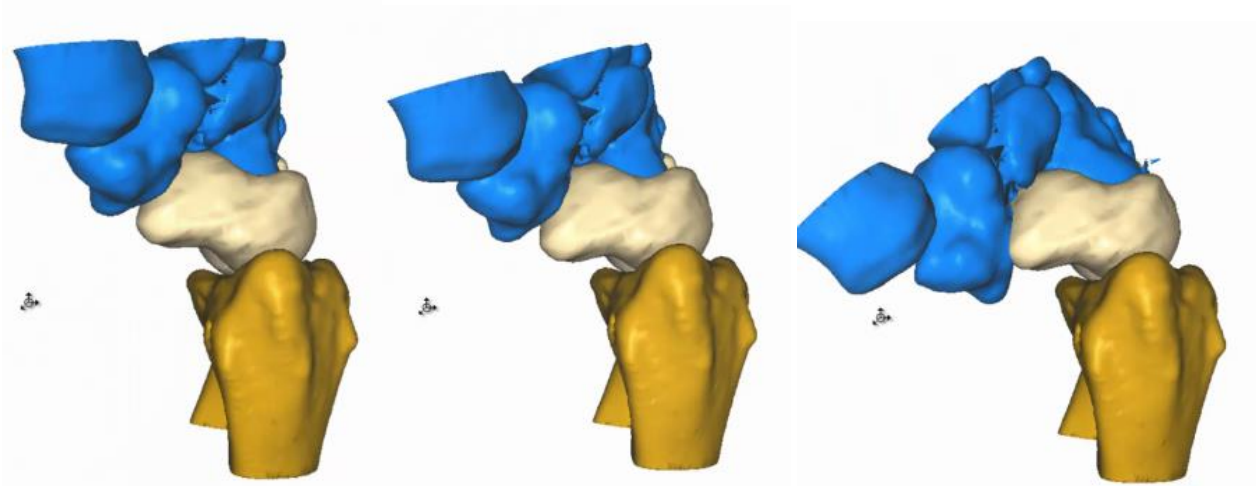

Figure 4B. Lateral view of wrist flexion (from left to right): (i) neutral, (ii) proximal row flexed, and (iii) distal row flexed.

2. Adequate side to side rotation motion adjusting to holding in different angles

Fixed cylinders acting around a single rotation axis 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 cylinders of the wrist, with each cylinder moving in opposite directions.

While the proximal row remains fixed in its rotational 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 mobility of the triquetrum), the axial alignment of the distal row can change. The dorsal translation of the triquetrum 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 (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 (pronated) distal row extends. Similarly, in ulnar deviation, the proximal row extends and the offset (pronated) distal row flexes (see Figure 5) (Sandow, 2020b).

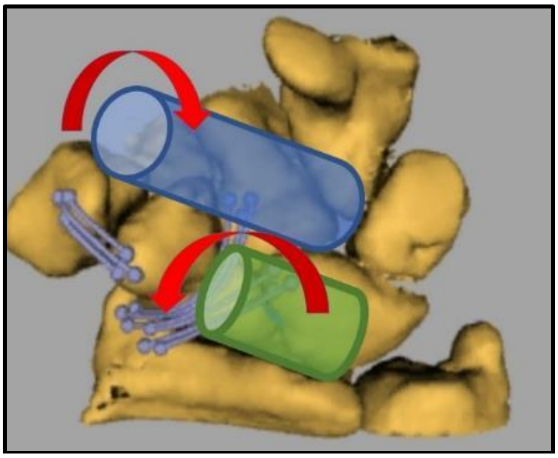

Figure 5. The proximal and distal rows stylised as offset single-axis cylinders moving in opposite directions to achieve radial and ulnar deviation.

The concept of the proximal row controlling midcarpal alignment and motion explains not only the general carpal biomechanics but, as part of the RBM concept, the many normal carpal functional and morphological variants. The ligamentous stabilisers of the intercalated segment (principally the lunate) is 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 explaining 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 2 degrees of freedom (see Figures 3, 4A, 4B and 5). A detailed diagrammatic explanation is provided in the monograph (Sandow 2020b).

3. Deliver powerful rotational force

One of the functional requirements of the forearm and wrist is that it has a slim distal aspect that can 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 ligament connections, which are well described by Garcia-Elias (1997, 2008) as the rotation resisting constraints: anti-pronation and anti-supination ligaments.

4. **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). Although the short radio-lunate ligament has been described as an important structure in controlling lunate extension, it is not anatomically positioned for this function and serves more as a longitudinal restraint to resist distraction of the wrist when the wrist is in slight ulnar deviation (Sandow, 2020a; Sandow, 2020b). Quantitative analysis of length changes during wrist motion has shown that the short radio-lunate ligament does not remain isometric through flexor and extension, but is ideally positioned to resist distraction of the radiocarpal joint due to longitudinal traction (Sandow, 2020b).

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

A unique characteristic of the human wrist is 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 utilises 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 (which constitutes an important stabiliser between the proximal and distal rows) 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 (Crisco et al., 2005; Moritomo et al., 2006; Moritomo et al., 2007; Wolfe et al., 2006). 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 et al., 2014). More details regarding the oblique power grip can be found in Sandow et al. (2014) and Sandow (2020b).

6. **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. This indicates that the wrist position, both in flexion and extension, will have little effect on the moment of inertia on the flexor muscle tension (Sandow, 2020b). However, the wrist motor muscle tendons (flexor and extensor carpi ulnaris and flexor and extensor carpi radialis) are located on the maximum volar and dorsal positions to increase the moment of inertia and allow optimal control of wrist motion. The finger long extensor tendons are positioned on the dorsal aspect of the carpus; however, it should be noted that although the long finger extensors assist with wrist extension, they principally act to produce extension of the metacarpophalangeal joints. Interphalangeal joint extension is controlled by the intrinsic muscles within the carpus, which are positioned so that wrist movements have a minimal effect on their function. Thus, there is an elegant spatial arrangement of long and short muscle tendon action within the forearm and hand to achieve independent finger and wrist motion.

7. **Low profile in the distal extremity**

The distal forearm and wrist must have a narrow profile to optimise 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.

Functional 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 stabilised by the spanning scaphoid, as demonstrated by the stable central column theory. The identified connections between the proximal and distal rows can be characterised 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).

CONCLUSION

The wrist is a complex, intricate and highly specialised biomechanical system. There exists great variation between individuals and a reliable and unified explanation on which to base the understanding of 'normal' mechanical performance has been elusive (Garcia-Elias, 2013). It has been even more challenging to assess and understand failures in wrist dysfunction and identify methods for addressing such failures. Many repairs have been unable to restore the mechanics of the wrist predictably (Lee et al, 2014). However, 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 characterised by a variable loss of constraint between the trapezium and scaphoid in the form of the scaphoid trapezium ligaments, the LRL, the dorsal scapholunate connection, and the connection of the lunate to the dorsal intercarpal ligaments. 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 paper and is covered by other publications (Sandow and Fisher, 2020; Sandow, 2020b).

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 (see Figure 6) has restored carpal function in a series of patients (Sandow and Fisher, 2020). This constitutes an initial proof of concept.

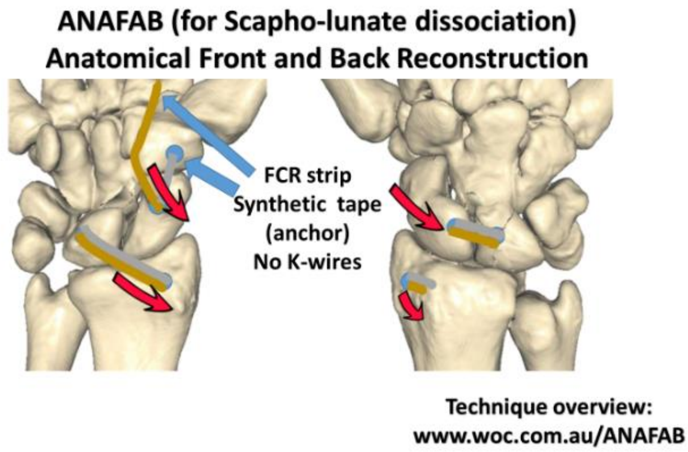

Figure 6. The ANAFAB procedure aims to address the identified deficits.

The application of computer-based quantitative analysis using specifically designed software (True Life Anatomy Pty Ltd, Adelaide, Australia) has allowed the characterisation of the key biomechanical linkage of the wrist as a stable central carpal column. This has enabled the recognition of certain biomechanical deficits in injured wrists, which has led to the identification of potential therapeutic solutions for wrist disorders. To this extent, it has also helped explain the wrist and its variable but uniquely human functionality.

Acknowledgements
The acknowledgements are contained in the monograph (Sandow, 2020b) and thesis (Sandow, 2020a).

Conflict of interest statement
Clinical Associate Professor Michael Sandow acknowledges a commercial interest in the development of the software used to support this research. 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 or its application.

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